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ACCURACY ASSESSMENT STUDY OF UNB3M NEUTRAL ATMOSPHERE MODEL FOR GLOBAL TROPOSPHERIC DELAY MITIGATION

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ABSTRACT

Tropospheric delay is the second major source of error after the ionospheric delay for satellite navigation systems. The transmitted signal could face a delay caused by the troposphere of over 2m at zenith and 20m at lower satellite elevation angles of 10 degrees and below. Positioning errors of 10m or greater can result from the inaccurate mitigation of the tropospheric delay. Many techniques are available for tropospheric delay mitigation consisting of surface meteorological models and global empirical models. Surface meteorological models need surface meteorological data to give high accuracy mitigation while the global empirical models need not. Several hybrid neutral atmosphere delay models have been developed by (University of New Brunswick, Canada) UNB researchers over the past decade or so. The most widely applicable current version is UNB3m, which uses the Saastamoinen zenith delays, Niell mapping functions, and a look-up table with annual mean and amplitude for temperature, pressure, and water vapour pressure varying with respect to latitude and height. This paper presents an assessment study of the behaviour of the UNB3m model compared with highly accurate IGS-tropospheric estimation for three different (latitude/height) IGS stations. The study was performed over four non-consecutive weeks on different seasons over one year (October 2014 to July 2015). It can be concluded that using UNB3m model gives tropospheric delay correction accuracy of 0.050m in average for low latitude regions in all seasons. The model's accuracy is about 0.075m for medium latitude regions, while its highest accuracy is about 0.014m for high latitude regions.

Keywords: UNB3m model, Different latitude, Troposphere, IGS

1. INTRODUCTION

The most widely used formula for tropospheric refractivity N is the (Smith and Weintraub, 1953) simplified two-term formula:

$$N = 77.6\frac{P}{T} + 3.73x10^5\left(\frac{e}{T^2}\right), \quad (1.1)$$

where,

P	:	the total atmospheric pressure in (mbar),
T	:	temperature in Kelvin,
e	:	partial pressure of water vapour (mbar).

Three basic types of models exist that relate the parameters in equation (1.1) to either empirical Surface Meteorological (SM) measurements (surface meteorological models) or global standard atmospheres (global empirical models) or numerical weather predication models.

Surface Meteorological models are based on radiosonde profiles and relate the parameters of equation (1.1) to measurements taken at the ground surface. The most well known models are the Hopfield and Saastamoinen models (Farah, 2004). Global Empirical Models avoid the use of surface meteorological data and assume that the atmosphere behaves in a certain manner depending on the behaviour of the temperature, pressure, and humidity such as Bomford, Bernese, Magnet, EGNOS and UNB models. Global weather prediction models uses mathematical models of the atmosphere and oceans to predict the weather based on current weather conditions such as the North American Mesoscale Model (NAM), the Global Forecast System (GFS) , and the long standing Nested Grid Model (NGM) (NCEI, 2015).

Several hybrid neutral atmosphere delay models have been developed by UNB researchers over the past decade or so. The most widely applicable current version is UNB3, which uses the Saastamoinen zenith delays, Niell mapping functions, and a look-up table with annual mean and amplitude for temperature, pressure, and water vapour pressure varying with respect to latitude and height. These parameters are computed for a particular latitude and day of year using a cosine function for the annual variation and a linear interpolation for latitude. The UNB3 model has been extensively used in several regions of the world, being capable of predicting total zenith delays with average uncertainties of 0.05m under normal atmospheric conditions. UNB3m is a modified version of UNB3 has been used in GPS receivers utilizing the Wide Area Augmentation System and other space-based augmentation systems

This paper presents an assessment study for the UNB3m model. The zenith tropospheric estimations were compared from the model with IGS-estimates for three varying (latitude & height) IGS stations (badg, mas1and nklg) (see Table 1.1). The tropospheric zenith delay data from four weeks in different seasons were chosen to assess the seasonal variation of the weather conditions (see Table 1.2). With the highly accurate estimation of the total tropospheric delay from the IGS-Tropospheric products, the differences of total zenith delay between the UNB3m model and the IGS-Troposphere estimation will give an indication of the quality of the model and assess its adequacy for tropospheric delay correction globally.

Table 1.1: The geographic positions of the tested IGS stations

Station	Latitude (degrees)	Longitude (degrees)	Orthometric Height (metres)
badg	51.7697 N	102.2350 E	850.250
mas1	27.7637 N	15.6333 W	155.494
nklg	0.3539 N	9.6721 E	21.477

Table 1.2: The dates for (different-seasons) four weeks used in tropospheric delay mitigation study

GPS week	1814	1828	1840	1852
Date	12/10/2014- 18/10/2014	18/1/2015- 24/1/2015	12/4/2015- 18/4/2015	05/7/2015- 11/7/2015
Season	Autumn	Winter	Spring	Summer

2. UNB3M TROPOSPHERIC MODEL

(Collins and Langley, 1997) proposed a hybrid neutral atmosphere model designed for Wide Area Augmentation System (WAAS) users. This model, called UNB3, has its algorithm based on the prediction of meteorological parameter values, which are then used to compute hydrostatic and non-hydrostatic zenith delays using the Saastamoinen models. The slant delays are determined using the Niell mapping functions. A modified version of UNB3 was actually adopted for WAAS with the Niell mapping functions being replaced by the single Black and Eisner mapping function and with some other minor simplifications (RTCA, 2001). The WAAS version of UNB3 has been favourably assessed for use with the European Geostationary Navigation Overlay Service (Dodson et al., 1999; Penna et al., 2001) and the Japanese Multi-functional Transport Satellite Augmentation System (Ueno et al., 2001). In order to account for the seasonal variation of the neutral atmosphere behaviour, a look-up table of meteorological parameters is used. The parameters are barometric pressure, temperature, water vapour pressure (WVP), temperature lapse rate (β) and water vapour pressure height factor (λ). This look-up table was derived from the U.S. Standard Atmosphere Supplements, 1966 (COESA, 1966). Table 2.1 shows the look-up table values for UNB3. The data is divided into two groups, to account for the annual average (mean) and amplitude of a cosine function for each parameter. Both amplitudes and averages vary with respect to latitude, for all parameters. The first step in the UNB3 algorithm is to obtain the meteorological parameter values for a particular latitude and day of year using the look-up table. By definition, the origin of the yearly variation is day of year (doy) 28. This procedure is similar to the one used in the Niell mapping functions computation. The interpolation between latitudes is done with a linear function. The annual average of a given parameter can be computed as:

Table 2.1. Look-up table of UNB3 model

Average					
Latitude (degrees)	**Pressure (mbar)**	**Temperature (K)**	**WVP* (mbar)**	**β (K m $^{-1}$)**	**λ (-)**
15	1013.25	299.65	26.31	6.30e-3	2.77
30	1017.25	294.15	21.79	6.05e-3	3.15
45	1015.75	283.15	11.66	5.58e-3	2.57
60	1011.75	272.15	6.78	5.39e-3	1.81
75	1013.00	263.65	4.11	4.53e-3	1.55
Amplitude					
Latitude (degrees)	**Pressure (mbar)**	**Temperature (K)**	**WVP* (mbar)**	**β (K m $^{-1}$)**	**λ (-)**
15	0.00	0.00	0.00	0.00	0.00
30	-3.75	7.00	8.85	0.25e-3	0.33
45	-2.25	11.00	7.24	0.32e-3	0.46
60	-1.75	15.00	5.36	0.81e-3	0.74
75	-0.50	14.50	3.39	0.62e-3	0.30

$$\mathrm{Avg}_{\phi}=\begin{cases}\mathrm{Avg}_{15},\ \text{if } \phi\le 15\\ \mathrm{Avg}_{75},\ \text{if } \phi\ge 75\\ \mathrm{Avg}_{i}+\dfrac{\left(\mathrm{Avg}_{i+1}-\mathrm{Avg}_{i}\right)}{15}\cdot\left(\phi-\mathrm{Lat}_{i}\right),\\ \qquad\qquad\qquad\qquad \text{if } 15<\phi<75\end{cases}\tag{2.1}$$

where ϕ stands for the latitude of interest, in degrees, Avg_{ϕ} is the computed average, i is the index of the nearest lower tabled latitude and Lat stands for latitude (from the table 2.1). The annual amplitude can be computed in a similar manner:

$$\mathrm{Amp}_{\phi}=\begin{cases}\mathrm{Amp}_{15},\ \text{if } \phi\le 15\\ \mathrm{Amp}_{75},\ \text{if } \phi\ge 75\\ \mathrm{Amp}_{i}+\dfrac{\left(\mathrm{Amp}_{i+1}-\mathrm{Amp}_{i}\right)}{15}\cdot\left(\phi-\mathrm{Lat}_{i}\right),\\ \qquad\qquad\qquad\qquad \text{if } 15<\phi<75\end{cases}\tag{2.2}$$

where Amp_{ϕ} stands for the computed amplitude. After average and amplitude are computed for given latitude, the parameter values can be estimated for the desired day of year according to:

$$\mathrm{X}_{\phi,\mathrm{doy}}=\mathrm{Avg}_{\phi}-\mathrm{Amp}_{\phi}\cdot\cos\left((\mathrm{doy}-28)\frac{2\pi}{365.25}\right),\tag{2.3}$$

where, $\mathrm{X}_{\phi,\mathrm{doy}}$ represents the computed parameter value for latitude ϕ and day of year doy . This procedure is followed for each one of the five parameters. Once all five parameters are determined for given latitude and day of year, the zenith delays can be computed according to

$$\mathrm{d}_\mathrm{h}^\mathrm{z} = \frac{10^{-6}\mathrm{k}_1\mathrm{R}}{\mathrm{g_m}} \cdot \mathrm{P}_0 \cdot \left(1 - \frac{\beta\mathrm{H}}{\mathrm{T}_0}\right)^{\frac{\mathrm{g}}{\mathrm{R}\beta}} \tag{2.4}$$

and

$$d_{nh}^{z} = \frac{10^{-6}\left(T_m k_2' + k_3\right)R}{g_m\,\lambda' - \beta R} . \frac{e_o}{T_o} . \left(1 - \frac{\beta H}{T_o}\right)^{\frac{\lambda' g}{R\beta} - 1} \tag{2.5}$$

Where,

- T_o, P_o, e_o, β, and λ are the meteorological parameters computed according to (2.1) to (2.3);
- H is the orthometric height in m;
- R is the gas constant for dry air (287.054 J kg^{-1-} K^{-1});
- g_m is the acceleration of gravity at the atmospheric column centroid in m s^{-2} and can be computed from

$$\mathrm{g_m} = 9.784(1 - 2.66\mathrm{x}10^{-3}\cos(2\phi) - 2.8\mathrm{x}10^{-7}\mathrm{H}) \tag{2.6}$$

- g is the surface acceleration of gravity in m s^{-2};
- T_m is the mean temperature of water vapour in K and can be computed from

$$\mathrm{T_m} = \mathrm{T}\left(1 - \frac{\beta\mathrm{R}}{\mathrm{g_m}\lambda'}\right) \tag{2.7}$$

- $\lambda' = \lambda + 1$ (unitless)

- k1, k2$^{'}$, and k3 are refractivity constants with values 77.60 K mbar^{-1}, 16.6 K mbar^{-1} and 377600 K^{2} mbar^{-1}, respectively.

The total slant delay can be finally computed according to

$$\mathrm{d_t} = \mathrm{m_b}\mathrm{d}_\mathrm{h}^\mathrm{z} + \mathrm{m_{nb}}\mathrm{d}_\mathrm{nb}^\mathrm{z}, \tag{2.8}$$

where m_h and m_{nh} stand for hydrostatic and nonhydrostatic (Niell, 1996) mapping functions, respectively. Further details about UNB3 development and performance can be found in (Collins and Langley, 1997). An extensive discussion of neutral atmosphere propagation delay modelling and testing can be found in (Mendes, 1999).

UNB3m was created by modifying parameter values in the UNB3 look-up table and the associated UNB3 algorithms. These changes were made in order to carry out the predictions using relative humidity rather than water vapour pressure. The part of the table that was related to water vapour pressure was replaced with values related to relative humidity. In UNB3m, all the computations for the point of interest are done initially using relative humidity, which is subsequently converted to water vapour pressure for use in the zenith delay computation. Further details about UNB3M development and performance can be found in (Leonardo et al., 2006).

3. ASSESSMENT STUDY

3.1 Low-Latitude Region

The total tropospheric zenith delay estimates from UNB3m model and the IGS-Tropospheric delay estimates for (nklg) station (low latitude) , for each of the four weeks are shown in Figures 1, 2, 3 and 4. Table 3.1.1 shows the total zenith delay difference analysis between the UNB3m model and the IGS-Tropospheric delay estimation for (nklg) station.

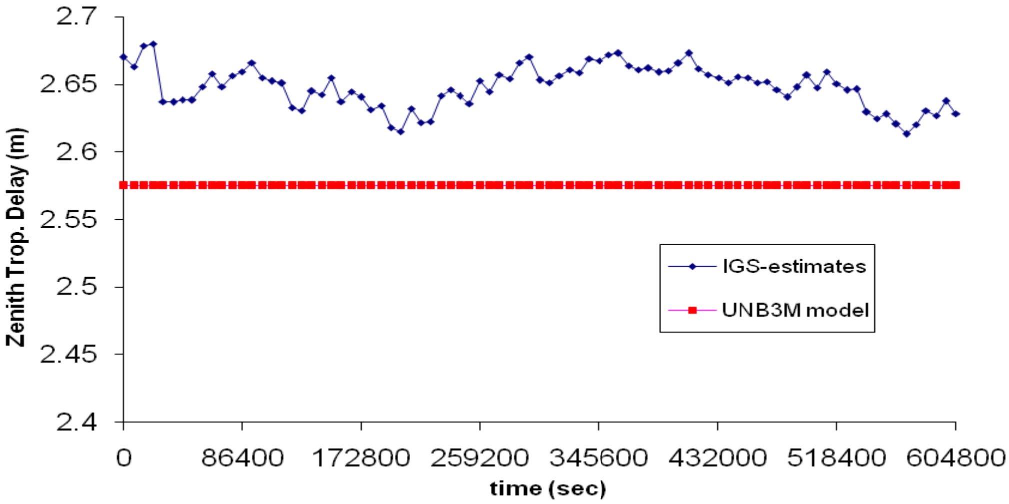


Fig. (1): Zenith tropospheric Correction for IGS station (nklg) from UNB3m model and IGS-Estimates during GPS week (1814)

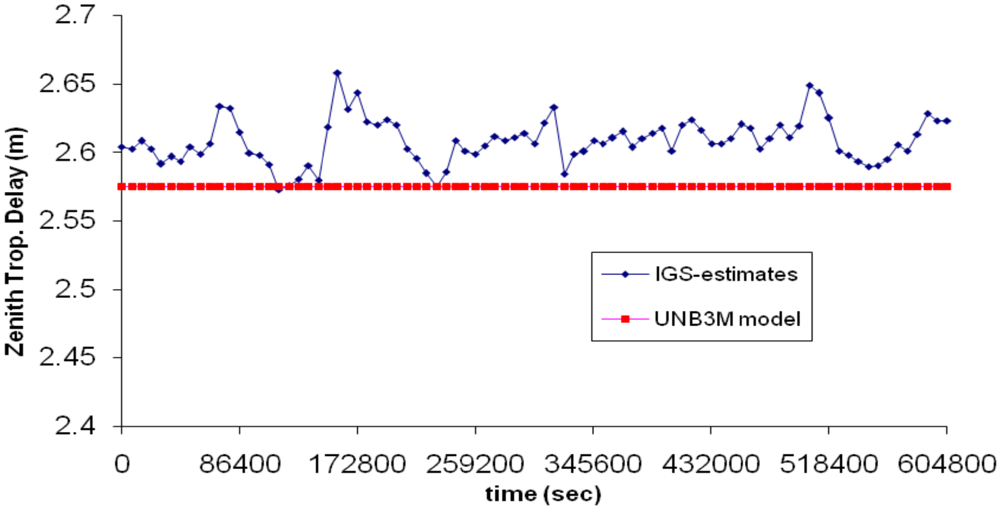


Fig. (2): Zenith tropospheric Correction for IGS station (nklg) from UNB3m model and IGS-Estimates during GPS week (1828)

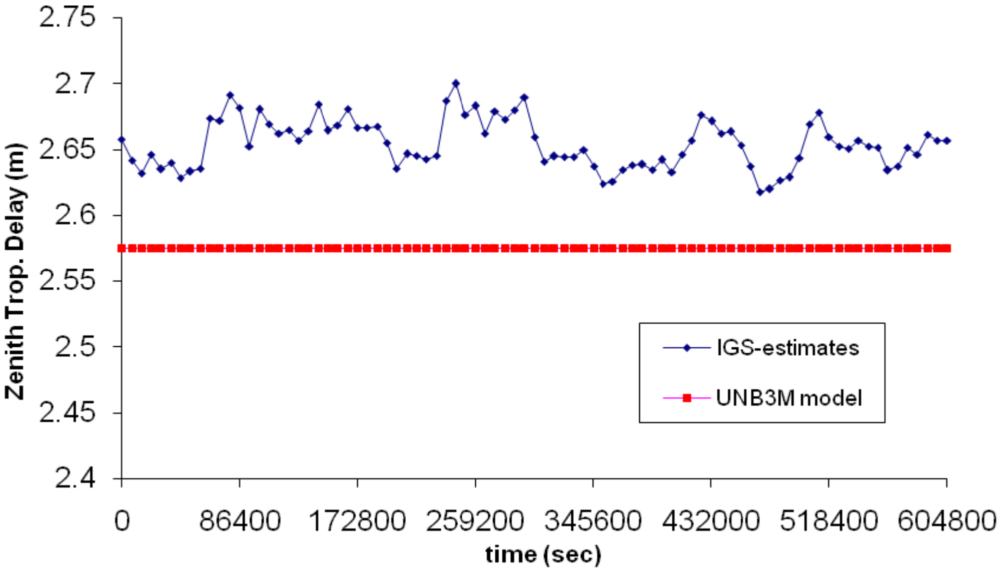


Fig. (3): Zenith tropospheric Correction for IGS station (nklg) from UNB3m model and IGS-Estimates during GPS week (1840)

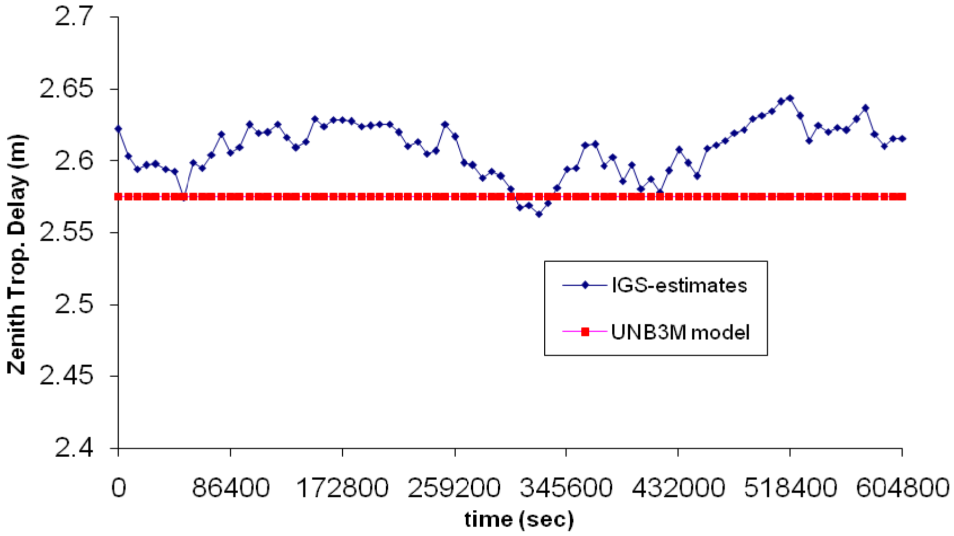


Fig. (4): Zenith tropospheric Correction for IGS station (nklg) from UNB3m model and IGS-Estimates during GPS week (1852)

Table 3.1.1: Total Tropospheric Zenith Delay Difference analysis between UNB3M Model and IGS-tropospheric estimation for (nklg- low latitude IGS station)

Station	GPS week	Min. (m)	Max. (m)	Mean (m)	RMS (m)
Nklg	1814	-0.1051	-0.0384	-0.0733	0.0154
	1828	-0.0833	0.0022	-0.0334	0.0163
	1840	-0.1248	-0.0427	-0.0794	0.0184
	1852	-0.0686	0.0120	-0.0333	0.0180

3.2 Medium-Latitude Region

The total tropospheric zenith delay estimates from UNB3m model and the IGS-Tropospheric delay estimates for (mas1) station (med. latitude) , for each of the four weeks are shown in Figures 5, 6, 7 and 8. Table 3.2.1 shows the total zenith delay difference analysis between the UNB3m model and the IGS-Tropospheric delay estimation for (mas1) station.

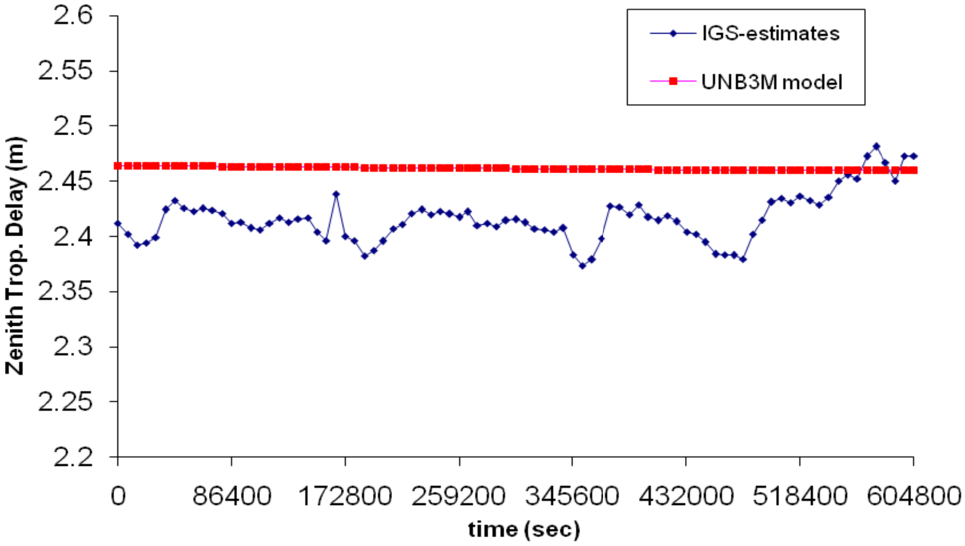


Fig. (5): Zenith tropospheric Correction for IGS station (mas1) from UNB3m model and IGS-Estimates during GPS week (1814)

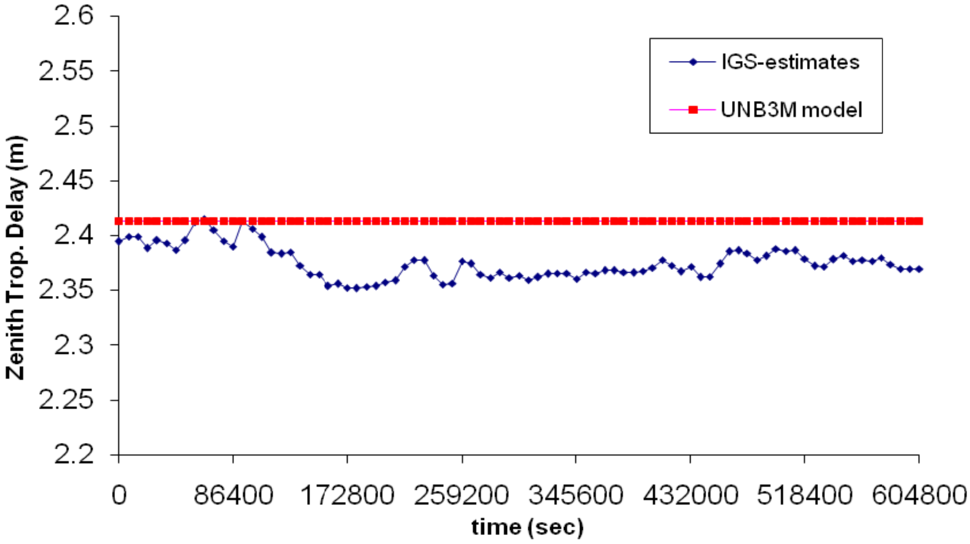


Fig. (6): Zenith tropospheric Correction for IGS station (mas1) from UNB3m model and IGS-Estimates during GPS week (1828)

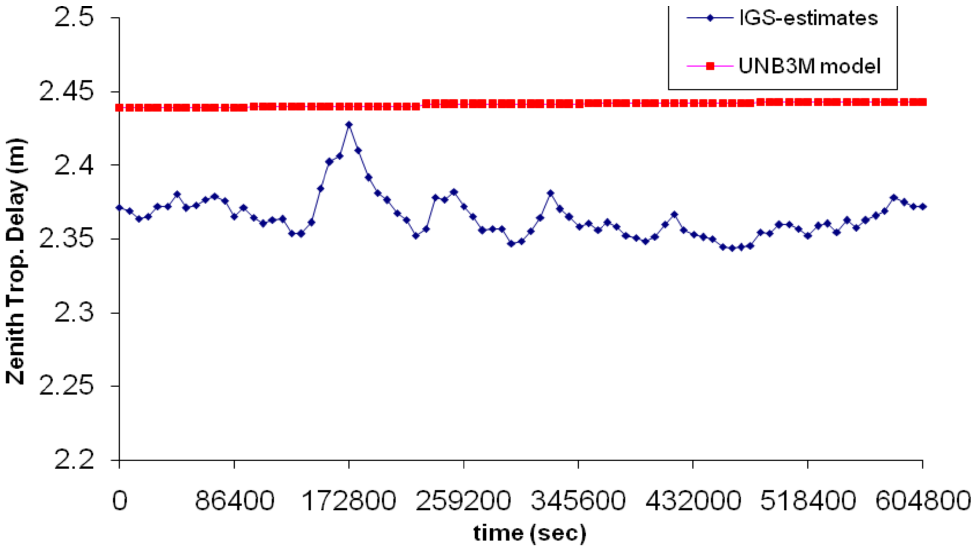


Fig. (7): Zenith tropospheric Correction for IGS station (mas1) from UNB3m model and IGS-Estimates during GPS week (1840)

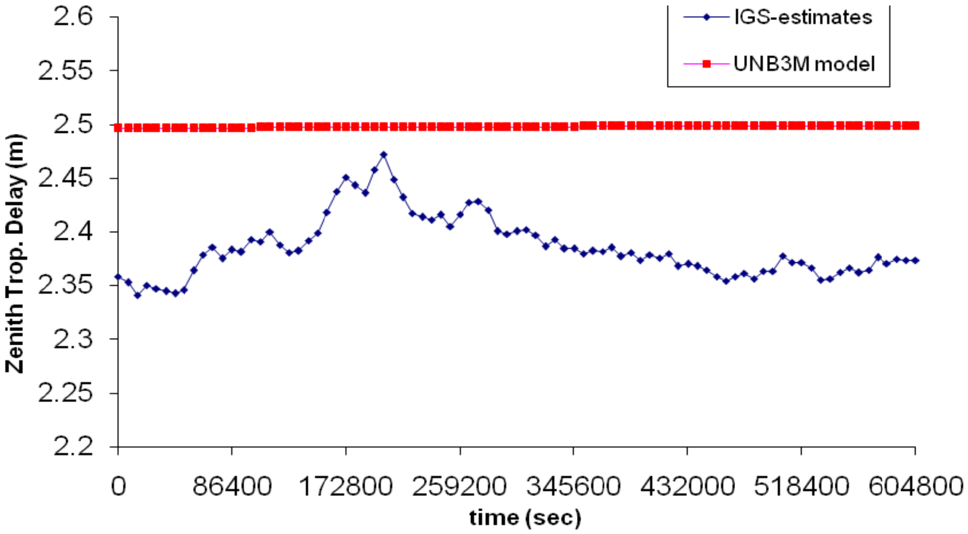


Fig. (8): Zenith tropospheric Correction for IGS station (mas1) from UNB3m model and IGS-Estimates during GPS week (1852)

Table 3.2.1: Total Tropospheric Zenith Delay Difference analysis between UNB3M Model and IGS-tropospheric estimation for (mas1-medium latitude IGS station)

Station	**GPS week**	**Min. (m)**	**Max. (m)**	**Mean (m)**	**RMS (m)**
mas1	1814	-0.0214	0.0877	0.0449	0.0225
	1828	-0.0019	0.0613	0.0378	0.0148
	1840	0.0125	0.0982	0.0757	0.0153
	1852	0.0246	0.1547	0.1117	0.0284

3.3 High-Latitude Region

The total tropospheric zenith delay estimates from UNB3m model and the IGS-Tropospheric delay estimates for (badg) station (high latitude) , for each of the four weeks are shown in Figures 9, 10, 11 and 12. Table 3.3.1 shows the total zenith delay differences analysis between the UNB3m model and the IGS-Tropospheric delay estimation for (badg) station. Note that some of the IGS estimation in Figure 10 contains null periods due to a lack of data.

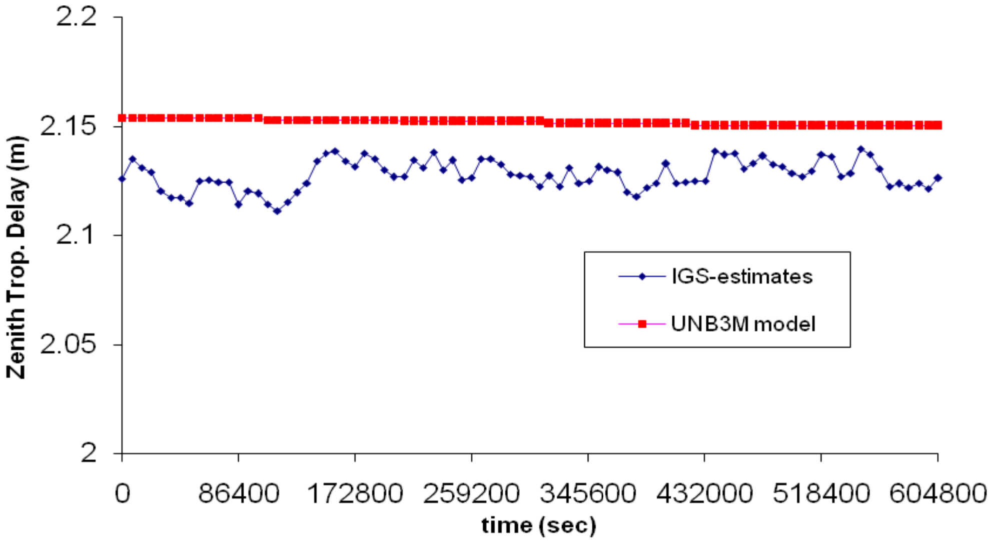


Fig. (9): Zenith tropospheric Correction for IGS station (badg) from UNB3m model and IGS-Estimates during GPS week (1814)

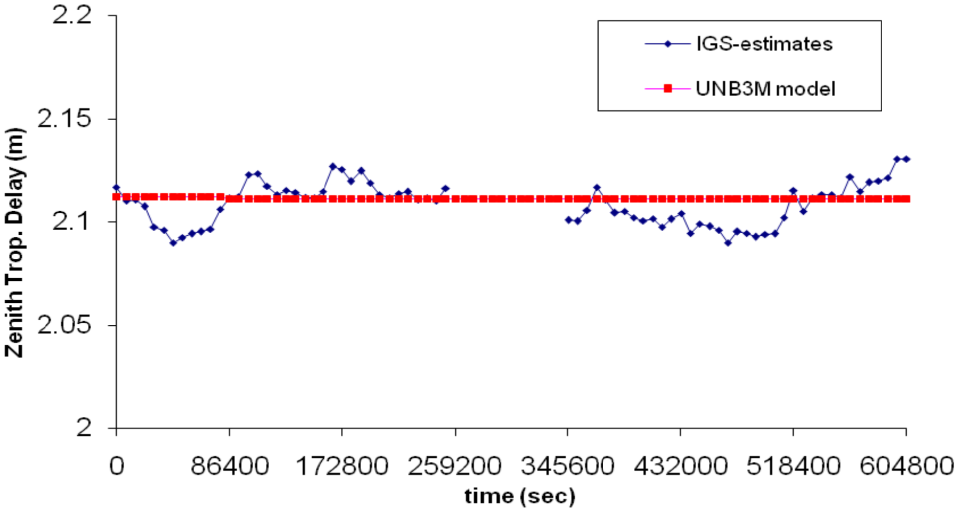
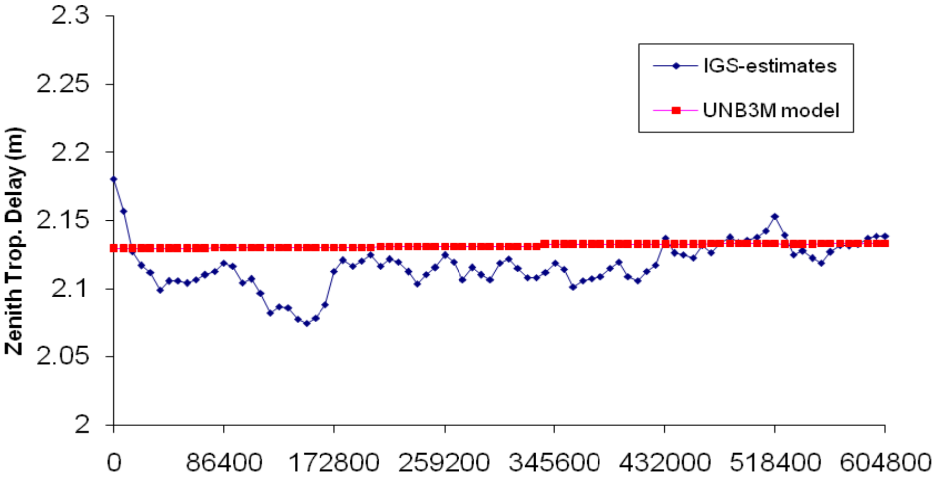


Fig. (10): Zenith tropospheric Correction for IGS station (badg) from UNB3m model and IGS-Estimates during GPS week (1828)



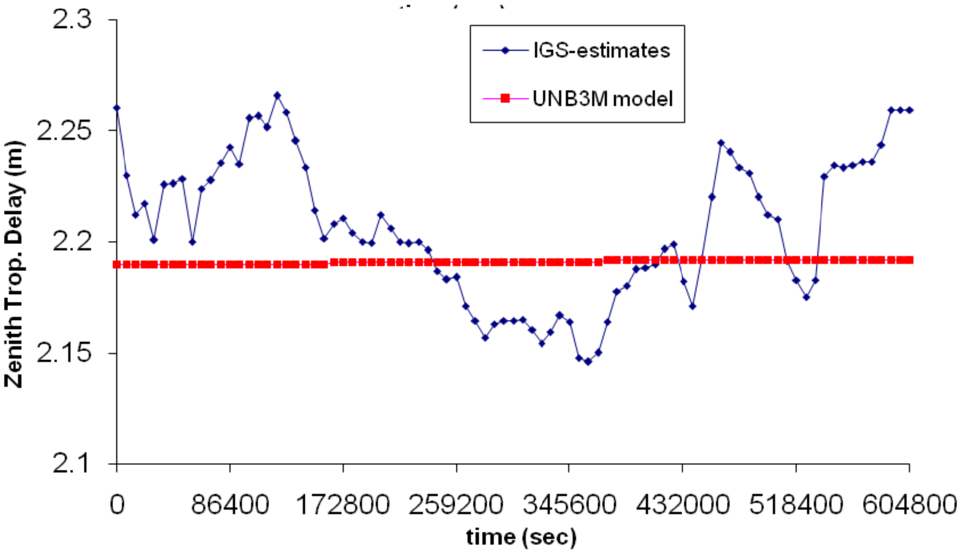


Fig. (12): Zenith tropospheric Correction for IGS station (badg) from UNB3m model and IGS-Estimates during GPS week (1852)

Table

3.3.1: Total Tropospheric Zenith Delay Difference analysis between UNB3M Model and IGS-tropospheric estimation for (badg-high latitude IGS station)

Station	GPS week	Min. (m)	Max. (m)	Mean (m)	RMS (m)
badg	1814	0.0105	0.0419	0.0240	0.0072
	1828	-0.0195	0.022	0.0026	0.0112
	1840	-0.0513	0.0555	0.0139	0.0167
	1852	-0.0758	0.0451	-0.0152	0.0322

4. DISCUSSION

From the above shown figures (1 to 4) & table 3.1.1 for low latitude region, it is shown that the UNB3m model is giving better behavior in winter and summer seasons comparing with its behavior in autumn and spring seasons. The average mean difference between the model and IGS estimates is about 0.030m in winter and summer seasons. While the average mean difference between the model and IGS estimates is about 0.070 m in autumn and spring seasons.

From the above shown figures (5 to 8) & table 3.2.1 for medium latitude region, it is shown that the UNB3m model is following closely IGS estimates in winter and autumn seasons rather than summer and spring seasons. The model is giving its best behavior in winter season with average mean difference of about 0.030m while the average mean difference is about 0.040m in autumn season. While, the average mean difference between the model and IGS estimates is about 0.070m in spring season. The model is shown its worst behavior in summer season with an average mean difference of 0.110m.

From the above shown figures (9 to 12) & table 3.3.1 for high latitude region, it is shown that the UNB3m model is following closely the IGS estimates in winter, spring and summer seasons better than autumn season. The average mean differences are 0.003m, 0.013m and 0.015m in winter, spring and summer seasons respectively. While the average mean difference is 0.024m in autumn season.

It can concluded in general that the UNB3m model is giving better behavior for high latitude regions rather than medium and low latitude regions. This could be explained by the fact that the model look up table (table 2.1) for atmospheric parameters was derived from the U.S. Standard Atmosphere Supplements, 1966 (COESA, 1966).

5. CONCLUSIONS

It is recommended to use UNB3M model for estimating the zenith trop. delay correction for low latitude regions in seasons; winter and summer. For medium latitude regions, the model is behaving better in winter and autumn seasons, while it is recommended to use the model for trop. delay correction in winter and spring seasons.

UNB3m model gives tropospheric delay correction accuracy of 0.050m in average for low latitude regions in all seasons. The model's accuracy is about 0.075m for medium latitude regions, while its highest accuracy is about 0.014m for high latitude regions.

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