Troposphere Delay Remote Sensing Using Single GPS Receiver

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Abstract

The most prominent spatially correlated errors in GNSS observations are well known to be atmospheric effects. The ionosphere and troposphere are the two main layers of the Atmosphere that cause delays in GNSS observations. A linear combination of the dual-frequency data can be used to reduce ionospheric delay. Unlike the ionospheric delay, the tropospheric delay cannot be eliminated using the same methods. The troposphere is primarily associated with GPS. The delay it causes in GPS signals is regarded as one of the primary sources of errors that must be eliminated to determine accurate positions.

This paper's main purpose is to develop a new source code that can estimate the effect of tropospheric delay over any GPS station. The tropospheric delay in this proposed code is estimated utilizing sequential least-squares adjustment using a model depending on Niell Mapping Function (NMF). This model, known as the Tropospheric Delay Estimation program, was created in the MATLAB® environment (TDE).

This research presents the results of tropospheric delay during DOY 2, 2020 of actual data from ten ground-based IGS stations distributed over Antarctica, China, Canada, Fiji, Russia, Greenland, and Portugal IGS stations worldwide. For validation of the proposed code results, they were compared with troposphere delay results of the International GNSS Service (IGS). Good agreement and high correlation were found between both results. In comparison to IGS, the

proposed code's standard deviations range from 0.0000525 m to 0.008154 m, indicating how accurate this study is in terms of agreement of solutions provided by IGS. Finally, the MATLAB software can accurately estimate troposphere delay with an adaptable temporal resolution for GPS users.

Keywords: GNSS, NMF, Troposphere Delay, IGS.

1. Introduction

The ionosphere and troposphere layers delay GNSS signals. The lowest layer of our Atmosphere is the troposphere, extending 5 to 9 miles above sea level from the Earth's surface. Because of the change in the refractive index of the medium during the transmission of Global Navigation Satellite System (GNSS) signals through the Atmosphere, a tropospheric delay occurs. As a result, the tropospheric effect is closely related to GPS and is regarded as one of the most prominent sources of all errors in point positioning using GPS techniques (Ghilani et al., 2014). There are two parts to the delay induced by the neutral Atmosphere. The hydrostatic or dry component (HZD) is the first component that can be rectified using Tropospheric correction modeling. The wet delays (ZWD) are the second portion, caused mainly by water vapor in the Atmosphere.

The troposphere's effect on GNSS signals causes an extra delay in measuring the signal traveling from satellite to receiver. This delay is determined by the station's location and meteorological parameters such as temperature, pressure, and humidity. (Hofmann-Wellenhof et al., 2008). The troposphere delay can be divided into wet and dry components according to physical parameters. On the first hand, water vapor content in the troposphere layer causes the tropospheric wet delay. On the other hand, particles and dry gases in the troposphere layer cause a hydrostatic delay that equals about 85 % of the total tropospheric delay (Zhang et al., 2021).

Knowing that the tropospheric delay cannot be eliminated by combining dual or multi-frequency GNSS observations because the troposphere is a non-dispersive medium (not frequency-dependent). Thus, researchers have developed a variety of modeling approaches and

methodologies for mitigating tropospheric delay, including Saastamonien, modified Hopfield, and simplified Hopfield, MOPS, Ifadis, and Mendes (Kitpracha et al., 2017).

The current study's major goal is to create a MATLAB source code that will allow GPS users to precisely estimate the troposphere delay induced by the Atmosphere using GNSS observations.

The results reveal a good convergence between the proposed code's estimated troposphere delay and IGS's estimated troposphere delay. The suggested model has a temporal resolution of thirty seconds, whereas IGS and other techniques such as GAPS and magicGNSS provide troposphere delay results with ten minutes temporal resolution.

2. Troposphere Delay Estimation Technique.

The troposphere's effect is modeled in the current study using the Niell Mapping Function (NMF) and tropospheric zenith delays. The troposphere delay between the satellite and the receiver is calculated as follows in terms of elevation angle (E) and azimuth angle (AZ) (Astudillo et al., 2018):

$$TD = M_h \, Z_H + M_w \, (1 + \cot E \, (G_N \, \cos AZ \, + \, G_E \, \sin AZ)) \, Z_W \qquad (1)$$

where TD the total tropospheric delay in meters is estimated using sequential least-squares along with the tropospheric gradient's north component (G_N) and the east component of the tropospheric gradient (G_E). In additions, M_h , M_w are the hydrostatic and wet mapping functions, respectively (Abdelfatah et al., 2018).

Z_H, Z_W are the tropospheric zenith hydrostatic and wet delay in meters, respectively, which can be calculated using a tropospheric model, such as Saastamoinen, Hopfield, or a modified Hopfield model with zero zenith angle. They can be calculated using the receiver's height and estimates of five meteorological parameters, namely, $P, T, e, \beta \ and \ \lambda$, which stand for pressure, temperature, water vapor pressure, temperature lapse rate, and water vapor lapse rate, respectively (Isioye et al., 2015):

$$Z_H = (1 - \frac{\beta H}{T})^{\frac{g}{R_d \, \beta}} \, * \, \frac{10^{-6} \, k_1 \, R_d \, P}{g_m} \qquad (2)$$

$$Z_W = (1 - \frac{\beta H}{T})^{\frac{(\lambda+1)g}{R_d \beta} - 1} * \frac{10^{-6} k_2 R_d}{(\lambda+1)g_m - \beta R_d} \frac{e}{T} \tag{3}$$

Where: H is the height in meters above mean sea level, K_1=77.604 $K/mbar$, K_2=382000 $K^2/mbar$, $R_d = 287.054$ $J/Kg/K$, $g_m = 9.784$ m/s^2 and $g = 9.80665$ m/s^2 and the parameters P, T are obtained directly from the meteorological file. In addition, Equations (4 and 5) are used to calculate the parameters β, λ using the receiver latitude (ϕ), Day-Of-Year (D) and D_{min} which are 28 and 211 for North and South latitudes, respectively (Sharifi and Souri, 2013).

$$\beta = \beta_0(\phi) - \Delta\beta(\phi)\cos\left(\frac{2\pi(D-D_{min})}{365.25}\right) \tag{4}$$

$$\lambda = \lambda_0(\phi) - \Delta\lambda(\phi)\cos\left(\frac{2\pi(D-D_{min})}{365.25}\right) \tag{5}$$

Table 1. Values of average and seasonal variation meteorological parameters (Schueler, 2001).

Latitude (ϕ)	Average			Seasonal Variation		
	β_0 (^oK) /m	λ_0	e_0 ($mbar$)	$\Delta\beta$ (^oK)/m	$\Delta\lambda$	Δe ($mbar$)
$\|\phi\| \leq 15^o$	0.0063	2.77	26.31	0.0	2.77	0.0
$15^o<\|\phi\|\leq 30^o$	0.00605	3.15	21.79	0.00025	3.15	8.85
$30^o<\|\phi\|\leq 45^o$	0.00558	2.57	11.66	0.00032	2.57	7.24
$45^o<\|\phi\|\leq 75^o$	0.00539	1.81	6.78	0.00081	1.81	5.36
$\|\phi\|\geq75^o$	0.00543	1.55	4.11	0.00062	1.55	3.39

The following sequence of least-squares adjustments is used to estimate troposphere delay, the north component of tropospheric gradient (G_N) and the east component of the tropospheric gradient (G_E) (Guochang Xu, 2007):

$$L=AX \tag{6}$$

$$X = (A_1^T.P_1.A_1 + A_2^T.P_2.A_2)^{-1}(A_1^T.P_1.L_1 + A_2^T.P_2.L_2) \tag{7}$$

Where: L_1 and L_2 are the first and the second group vector of observations, respectively, A_1 and A_2 are the observation design matrices for the first and second groups of observations, respectively, P_1 and P_2 are the first and second groups of observations' weight matrices, respectively, and X is

the vector of unknown parameters. Tropospheric Delay Estimation (TDE) was the name of the proposed model, which was created in the MATLAB® environment.

meteorological parameters from the meteorological file, in addition to receiver latitude (ϕ), elevation (H), constants of R_d, g_m , g, K_1, K_2, K_3, Elevation angle (E) and azimuth angle (AZ) between satellite and receiver are the input parameters of the proposed code. Then, β and λ, which stand for temperature lapse rate, and water vapor lapse rate, respectively, are estimated using equations (4) and (5) and table 1. After that, Z_H and Z_W which represent the tropospheric zenith hydrostatic and wet delay in meters, respectively, are calculated using equations (2) and (3). Then, M_h , M_w The hydrostatic and wet mapping functions are calculated using the NMF equation. Finally, the total tropospheric delay TD in meters is estimated using equation (1) using sequential least-squares figure (1) shows the block diagram of the input, processing, and output stages of the TDE program.
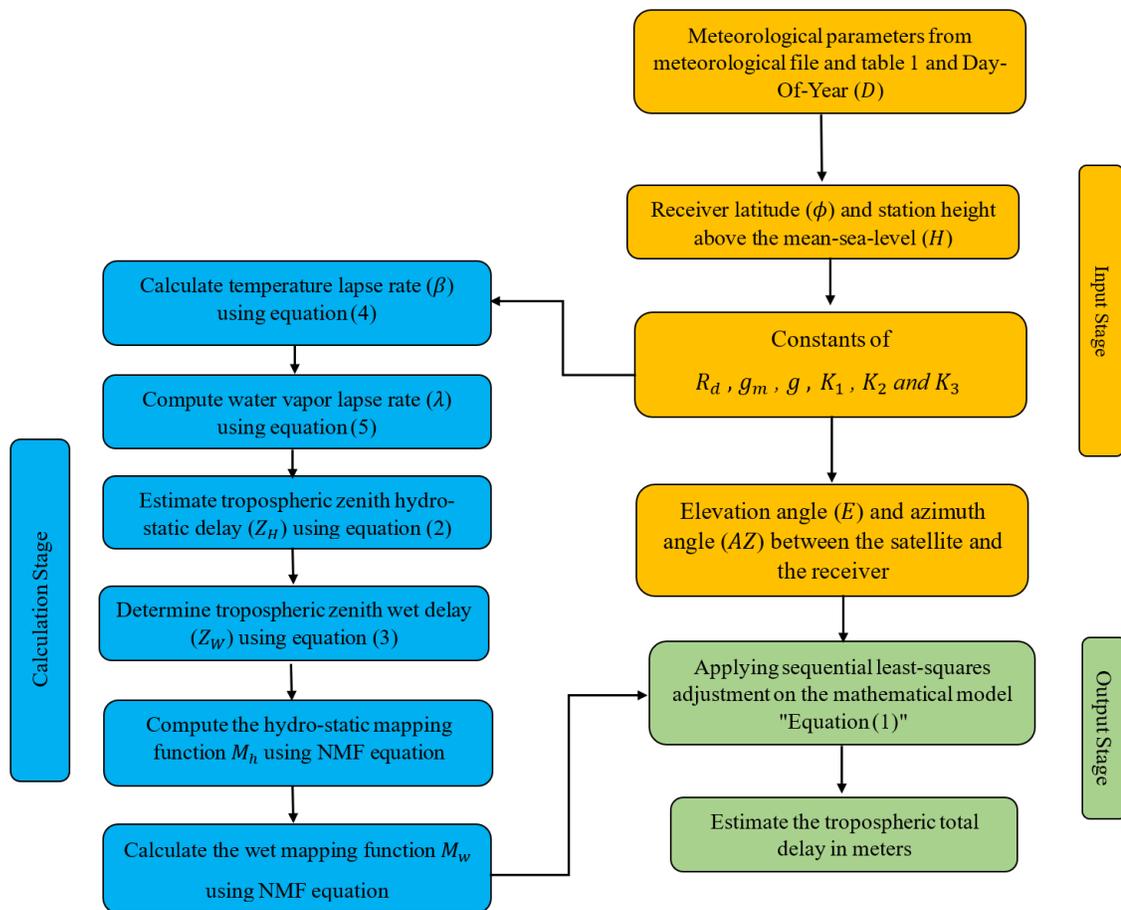
Figure 1 the block diagram of the input, processing, and output stages of the TDE program.

3. Results

In the current study, the TDE program was applied to estimate the tropospheric delays of DOY 2, 2020 for ten IGS stations that are distributed over Antarctica, China, Canada, Fiji, Russia, Greenland, and Portugal. The proposed model results were compared to the results of IGS, as shown in the following figures, to assess its performance in Greenland and Portugal.

Astudillo et al., 2018 estimated the total tropospheric delay in meters using the open-source positioning software RTKLIB which uses the same mathematical model that was used in our proposed code. The Root Mean Square Error (RMSE) was used as an indicator of the accuracy of the estimation to indicate how different the estimated value is from the ground truth, which ranged between 18.67 and 2.06 cm.

While in the current study Figures (2 to 11) show the good fitting of the estimated tropospheric delay from the TDE program and tropospheric delay provided by IGS, where the maximum difference (in meters) between the developed code results and IGS for HKSL, BAMF, UNBJ, LAUT, NVSK, SVTL, THU, FUNC, and PDEL stations is 0.028796, 0.060988, 0.162082, 0.11006, 0.209486, 0.11459, 0.070855, 0.118777 and 0.128709, respectively. On the other hand, the minimum difference (in meters) between results for the same stations is 0.00872, 0.000178, 0. 0.008537, 0.017358, 0.001634, 0.11886, 0.048665, 0.001371, 0.000558 and 0.022932, respectively. Also, table (2) shows the standard deviation of the estimated TD using the TDE program.
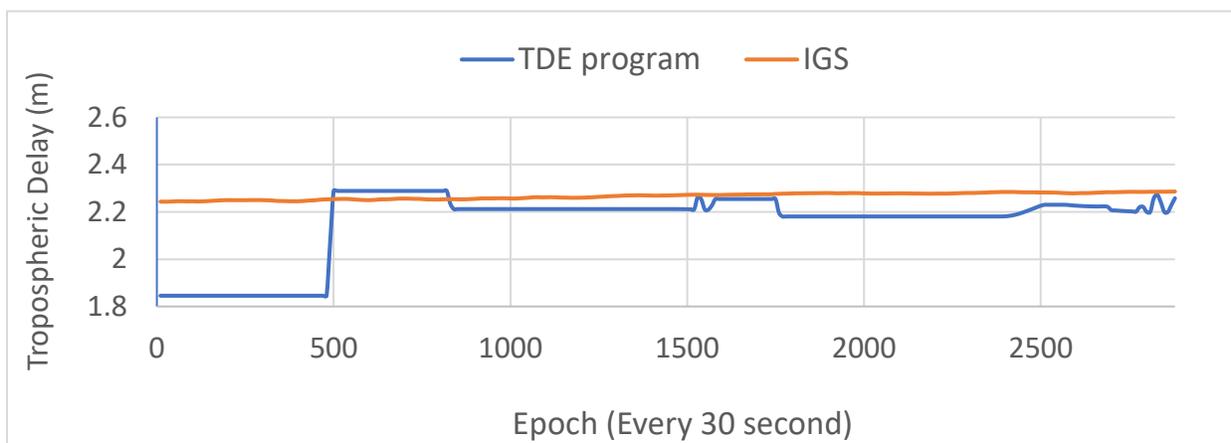
Figure 2 Estimated delay of the troposphere for DAV station by TDE program and IGS of DOY 2, 2020.
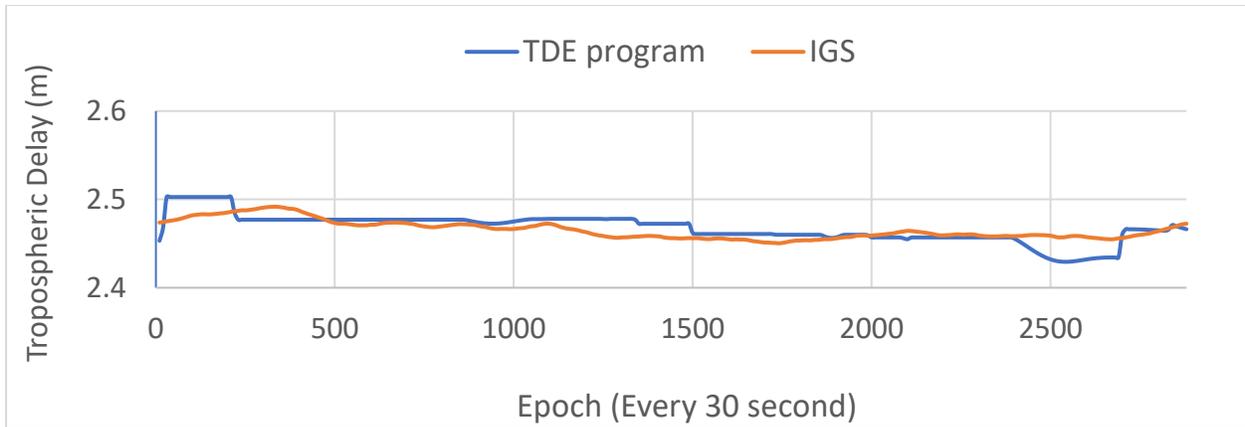
Figure 3 Estimated delay of the troposphere for HKSL station by TDE program and IGS of DOY 2, 2020.
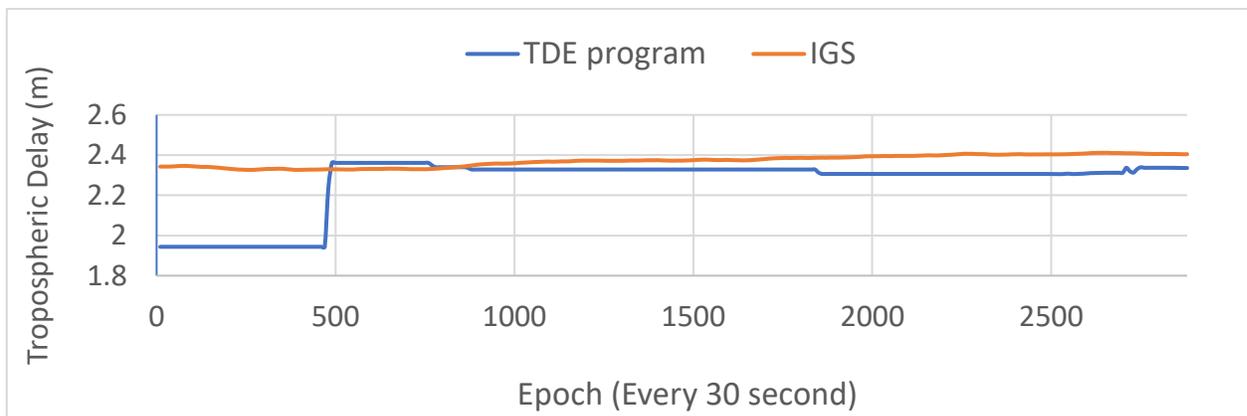
Figure 4 Estimated delay of the troposphere for BAMF station by TDE program and IGS of DOY 2, 2020.
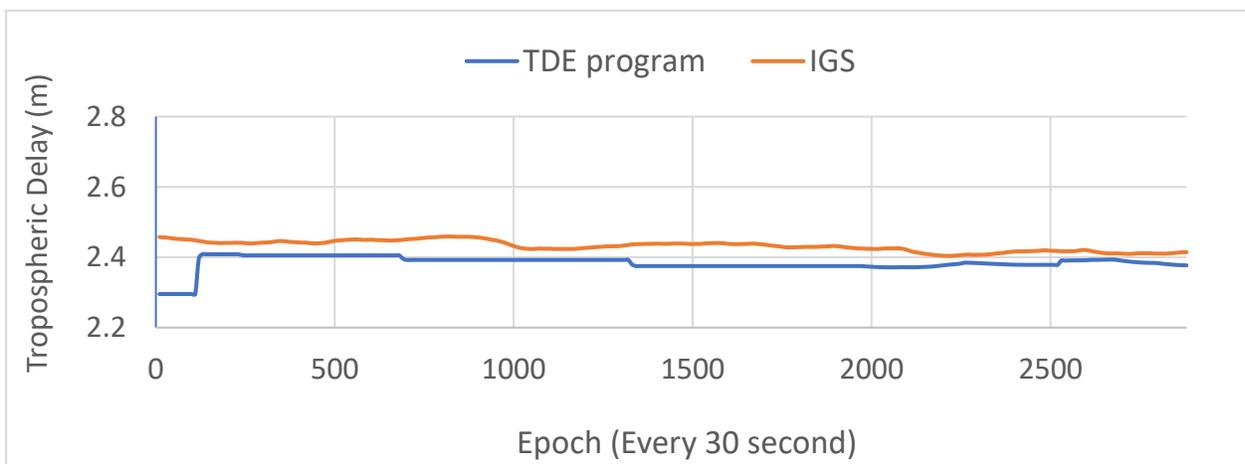
Figure 5 Estimated delay of the troposphere for UNBJ station by TDE program and IGS of DOY 2, 2020.

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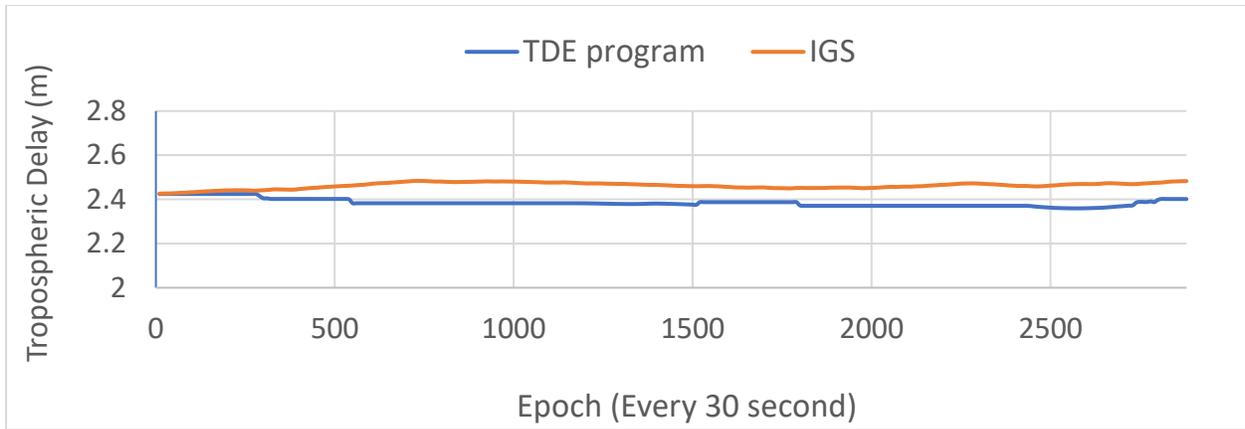
Figure 6 Estimated delay of the troposphere for LAUT station by TDE program and IGS of DOY 2, 2020.
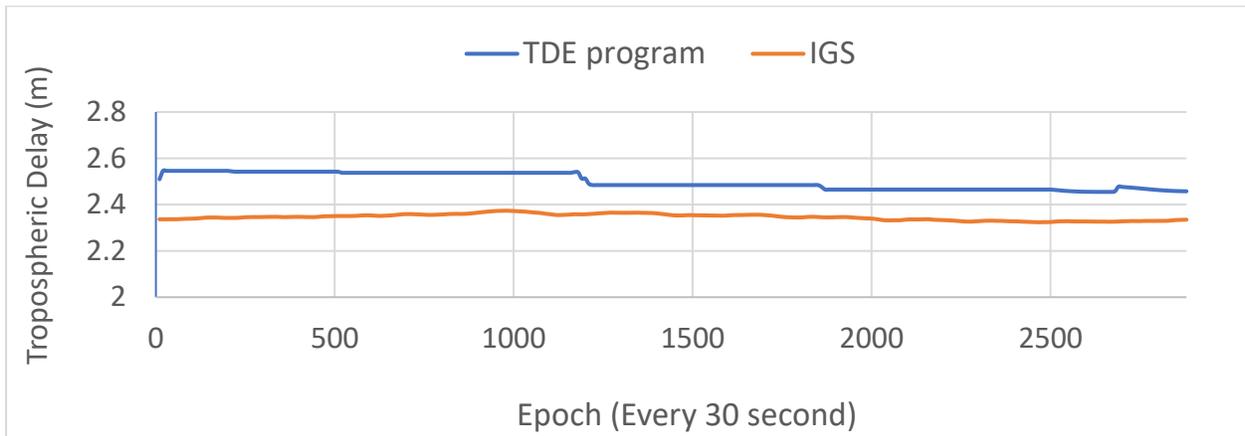
Figure 7 Estimated delay of the troposphere for NVSK station by TDE program and IGS of DOY 2, 2020.
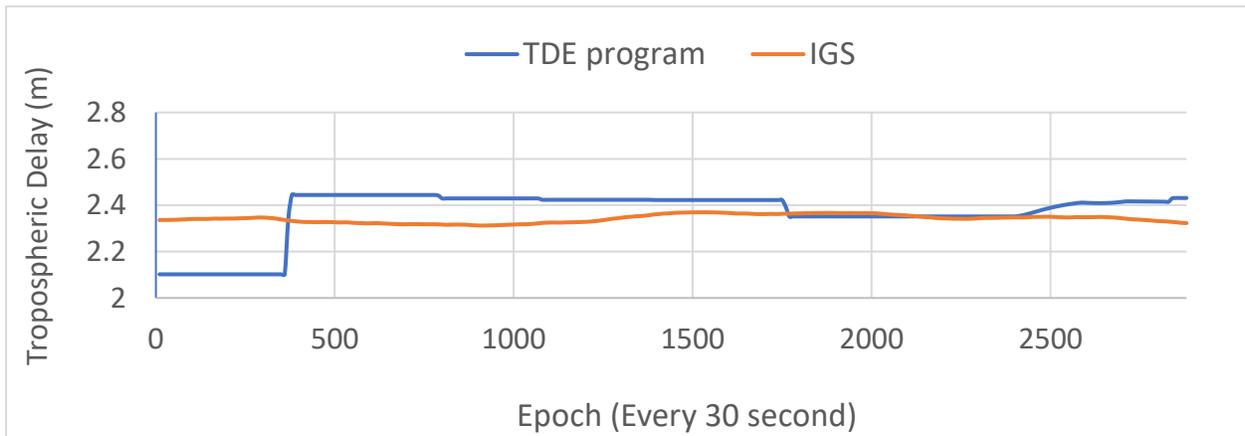
Figure 8 Estimated delay of the troposphere for SVTL station by TDE program and IGS of DOY 2, 2020.

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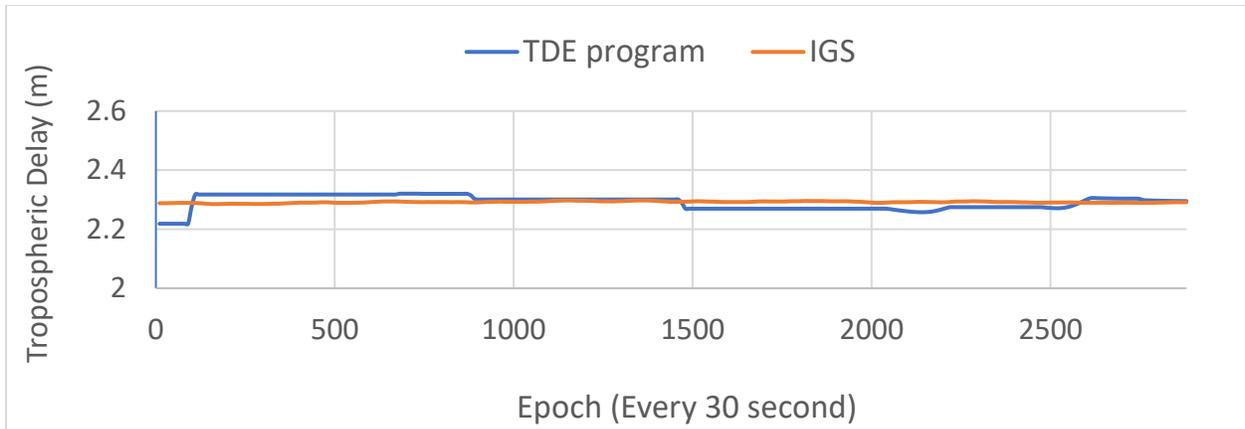
Figure 9 Estimated delay of the troposphere for THU station by TDE program and IGS of DOY 2, 2020.
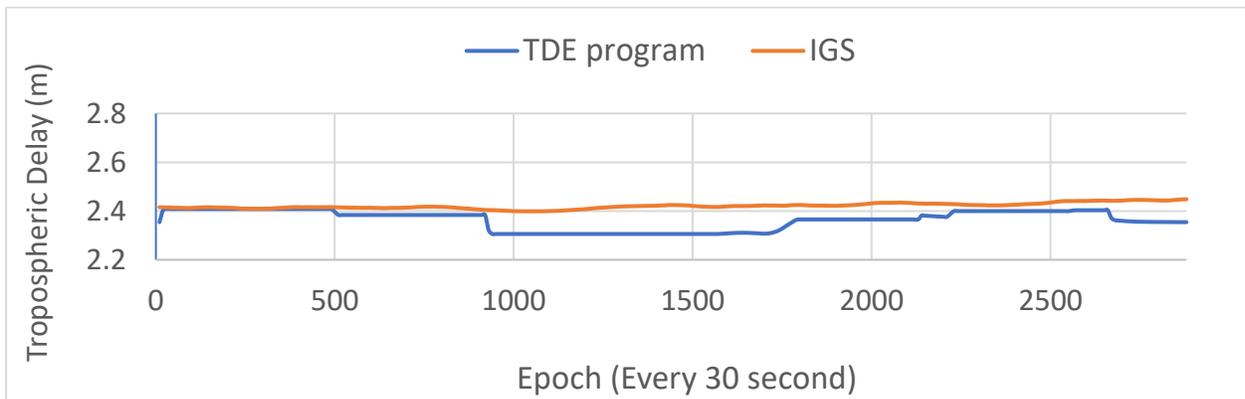
Figure 10 Estimated delay of the troposphere for FUNC station by TDE program and IGS of DOY 2, 2020.
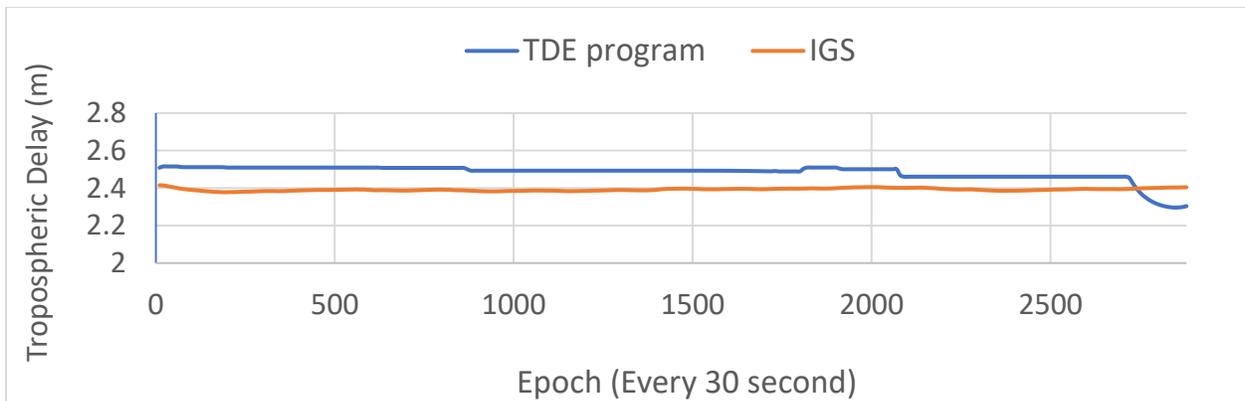
Figure 11 Estimated delay of the troposphere for PDEL station by TDE program and IGS of DOY 2, 2020.

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Table 2. The average Troposphere Delay at each station of DOY 2, 2020, using TDE and IGS.

Station Coordinates (Degree)			Average Troposphere Delay (m)			Standard Deviation (m)
Name	Latitude	Longitude	Code	IGS	Difference	
DAV	-68.577	77.973	2.156315	2.267002	0.110690	0.006534
HKSL	22.372	113.928	2.467586	2.465433	0.002153	0.000127
BAMF	48.835	-125.135	2.335117	2.371014	0.035900	0.002119
UNBJ	45.950	-66.642	2.383887	2.431888	0.048000	0.002833
LAUT	-17.609	177.447	2.386173	2.462589	0.076420	0.004511
NVSK	54.841	83.236	2.484259	2.346127	0.138132	0.008154
SVTL	60.533	29.781	2.367152	2.342095	0.025057	0.001479
THU	76.537	-68.825	2.290853	2.291742	0.000890	0.000053
FUNC	32.648	-16.908	2.393808	2.420998	0.027190	0.001605
PDEL	37.748	-25.663	2.482328	2.392042	0.090285	0.005329

The tropospheric delays computed with the proposed code and IGS are compared in the previous figures. Table (2) also summarises the previous figures, indicating that the differences between the proposed code and IGS results of the estimated tropospheric delay range from 0.000890 m to 0.138132 m. Otherwise, the estimated tropospheric delay standard deviations range from 0.0000525 m to 0.008154 m. These findings describe how accurate this study is regarding the agreement of solutions provided by IGS. The following section clarifies the current study's conclusions.

4. CONCLUSIONS

In general, the troposphere affects GPS signals. The refraction created in GPS signals is one of the primary sources of inaccuracies that must be avoided to calculate precise positions. As a result, the current study addresses a crucial aspect of GPS positioning. The following are the present study's conclusions based on the objectives and outcomes:

- For GPS observations using data from a single GPS receiver, MATLAB-based software was developed to estimate tropospheric delay accurately.
- The proposed code's results demonstrate a good fit with the IGS results, which define how much precision this model can provide, implying that this model is easy to use.
- Thirty seconds temporal resolution, the TDE program returns tropospheric delay results. This temporal resolution offers a relatively good representation of the tropospheric

effect on GPS observations. IGS and other techniques, like GAPS and magicGNSS, provide troposphere delay results with 10 minutes temporal resolution.

- Finally, utilizing this software, we created an expressive tropospheric delay for GPS observations using data from any GPS receiver.

6. References

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