

Application of Digital Model of Meteorological Data in Tropospheric Delay Errors Estimation of GNSS Measurements

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ABSTRACT: A major source of error in space-based geodesy is the tropospheric delay, which results in excess path length of the Global Navigation Satellite Systems (GNSS) signal as it passes through the neutral atmosphere. Tropospheric models that use real, predicted or empirical meteorological data have been applied to account for this error. The models widely used in geodesy are Hopfield, Saastamoinen, Black, GPS-Code-Analysis–Tool (GCAT) and Minimum Operational Performance Standards (MOPS). In current study, a methodology that utilized real meteorological data obtained by Global Forecast System (GFS) digital weather model in GRIB format was defined and used. Based on data obtained for different months in 2019, which coverage all seasonal variations of ZTDs, it was found that the accuracy obtained by using of real meteorological data of GFS was 1.5 to 2 times higher than that obtained from standard or empirical models. The RMS of Hopfield, Saastamoinen, and Black's using predicted meteorological parameters showed less than 5% difference from one another (0.063 m, 0.061 m, and 0.062 m, respectively). Real GPS data of nine GPS stations in 7-day period were used for evolution the zenith part obtained by using of real meteorological data of GFS against that used standard or empirical models. The data were processed using Bernese software version 5.0. The closure error results prove that the model used real meteorological data is the best model in all session.

Keywords: Digital meteorological data model; Hopfield model; Saastamoinen model; Black model; GCAT models; MOPS model; IGS.

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I. INTRODUCTION:

Tropospheric delay is well-known to be a major source of error in Global Navigation Satellite Systems (GNSS) surveying. Many standard or empirical tropospheric delay models have been established based on global radiosonde data, including the Saastamoinen model and the Hopfield model. Because of large spatial-temporal heterogeneities in the lower atmosphere, these empirical models can easily result in residual tropospheric errors that are several centimeters at the zenith [Penna N. et al., 2001], and are highly variable between different seasons and regions [Ashraf K. et al., 2012]. However, it is very difficult for standard or empirical models to satisfy the accuracy requirements for various GNSS surveys, such as regional precipitable water retrieved, atmospheric In SAR corrections and precise point positioning [Ashraf K. et al., 2012].

In practice, a user often employs a certain troposphere model based on the popularity of the model without giving enough justification as to why it should be used. Limited comparisons between some of the models have been carried out in the past for local or regional applications. However, in this contribution, this issue is addressed more comprehensively considering the peculiarities of the GNSS network. Most GNSS stations continent are characterized by the lack of collocated meteorological sensors, as it is required for such to be collocated with the GNSS antenna if the GNSS data are to be processed for integrated water vapour content determination [Isioye O.A., et al., 2015]. Thus, the inversion of ground meteorological data into the variable vapour content in the atmosphere is very difficult.

The inputs of the most tropospheric models include meteorological parameters (air temperature, atmospheric pressure, and air humidity) at the point of observation obtained directly or indirectly. If it is not possible to obtain such meteorological parameters, standard or empirical tropospheric delay models are used,

such as the GCAT and MOPS models. The accuracy of such models has been reported to range between 22 mm [Torben S., 2001] and 54 mm [Eva K., et al., 2005]. An alternative approach to obtain the meteorological parameters at the point of observation is the use of a numerical weather forecast. The Global Forecast System (GFS) is an important numerical weather prediction model that provides medium-range weather forecasts. Each GFS run needs a set of initial values system state variables (Yin J. et al., 2019). The GFS operationally running is a three-dimensional hydrostatic global spectral model. It uses the Global Data Assimilation System (GDAS) to provide guess fields for the full forecasts.

Thus, the main aim of this paper was to compare different digital and standard or empirical models to calculate the tropospheric delays. The accuracy of tropospheric delay calculation using the Hopfield, Saastamoinen, and Black models using meteorological parameters obtained from a numerical weather forecast was investigated. In addition, the accuracy of calculating the tropospheric delay using the standard or empirical tropospheric delay models GCAT, MOPS, and Saastamoinen, was examined. The results are then compared to the ground truth. RMSE and maximum error are used to evaluate the performance of each model. The tropospheric estimations were compared from models with the International GNSS Service (IGS) estimates. The study utilized the new IGS product for the interval of five months, which coverage all seasonal variations of ZTDs; February, April, July, September, and October 2019 and for 21 sites. The new IGS ZTD product is based on the precise point positioning (PPP) technique. It has a higher sampling rate and lower formal errors than the legacy IGS ZTD product and can be obtained with typical formal errors of 1.5–5 mm from the IGS [Byun and Bar-Sever, 2009]. Gaps are common in the data, but at least 5 month of ZTD estimates is available for each site.

During the last several years, in Egypt, a number of models have been developed and reported in scientific literature by scientists for evaluations and correction of the delay induced by the troposphere in the GPS signal. Abdelfatah et al. (2009) carried out an assessment of tropospheric delay models and recommended Saastamoinen and Hopfield model for Egypt. Mousa and El-Fiky (2005) have developed a local model for Egypt. Younes S.A., (2014) have investigated several models, including those developed by Hopfield, Saastamoinen, Niell (NMF), Chao, Black & Eisner (B&E), Yan & Ping, Vienna (VMF) and Isobaric (IMF), to assess these models in predicting dry tropospheric delay and developed a new mapping function which has better low elevation angle performance up to 5° and is suitable for the atmospheric conditions of Egypt. Abdelfatah et al., (2015) have derived precise troposphere slant delay model (PTD) based on radiosonde data well-distributed over and around Egypt. Ray tracing technique of actual signal path traveled in the troposphere is used to estimate tropospheric slant delay.

In this study, Real GPS data of nine GPS stations in Egypt in 7-day period 2018 were used for the assessment of zenith part obtained by using real meteorological data of GFS against that used standard or empirical models. The data were processed using Bernese software version 5.0.

II. Tropospheric Delay Models:

GNSS tropospheric correction models combine multiple scientific research disciplines, including radio physics, atmospheric physics, and geodesy. Tropospheric delay is handled by means of global tropospheric delay models based on climate data. Some models are explicitly dependent on surface meteorological data and others use the coordinates (latitude and height) of the GPS station [Abdelfatah et al., 2015].

This section gives the details of the tropospheric delay models used in this study: the Hopfield model, the Saastamoinen model, the Black model, the MOPS model, and the GCAT model.

1. Hopfield Model:

The Hopfield model, developed by Helen Hopfield [Hopfield H.S., 1969], is based on the relationship between the refractive indices at the Earth's surface and at a given height. The zenith tropospheric delay is calculated as follows, for the dry and wet components, respectively:

$$D_d = 10^{-6} K_1 \frac{P_s h_d - h_s}{T_s}, \quad (1)$$

$$D_w = 10^{-6} (K_3 + 273 (K_2 - K_1)) \frac{e_s h_w - h_s}{T_s}, \quad (2)$$

Where, D_d and D_w are the zenith dry and zenith wet tropospheric delays respectively.

Parameters with a subscript s are indicators of meteorological parameters taken at a specific point on the Earth's surface; T_s is the temperature at the point (in K); P_s is the pressure at the point (in hPa); e_s is the partial pressure of water vapor at the point (in hPa); K_1 , K_2 , K_3 are the refraction constants ($K_1 = 77.64 \text{ K} / \text{hPa}$, $K_2 = 64.8 \text{ K} / \text{hPa}$, $K_3 = 3.718 \cdot 10^5 \text{ K}^2 / \text{hPa}$); $h_d - h_s$ is the height of the zenith dry part and zenith wet part respectively of the neutral atmosphere from a point on the Earth's surface to the border of the stratospheric layer, m. It is assumed to be 45,000 m or calculated formulas as in Eq. (3) and Eq. (4).

$$h_d - h_s = 148.98 (T_s - 4.12); \quad (3)$$

$$h_d = 40136 + 148.72 t_s, \quad (4)$$

where t_s is the temperature (in C).

The calculated heights of the dry part of the neutral atmosphere according to Eq. (3) and Eq. (4) differ from one another by less than 0.5%.

$h_w - h_s$ is the height (m) of the humid part of the neutral atmosphere from a point on the Earth's surface to the boundary of the tropospheric layer. It is assumed to be 11,000 m. h_s is the height (m) of Earth's surface above sea level. The relationship between temperature and the height of the tropospheric layer was also derived [Mendes V.B. and Langley R.B, 1998]:

$$h_w - h_s = \left[7508 + 2421 \left(\frac{t_s}{22.90} \right) \right]. \quad (5)$$

.2. Saastamoinen Model:

The Saastamoinen model assumes that the delay integral can be calculated without previous knowledge of the height of the neutral atmosphere. This simplifies and increases the accuracy of determining the tropospheric delay since the height is directly proportional to the pressure in a dry atmosphere [Saastamoinen J., 1971].

The model, being a general tropospheric delay model, combines both dry and wet components, and depends on the satellite elevation angle, representing a display function [Torben S., 2001]:

$$T = \frac{0.002277(1+D)}{\cos Z} \left\{ P_s + \left(\frac{1255}{T_s} + 0.05 \right) e_s - V \operatorname{tg}^2 Z \right\} + \delta_R, \quad (6)$$

where T is the total tropospheric delay; Z is the zenith angles (degrees); D is the gravitational correction (m), calculated following the formula: $D = 0.0026 \cos 2B + 2.8 \cdot 10^{-7} h_s$; δ_R is a correction, depending on the zenith distance (m); V is a correction, depending on the height of the item (hPa).

This formula is found in abbreviated form in Eq. (3) [URL: http://www.rtklib.com/prog/manual_2.4.2.pdf]:

$$T = \frac{0.002277}{\cos Z} \left\{ P_s + \left(\frac{1255}{T_s} + 0.05 \right) e_s - \operatorname{tg}^2 Z \right\}. \quad (7)$$

It is also possible in some cases to split the Saastamoinen model into dry and wet components. The calculation of the dry component of the tropospheric delay Saastamoinen is carried out following the formula:

$$D_d = 0.002277 P_s (1 - 0.0026 \cos 2\beta - 2.8 \cdot 10^{-7} h_s) \quad (8)$$

Where β is the latitude of a point on the Earth's surface (angle, degrees); P_s is the pressure at the point (hPa); h_s is the height of a point on the Earth's surface (m).

The wet component can be calculated as follows:

$$D_w = 0.002277 \left(0.05 + \frac{1255}{T_s} \right) e_s, \quad (9)$$

where T_s is the temperature (K); e_s is the partial pressure of water vapor at the point (hPa).

Some post-processing software packages, such as RTKLIB, calculate the tropospheric delay according to the Saastamoinen model by implementing a normal atmosphere. The meteorological parameters in this case can be obtained as follows [URL: http://www.rtklib.com/prog/manual_2.4.2.pdf]:

$$P_s = 1013.25 (1 - 2.557 \cdot 10^{-5} h_s)^{5.2568}; \quad (10)$$

$$T_s = 15.0 - 6.50 \cdot 10^{-3} h_s + 273.15; \quad (11)$$

$$e_s = 6.108 \exp \left(\frac{17.15 T_s - 4684.0}{T_s - 38.45} \right) \frac{h_{rel}}{100}, \quad (12)$$

Where h_s is the height of the point (m); h_{rel} is the relative humidity (%).

.3. Black model.

The Black model is considered an improvement above the Hopfield model [Black H.D., 1998]. Black's tropospheric delay is calculated as follows, for the dry and wet components, respectively:

$$D_d = \frac{1.552 \cdot 10^{-5} P_s h_d}{\sqrt{1 - \left(\frac{\cos E}{1 + l_c \frac{h_d}{r}} \right)^2}} - \frac{1.92}{E^2 + 0.6}, \quad (13)$$

$$D_w = \frac{0.07465 \frac{e_s}{T_s} h_w}{\sqrt{1 - \left(\frac{\cos E}{1 + l_c \frac{h_w}{r}} \right)^2}} - \frac{1.92}{E^2 + 0.6}, \quad (14)$$

where T_s is the temperature (K); P_s is the pressure at the point (hPa); e_s is the partial pressure of water vapor at the point (hPa); h_d and h_w are the heights (m) of the dry layer, calculated following formula (2), and the wet layer, assumed to equal 11 km, respectively; r is the radius vector of the item (m); E is the satellite elevation angle (degrees); l_c is the scale factor, calculated as follows:

$$l_c = 0.167 - (0.076 + 0.00015 t_s) \exp(-0.3 E). \quad (15)$$

4. MOPS Model:

MOPS model is based on estimating the troposphere delay using terrestrial meteorological data and meteorological parameter gradients [MOPS, 1998]. The input meteorological parameters and gradient values are contained in Table 1 and Table 2, calculated by latitudes. These characteristics introduce a certain error, and if the troposphere deviated significantly from the MOPS model, the un-modeled error of the tropospheric delay and the pseudo-range error as a result can exceed the permissible error level [Storm van L., 2004].

The tropospheric delay is calculated formulas as follows [Szabolcs R., 2014]:

$$D_d = 10^{-6} \frac{K_1 R_d P_s}{g_m} \left(1 - \frac{\beta h_s}{T_s} \right)^{\frac{g_m}{R_d \beta}} ; \tag{16}$$

$$D_w = 10^{-6} \frac{K_3 R_d}{g_m (\lambda + 1) - \beta R_d T_s} \frac{e_s}{T_s} \left[1 - \frac{\beta h_s}{T_s} \right]^{\frac{(\lambda - 1) g_m}{R_d \beta} - 1} , \tag{17}$$

Where h_s is the height of the point (m) and $K_1 = 77.64 \text{ K / hPa}$,

$K_3 = 3.718 \times 10^5 \text{ K}^2 / \text{hPa}$; R_d is the gas constant which equal $287,054 \text{ J / (kg} \times \text{K)}$; β is the temperature gradient (K / km); λ is the gradient of water vapor (mPa / km); g_m is the gravity, which is determined formulas follows:

$$g_m = 9.784 (1 - 0.00266 \cos 2 \phi - 0.00028 H_s); \tag{18}$$

Where ϕ is the latitude of the point (angle, degrees) and H_s is the point height (km).

The parameter values for calculating the statistical MOPS model are presented in Table 1 and Table 2 [Torben S., 2001]. To get the exact value of a parameter, its value on the current day needs to be calculated as follows:

$$X(\beta, d) = X_0(\beta) - \Delta X(\beta) \cos \left[\frac{2\pi(d - d_0)}{365.25} \right], \tag{19}$$

where β is the latitude of the station (angle, degrees); X_0 is the average value of the meteorological parameter; ΔX is the seasonal change in the meteorological parameter; d is the day of the year (January 1 = 1); d_0 is the maximum winter day (28 for the Northern and 211 for the Southern Hemisphere). The meteorological values themselves and their seasonal changes for the exact latitude are calculated by standard linear interpolation.

Table 1: Average statistical parameters of the MOPS model [Torben S., 2001].

B	P ₀ , hPa	T ₀ , K	e ₀ , hPa	β ₀ , K/km	λ ₀ , mb/km
0 – 15°	1013.25	299.65	26.31	0.0063	2.77
30°	1017.25	294.15	21.79	0.00605	3.15
45°	1015.75	283.15	11.16	0.00558	2.77
60°	1011.75	272.15	6.78	0.00539	1.81
75° – 90°	1013	253.65	4.11	0.00453	1.55

Table 2: Seasonal changes in meteorological parameters of the MOPS model [Torben S., 2001].

B	ΔP ₀ , hPa	ΔT ₀ , K	Δe, hPa	Δβ, K/km	Δλ, mb/km
0 – 15°	0	0	0	0	0
30°	- 3.75	7	8.85	0.0025	0.33
45°	- 2.25	11	7.24	0.0032	0.46
60°	- 1.75	15	5.36	0.0081	0.74
75° – 90°	- 0.50	14.5	3.39	0.0062	0.30

5. The GCAT model:

The GCAT model has been developed by the Polytechnic University of Catalonia and implemented in GPS software packages (Code Analysis Tool), and therefore has been referred to as the GCAT model. The model is a statistical model that does not require actual measurements. To calculate the zenith tropospheric delay, a formula is used that depends only on the height above sea level [Pajares M.H. et al., 2005]:

$$T_A = (D_d + D_w) = \left[(2.3 \exp(-0.11 * 10^{-3} h_s)) + 0.1 \right], \tag{20}$$

Where D_d is the dry tropospheric delay (m); D_w is the wet tropospheric delay (m); h_s is the height of the point above sea level (m). The average statistical parameters of the MOPS model and its Seasonal changes are presented in table 1 and in table 2 [Torben S., 2001].

6. Models of meteorological parameters:

To improve the accuracy of modeling, the tropospheric delay of a radio signal in the absence of measured meteorological information, predicted parameters from digital meteorological models can be used. The accuracy of the simulation will depend on both the errors of the model used and the errors in determining temperature, pressure and humidity.

In this study, the Global Forecast System (GFS) meteorological data model, which has been developed by National Centers for Environmental Prediction (NCEP), a division of the National Oceanic and Atmospheric Administration (NOAA), was used. The GFS model consists of four separate models (atmosphere model, ocean model, Earth model and sea ice model), which are updated four times a day. The combination of the four models provides an accurate picture of the weather conditions. The spatial resolution of the model is 27–35 km. The

main advantages of the GFS model are the ability to generate forecast data for several days in advance, and the full coverage of the entire globe. The main disadvantages of the meteorological data generated from the GFS model are that the data are averaged for $0.25^\circ \times 0.25^\circ$ squares, and the poor data quality for sites located on the sea-land border (WMO, 2013).

GRIB files containing the daily forecast of meteorological parameters were used to carry out a numerical experiment. In GRIB files, meteorological data are presented at a height of 2 m above sea level. To calculate the tropospheric delay, the meteorological parameters were reduced to the point height. For this, the vertical gradients of temperature, pressure and partial pressure of water vapor were calculated using the values of the parameters at sea level and at different altitude levels.

III. Methodology:

The purpose of the numerical experiment was to obtain an estimate of the accuracy of calculating the zenith tropospheric delay using tropospheric delay models and the GFS meteorological data model. Hopfield, Saastamoinen, Black, MOPS, and GCAT models were involved in the experiment. The True values were the zenith tropospheric delays estimated at IGS stations (IGS), distributed in the Tropo-SINEX format (Solution Independent Exchange format). Zenith Tropospheric Delay (ZTD) was estimated during post-processing of GNSS measurements using the PPP method [URL: <https://tinyurl.com/sqgtrae>]. This approach had been reported to obtain ZTD estimates with a standard error (RMS) of 4 mm and a resolution of 5 min [Christine H., 2015 and URL: www.igs.org/products]. This is an order of magnitude higher than the expected accuracy of the calculation using tropospheric delay models with GFS data, and these values were considered the true values. Twenty-one IGS stations were chosen with the code names BHR4, BRST, CHUR, DGAR, HERT, HNLC, KMNM, KOUC, KRGG, KUUI, LBCH, MAC1, MAYG, MELI, OHI2, ONS1, PBRI, REYK, SASS, SFER, WARN, which were located in different climatic zones as in figure 1. The true values of the zenith tropospheric delay were used for each of the selected points on five months: February, April, July, September and October 2019 with a resolution of 3 hours. The IGS data are down sampled from 5 minute to daily intervals. Interpolated meteorological parameters to a height of 2 m above sea level for each item were received using the geodetic coordinates of points and the GFS-model for the presented dates.

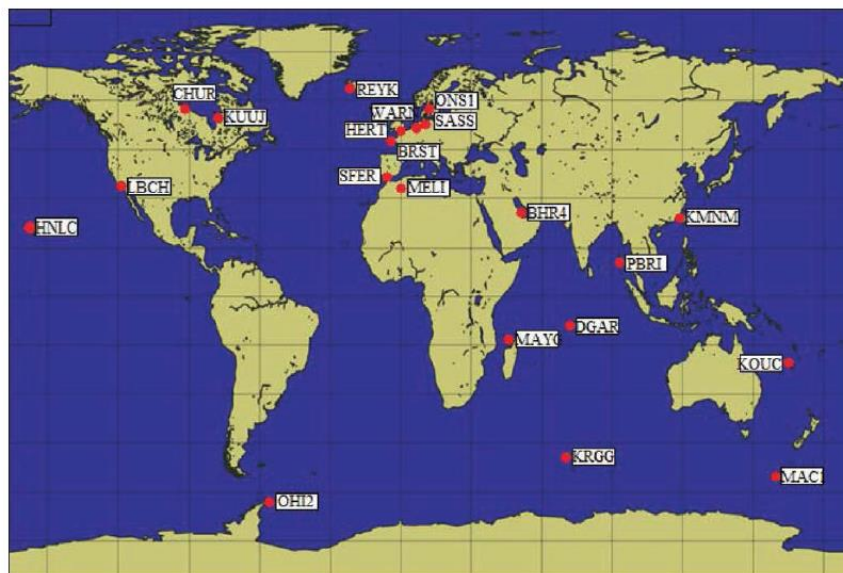


Fig.1. IGS point locations for experiment.

The meteorological parameters were reduced to the altitude of points. The tropospheric delays for each model (T_{Model}) were calculated. For the Hopfield model, the height of the wet part of the neutral atmosphere was set to 11,000 m, and the height of the dry part was calculated following to Eq. (3). For the Saastamoinen model, Eq. (7) was used. The Saastamoinen model was parameterized three times using three different sets of data: meteorological data obtained from the GFS model, the parameters of the normal atmosphere, and meteorological data obtained from the empirical models which use table of average parameters. For the Black model, the height of the wet part of the neutral atmosphere equaled 11,000 m, and the height of the dry part was determined from Eq. (4).

The Root Mean Square Error (RMS) was calculated by the formula:

$$m = \sqrt{\frac{[(T_{\text{model}} - T_{\text{IGS}})^2]}{n}}$$

where $n = 8$ when calculating the RMS model at the point, $n = 168$ when calculating the RMS model of the tropospheric delay.

To test the accuracy of determining the zenith tropospheric delay using tropospheric delay models and the GFS meteorological data model, nine GPS stations in Egypt are used (see figure2). Stations names, codes and their approximate coordinates are listed in Table 3. The GPS observations were carried out using Trimble NETR5 receivers. GPS stations data were processed as baselines. In the present research we only tested zenith path delay. A closed triangle formed by three GPS baselines is used to test the zenith path delay effect and closure error. The GPSEST program of Bernese GPS software version 5 (Dach et al., 2007) is used to test models of troposphere delay for baselines closure error.

Table 3: Coordinates of the GPS stations

Stations	Code	Longitude (°)	Latitude (°)
MarsaMatrouh	MTRH	27.230	31.345
Borg El-Arab	BORG	29.573	30.863
Mansoura	MNSR	31.352	31.041
Port Saeed	SAID	32.314	31.246
Arish	ARSH	33.617	31.107
Helwan	PHLW	31.343	29.862
MarsaAlam	ALAM	34.88	25.07
Aswan	ASWN	32.85	23.97
Abo-Sembel	ABSM	31.55	22.49

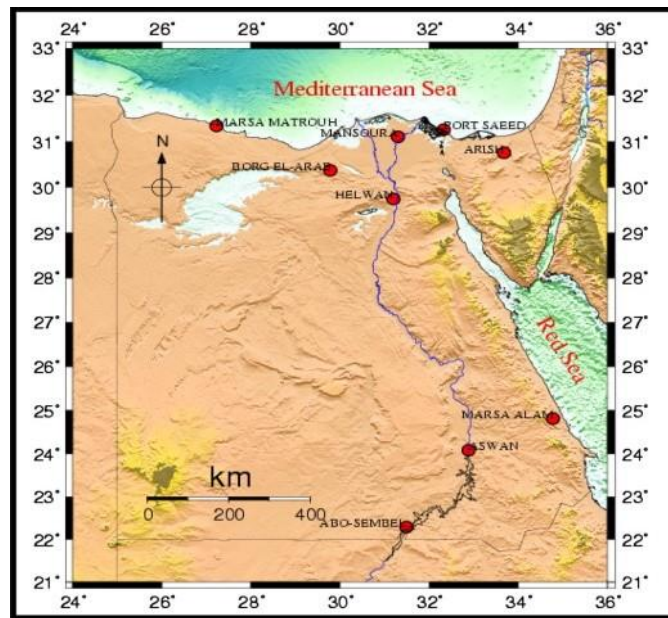


Figure 2: GPS stations used in this study.

Table 4: The available data of the GPS sites and GPS baseline loops

Date	Day of year (DOY)	GPS Week-day of week	Sampling (S)	Mask angle (°)	GPS stations loop
3-1-2018	3	1981-3	30	15	ABSM, ARSH, BORG
12-3-2018	71	1991-2	30	15	ASWN, MTRH, PHLW
25-5-2018	145	2001-5	30	15	ARSH, ASWN, MTRH
10-7-2018	191	2008-2	30	15	ARSH, MNSR, PHLW
11-9-2018	254	2017-2	30	15	SAID, ALAM, BORG
1-11-2018	305	2024-4	30	15	MNSR, ASWN, MTRH
5-12-2018	339	2029-3	30	15	SAID, PHLW, MTRH

IV. Results and Discussion:

The results of accuracy assessment (RMS and maximum error Δ) for the indicated time intervals are given in the table 5 for each model. In figure 3 and figure 4, the results are presented in the form of histograms. The values of RMS for the Hopfield, Saastamoinen, and Black models using meteorological data from Numerical Weather Prediction (NWP) models for all considered time intervals are less than their values which obtained from the empirical models, which use the average of standard meteorological parameters. Depending on the time intervals considered, a big difference in the values of RMS for these models are noticed, while the difference in RMS within one interval does not exceed 4%. For all considered time intervals, it is found that, the results obtained for the MOPS and GCAT models using the standard or empirical values of meteorological parameters are exceeded by 1.5 to 2 times as compared with their values that obtained by the digital meteorological data model. Since RMS error at February month varies from 0.037 m for Hopfield or Black model to 0.035 m for Saastamoinen model, but it varies from 0.093 m for MOPS model and 0.109 m for GCAT model up to 0.116 m for Saastamoinen model with empirical values. In September the difference of IGS and models used Meteorological data varies from 0.061 m (Saastamoinen) to 0.063 m (Hopfield) but the difference of IGS and empirical models varies from 0.078 m (Saastamoinen) up to 0.127 m (MOPS). But in July the difference of IGS and models used predicted meteorological data varies from 0.044 m (Saastamoinen) to 0.046 m (Hopfield) but the difference of IGS and empirical models varies from 0.117 m (Mops) up to 0.196 m (Saastamoinen with normal atmosphere).

Table 5: Tropospheric zenith delay differences analysis between used models and IGS-tropospheric estimation.

The difference	12/02/2019		20/09/2019		24/10/2019		15/04/2019		8/07/2019	
	RMS	Max. Δ	RMS	Max. Δ	RMS	Max. Δ	RMS	Max. Δ	RMS	Max. Δ
IGS and Hopfield	0.037	0.093	0.063	0.132	0.044	0.173	0.042	0.105	0.046	0.117
IGS and Saastamoinen	0.035	0.079	0.061	0.139	0.046	0.178	0.039	0.089	0.044	0.099
IGS and Black	0.037	0.089	0.062	0.132	0.046	0.177	0.042	0.104	0.046	0.112
IGS and GCAT	0.109	0.244	0.127	0.296	0.074	0.175	0.123	0.275	0.137	0.306
IGS and MOPS	0.093	0.208	0.095	0.180	0.117	0.197	0.105	0.235	0.117	0.261
IGS and Saast. (nor. atm.)	0.156	0.337	0.191	0.389	0.119	0.268	0.176	0.38	0.196	0.423
IGS and Saast. (Stat. Model)	0.116	0.241	0.078	0.173	0.077	0.209	0.131	0.272	0.145	0.302

From shown figures and tables, it is found that, the low accuracy achieved by using Saastamoinen model with parameters of normal atmosphere, since RMS of its difference with IGS varies from 0.119 m to 0.196 m at different times. At the same time, high accuracy can be achieved by using Saastamoinen Model with predicted meteorological data and the difference cannot be exceeded 0.061m.

The Saastamoinen model results are obtained using different sources of meteorological data, using the parameters of standard atmosphere and using empirical model for average meteorological parameters led to higher RMS than using predicted of meteorological data of GFS in all case studies.

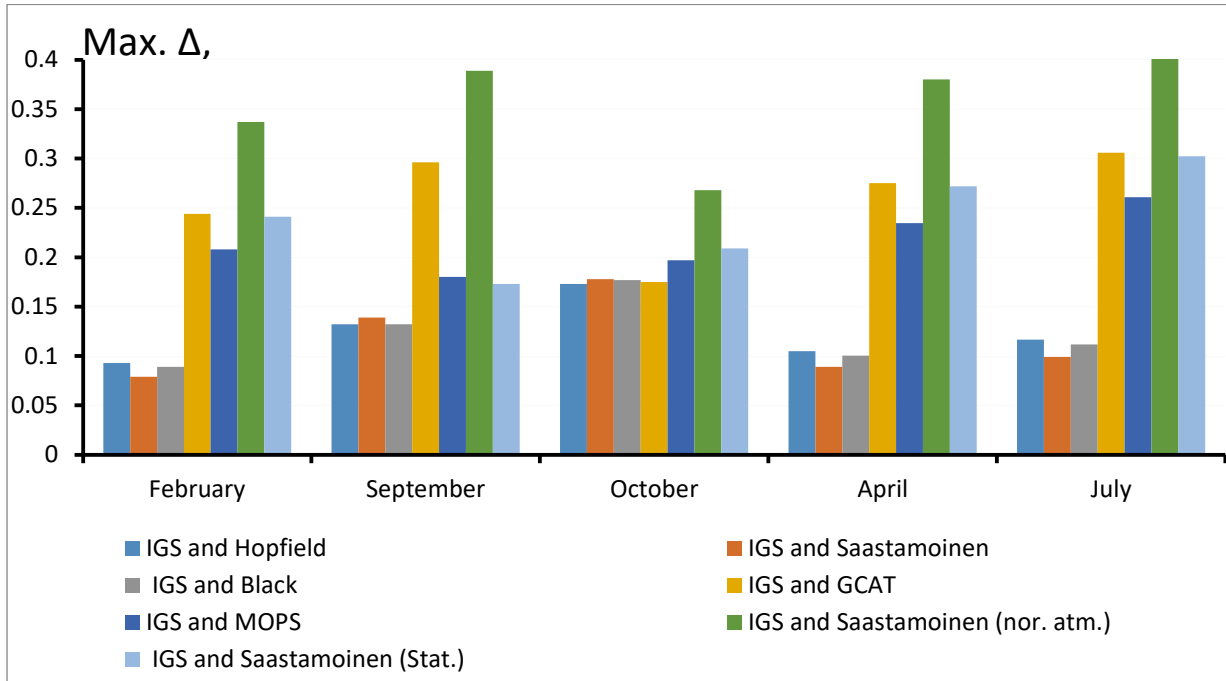


Figure 3: Maximum errors of the difference of used models to IGS estimation of ZTD.

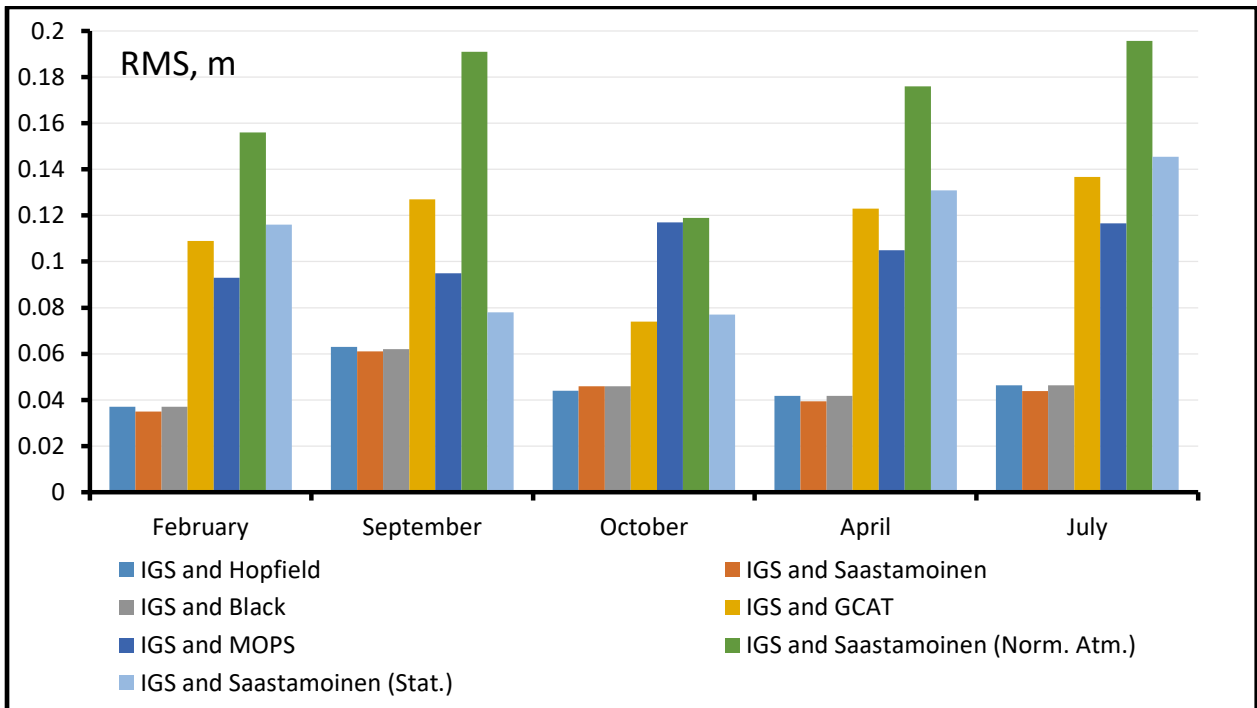


Figure 4: RMS errors of the difference of used models to IGS estimation of ZTD.

Figure 5 is presented a histogram of RMS value of each station on February, 2019 according to the models of Hopfield, Saastamoinen, and Black. For an individual station, the difference in RMS obtained from models does not exceed 30%, which is higher than the difference in RMS values calculated for all stations. The minimum value of RMS is obtained for CHUR station (0.004 m, Hopfield model), and the maximum value is obtained for MAYG station (0.075 m, Hopfield model). The differences in values of tropospheric delay between stations depend on temperate region of each station, since the tropospheric delay values are increased with a high temperature.

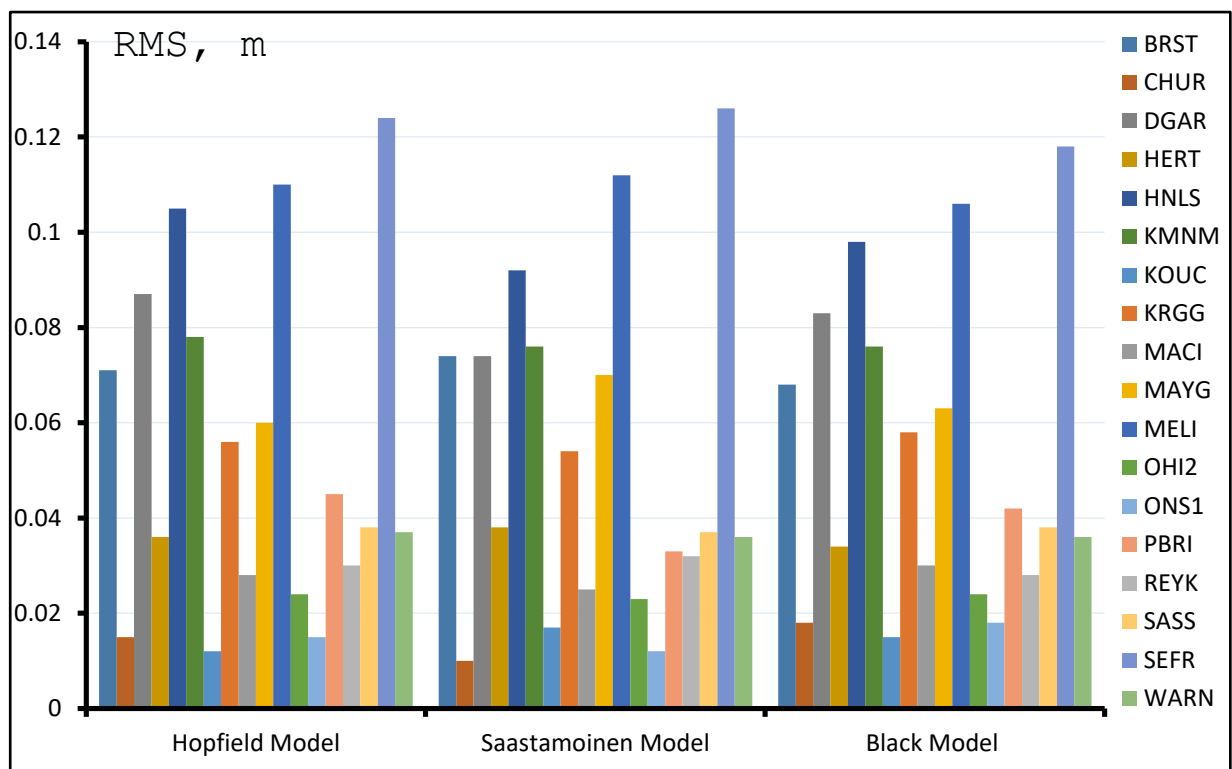


Figure 5: RMS error of the difference of Hopfield, Saastamoinen and Black models to IGS estimation of ZTD on February 12, 2019.

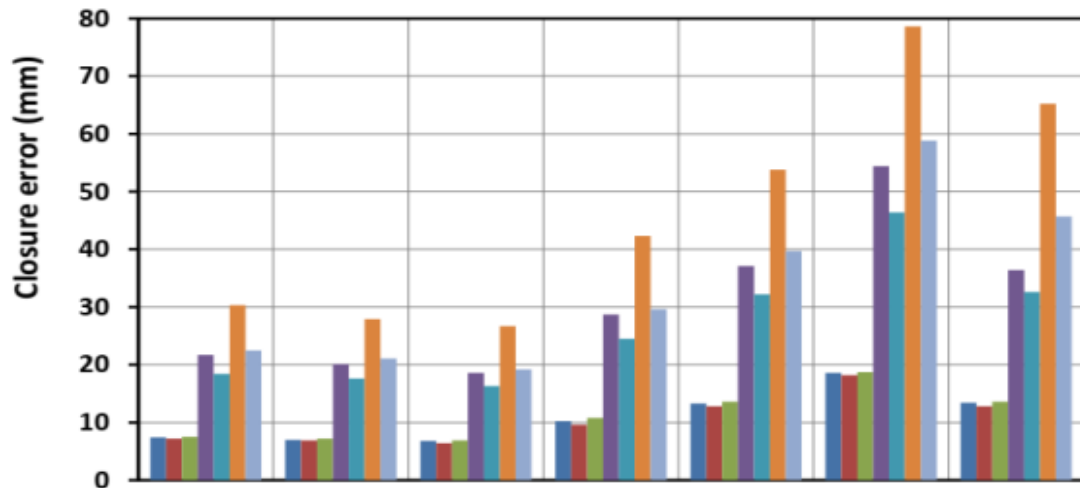
The results show that, the empirical models perform poorly with the use of standard atmospheric parameters and thus fail to address the peculiarities of the GNSS network which is characterized by a lack of sensors for measuring meteorological data. Thus, better estimates of ZTD from GNSS can be obtained with actual field measurements using meteorological parameters obtained from a numerical weather forecast.

In this study, the variations of zenith tropospheric delay (ZTD) for different seasons are considered. Data collected in 21 IGS stations at different months of year are analyzed. Results show that the annual variation of ZTD range from 20 mm to about 70 mm and the average amplitude is about 47 mm at most stations. Results prove that the annual variations depend on the latitude of station. Since the larger amplitudes of annual ZTD variations are mentioned at middle-low latitudes (eg. 67 mm at MELI station), and the amplitudes of annual ZTD variations are generally small at higher latitudes (eg. 32 mm at ONS1 station) or at equator area (eg. 28 mm at PBRI station). The analysis of results show also that the annual variation amplitudes of ZTD at IGS stations near to sea or ocean are more than in the continental inland in general. This may be for the combined effects of a rain shadow in the winter and high moisture in the summer.

To achieve of these results practically, the temporal variations of the closure errors of the tropospheric delay models using GFS meteorological data model and the other classic models over the 7-daysperiod in Egypt are presented in figure 6. Seven sessions were selected out from the observed baselines for the GPS network. The selected sessions covered all possible cases: (winter, spring, summer, and autumn).

Results of figure 6 show that, in all seasons, the saastamoinen model with meteorological data is the best model; however, Hopfield and Black models have very close results to it in all seasons. It is noticeable that the greatest closure errors are shown in the autumn season. The closure errors of Saastamoinen model in November session reached to 18.2 mm which is greater than one of summer sessions reached to 9.6 mm in July. In the most sessions, Mops and GSCT models shows low accuracy.

Moreover, it can also be deduced from the figure 6 that, the Hopfield, Saastamoinen and Black models produce comparable results as one group of models employ the values of meteorological parameter, while the other models likewise produce similar results as another group of models derived using the Standard Atmosphere Supplements data.



Closure error (mm)	3/1/2018	12/3/2018	25/5/2018	10/7/2018	11/9/2018	1/11/2018	5/12/2018
■ Hopfield	7.4	7	6.8	10.2	13.3	18.6	13.4
■ Saastamoinen	7.2	6.9	6.4	9.6	12.8	18.2	12.8
■ Black	7.5	7.2	6.9	10.8	13.6	18.7	13.6
■ GCAT	21.7	20.1	18.6	28.7	37.1	54.4	36.4
■ Mops	18.4	17.6	16.3	24.5	32.2	46.4	32.6
■ Saast. (nor. atm.)	30.3	27.9	26.7	42.3	53.8	78.6	65.2
■ Saast. (Stat.)	22.5	21.1	19.2	29.6	39.7	58.8	45.7

Fig. 6: GPS baseline closure error (mm). Here Hopfield, Saastamoinen, Black, GCAT, Mops, Saast. (normal atmosphere) and Saast. (statically atmosphere) respectively.

V. Conclusions

From this study, it is shown that the use of digital models of meteorological data for tropospheric correction of radio-ranging measurements can achieve accuracy 1.5 to 2 times higher than that achieved using standard or empirical models of the troposphere. The observed RMS values for different time periods and different stations within the same period have indicated that the accuracy of calculating zenith tropospheric delay used real values of meteorological parameters is superior to the existing tropospheric models use the normal atmosphere or statically standard atmosphere in all sessions as demonstrated for different cases of Saastamoinen models.

Regarding the accuracy of calculating zenith tropospheric delay, the Hopfield, Saastamoinen, and Black models has given equal results. For the time periods considered in this study, the RMS obtained for each of these models are differed by no more than 5%. Results of research have proved that the lower mean ZTD values are measured at the area of higher altitudes and higher mean values ZTD are observed at the area of middle-low latitudes.

Nine GPS stations within Egypt are used to test the used models performance. The test results indicate that, the digital models of meteorological data for tropospheric correction model shows the best performance, compared to standard or empirical models of the troposphere and it is recommended to be used when processing GPS data in order to get high accuracy results.

Finally, it can be concluded that, for real-time GNSS positioning and navigational applications, either Hopfield or Saastamoinen models can perform well in correcting tropospheric delay in the study area with using real meteorological data.

Data availability statement:

The data that support this study are observed and analyzed by Egyptian Meteorological Authority.

Conflict of interest:

The authors declare that there is no conflict of interest.

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