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ACCURACY IMPROVEMENT OF TROPOSPHERIC DELAY CORRECTION MODELS IN SPACE GEODETIC DATA. CASE STUDY: EGYPT

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Abstract. The tropospheric delay still remains a limiting factor to the accuracy of space based positioning techniques. The estimation of station positioning, especially height component, which is particularly important for more applications is susceptible to errors in modeling the tropospheric delay due to correlations between the station positioning and residual troposphere delay parameters. As the demand on positioning accuracy and precision has increased, it has begun a necessary of relaying on large external data sets, rather than relatively simple models for treating the tropospheric delay. This method has been possible by advances made in numerical weather models which provide accurate representations of global atmospheric conditions and by advances in computing speed which allow us to perform a large number of computations over a short period of time. The purpose of this work is to develop a new model for estimating the tropospheric delay and then assess the benefits of applying this model at various geographic atmospheric conditions of Egypt. By comparing new model with some common models such as Saastamoinen model, Hopfield model, Niell-MF, Black & Eisner-MF, UNB3 model and Vienna-MF, the results show that, new model for estimation tropospheric delay has an acceptable level of accuracy in describing the dry tropospheric delay in Egypt as it agrees closely with the numerical integration based model. The mean accuracy of this new model has been assessed to be about 9.64 mm with rms 11 mm at an elevation angle of 30° and for an elevation angle of 5°, the mean accuracy is about 83.23 mm with rms 96.42 mm for atmospheric conditions of Egypt.

Keywords: tropospheric delay models, EMA, homogeneous atmosphere, Egypt.

Introduction

GPS pseudorange and carrier-phase measurements are affected by several random and systematic errors. These errors are originated from satellites, receivers and signal propagation through the atmosphere. Neutral atmosphere is consisting of the troposphere and stratosphere. The GNSS signal propagating through the bottom part of the atmosphere is refracted and bended; size of the effects is directly correlated with the troposphere density variations (Thayer 1974).

Tropospheric delay depends on the temperature, humidity and pressure. It varies with the height of receiver setup point and the type of propagation media below signal path. The propagation media affect radio signals at all frequency and cause refraction with a time delay of the arriving signals. Signals from satellites at low elevation angles travel a longer path through the troposphere than those at higher elevation angles. Therefore, the tropospheric delay is minimized at the user's zenith and maximized near the horizon. The effect is a delay that reaches 2.0–2.5 m in the zenith direction (satellite directly overhead) and increases approximately with the co-secant of the elevation angle, yielding about a 20–28 m delay at a 5° elevation angle, about 9.30 m for a 15° elevation angle (Brunner *et al.* 1993).

The tropospheric delay may be divided into dry and wet components. The dry component contributes about 90% of the total delay and wet component is about 10% (Janes *et al.* 1991). It can be modeled to about 2–5% using surface pressure and temperature, predicted to high degree of accuracy using mathematical models. Several mathematical models such as Saastamoinen model (Saastamoinen 1972), Hopfield model (Hopfield 1969), Goad and Goodman model

(Good, Goodman 1974), Black model (Schuler 2000) etc, are used to predict quantity of tropospheric delay using surface meteorological measurements or default meteorological data.

Most standard tropospheric models were experimentally derived using available radiosonde data, which were mostly observed on the European and North American continents. The research results (Younes, Elmezayen 2012) shows that, for atmospheric conditions of Egypt, through comparison with numerical integration model, the mean accuracy of the Black & Eisner mapping function (B&E-MF) has been assessed to be about from 1646.73 mm at Helwan station (average data over the year) to 1995.72 mm at Aswan station (January) at an elevation angle of 5° and, the mean accuracy of the Hopfield model has been assessed to be about from 1493.38 at Helwan station (july) to 1864.20 mm at Aswan station (January) and from 2588.61 mm at Helwan station (july) to 2912.50 mm at Aswan station (January) for Saastamoinen model at an elevation angle of 5° (Younes 2012b).

The contribution of this work is divided into two parts. Firstly, develop new model for estimation dry tropospheric delay for elevation angles up to 5° at atmospheric conditions of Egypt with high accuracies than these achieved by other classical models. New model will be dependent in surface meteorological data. In the second part, new model is assessed by comparing with some common models, such as Saastamoinen model (Saastamoinen 1972), Hopfield model (Hopfield 1969), Niell-MF (Niell 1996), B&E-MF (Black, Eisner 1984), UNB3 model (Leonardo *et al.* 2004) and VMF (Boehm *et al.* 2006), using radiosonde data at different stations and different times of the year in Egypt. The meteorological data used in this study was taken from Egyptian meteorological Authority (EMA) as average values between 1990 and 2005.

1. Methodology

1.1. Data description

The data used in this research were collected from the Egyptian Meteorological Authority (EMA) as average values (from 1990 to 2005).These data include values of temperature, pressure and relative humidity at sea level and also include heights, temperatures and relative humidity values at 18 distinct levels of pressure. The pressure levels are [1000, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 60, 50, 40, 30, 20, 10] hPa, ranging from sea level to height about 32 km. These data are available for three stations covering a large variety of climatic conditions in Egypt. These stations, as shown in Table 1, are Aswan which represents southern region, Helwan which represents central region and Mersa-Matrouh which represents northern region (near Mediterranean-sea). The data are available in two months for the year (January, July) as a daily averages, which represent the worst case of the atmosphere and average data over the year (as a monthly average) is also presented. To calculate numerical integration reference model with sufficient accuracy, the distances between pressure levels have to be decreased and atmospheric parameters values over 10 hPa pressure level data have to be extrapolated.

Table 1. Stations coordinate

Station	Latitude (φ)	Longitude (λ)	H(m)
Mersa Matrouh	31° 52′	32° 47′	38
Helwan	29° 52′	31° 20′	139.26
Aswan	23° 58′	32° 47′	192

For isothermal layers like tropopause, temperature is constant and the values of pressure with height are found using Eq.:

$$P = P_{\circ} \exp\left(-\frac{g_{\circ}\varphi}{R_d T_0} \right). \quad (1)$$

But for other layers, linear interpolation is used for determining the temperature values using the formula of constant-Laps-rate atmosphere, which assumes that the temperature varies linearly with height (Mendes 1998):

$$T = T_{\circ} - \beta h \quad (2)$$

and the formula that represent pressure distribution with height in this layers is (Mendes 1998):

$$P = P_{\circ} \left(\frac{T_{\circ} - \beta\varphi}{T_{\circ}} \right)^{\frac{g_{\circ}}{R_d \beta}}, \quad (3)$$

where, = he pressure at surface in hPa, φ = geopotential height in Km. β = temperature laps rate K/Km, $T_{\circ}$ = surface temperature in Kelvin. R_d = gas constant (287.05 J·Kg^{-1}·K^{-1}), $g_{\circ}$ = surface gravity m/s^2.

Above the 10 hPa pressure level the temperature values are determined by a standard model for the atmosphere (U.S. Standard atmosphere 1976).

1.2. Numerical Integration model

We calculated dry tropospheric delay by developing Numerical integration model, which is derived for three different stations in Egypt (Aswan, Helwan and Mersa Matrouh) in different time of year (January, July and average data for one year) as follow:

Firstly, we calculated refractivity as it given by Smith and Weintraub and with greater accuracy by Thayer (1974):

$$N = K_1\left(\frac{P_d}{T}\right) + K_2\left(\frac{P_w}{T}\right) + K_3\left(\frac{P_w}{T^2}\right), \quad (4)$$

where, P_d is the partial pressure of dry gases in the atmosphere, P_w is the partial pressure of water vapor, T is the absolute temperature and K_i are constants empirically determined.

The dry refractivity and wet refractivity respectively are equal to:

$$N_d = K_1\left(\frac{P_d}{T}\right) \text{ and } N_w = K_2\left(\frac{P_w}{T}\right) + K_3\left(\frac{P_w}{T^2}\right),$$

where, K_1 = 77.6 K/mbar, K_2 = 64.8 K/mbar, K_3 = $3.776 \cdot 10^5$ K^2/mbar.

Secondly, we used the Simpson's formula for numerical integration (Younes 2012b) to calculate the tropospheric delay.

At zenith the refracted path length (S) equal geometric distance between receiver and satellite (H) and the dry tropospheric delay could be expressed as:

$$\Delta S_{zdtrop} = 10^{-6} \int_h N_d dh,$$

$$\Delta S_{zdtrop} = \frac{1}{6}\sum_{i=1}^{i=\frac{n}{2}} \left(H_{2i} - H_{2i-2}\right)\left(N_{d2i-2} + 4N_{d2i-1} + N_{d2i}\right). \quad (5)$$

At different zenith angles ($\boldsymbol{z}$) the dry tropospheric delay is expressed as:

$$\Delta S_{dtrop} = 10^{-6} \int_s N_d \sec z dh,$$

$$\Delta S_{dtrop} = \frac{1}{6}\sum_{i=1}^{i=\frac{n}{2}} \left(H_{2i} - H_{2i-2}\right) \left(N_{d2i-2}\sec z_{2i-2} + 4N_{d2i-1}\sec z_{2i-1} + N_{d2i}\sec z_{2i}\right). \quad (6)$$

We used the formula in Eq. (5) and (6) to determine dry tropospheric delay and integration nodes are distributed equally from earth surface to 100 Km height as below:

1. From surface to 26 Km we calculate delay every 1 Km (refractivity every 0.5 Km).
2. From 26 Km to 50 Km we calculate delay every 2 Km (refractivity every 1 Km).
3. From 50 Km to 100 Km we calculate delay every 4 Km (refractivity every 2 Km).

Accuracy of NIM results can be calculated by formula:

$$\Delta = \frac{I_2 - I_1}{15},$$

where: I_1, I_2 is the value of tropospheric delay by NIM at integration nodes h and $2h$ respectively. Δ Must be acceptable level of accuracy no more than mm.

2. Development of the new model

Delay of a radio signal arriving from different zenith angles caused by the neutral atmosphere can be derived from the next formula:

$$\Delta S_{trop} = 10^{-6} \int_0^S N\, dS, \quad (7)$$

where, s is the bended ray path length from the satellite to receiver.

Since $dS = dh \sec z$, then:

$$\Delta S_{trop} = 10^{-6} \int_{H_0}^{H_a} N \sec z\, dh = 10^{-6} \int_{H_0}^{H_a} N_d \sec z\, dh + 10^{-6} \int_{H_0}^{H_a} N_w \sec z\, dh = \Delta S_{dtrop} + \Delta S_{wtrop}. \quad (8)$$

Since, z is the zenith angle and N_d, N_w are dry and wet index of refractivity respectively, which can be determined by Eq. (4).

According to the equation Mendeleev D.I. – Clapeyron B.E.:

$$dh = -\frac{R_d\ T\, dP}{P\ g}, \quad (9)$$

where: g is the acceleration due to gravity (m/s^2), dh is differential height between two layers of a atmosphere, dp is a differential pressure between two layers, P is the atmospheric pressure in (mbar), T is the temperature in degree Kelvin and R_d = gas constant in J.Kg^{-1}.K^{-1}.

By substituting from Eq. (9) in Eq. (8). Then dry atmospheric delay can be written by:

$$\Delta S_{dtrop} = 10^{-6} \int_{P_0}^{P_a} N_d \sec z \frac{R_d\ T}{P\ g} dP. \quad (10)$$

From eq. Froome and Essen:

$$\frac{N_0\, T_0}{P_0} = \frac{NT}{P} = C_0 = Const.,$$

$$\Delta S_{dtrop} = 10^{-6} \frac{N_0 T_0}{P_0} R_d \int_{P_0}^{P_a} \frac{dP}{g} \sec z. \quad (11)$$

Use theory of a mean value with heights, we have:

$$\Delta S_{dtrop} = 10^{-6} \frac{N_0 T_0}{P_0} \frac{R_d}{g_h} \sec z_h (P_0 - P_a). \quad (12)$$

Since z_h is the mean value of zenith angle along the ray trace which changed with heights and determined by using Snell's law (Kleijer 2004) which state that:

$$n_i\, r_i\, \sin z_i = const.,$$

then:

$$n_0\, r_0\, \sin z_0 = n_h\, r_h\, \sin z_h \text{ and } \sin z_h = \frac{n_0\, r_0 \sin z_0}{n_h\, r_h}, \quad (13)$$

where, z0, n0 and r0 are respectively zenith angle, refractive index and geocentric distance at observation point. z_h, n_h and r_h are respectively zenith angle, refractive index and geocentric distance at each layer atmosphere. And:

$$n_h = 1 + N_h \cdot 10^{-6};$$

$$r_h = r_0 + H. \quad (14)$$

Since N_h is index of refractivity, and H is the height of atmosphere at observation point.

g_h in formula (12) is the mean value of gravity acceleration at any point along ray tracing which changed with heights. Assume $g_h = g_{h0} \cdot Q$ (Younes 2012a), where Q is the factor of gravity change with height, that are received by empirical methods for conditions of atmosphere of Egypt by formula (Younes 2012a):

$$Q = 1 - \frac{0.01\,H}{0.0263\,H^2 - 0.03398\,H + 46.5653}, \quad (15)$$

since H is the heights of the atmosphere.

Analysis data for atmospheric conditions of Egypt gave that it possible to consider the value of Q is constant for heights more than 44.0 km and equal 0.995416.

For value C_0 = 77.624 K/hPa, and R_d = 287.05 J/Kg·K with Eq. (12), the zenith dry delay can be written as:

$$\Delta S_{dtrop} = 22.281969 \frac{P_0 - P_a}{g_{h0}\, Q} \sec z_h, \quad (16)$$

where: g_{h0} is the gravity acceleration at surface for each station and can be received under the formula:

$$g_{h0} = 9.7803266 \cdot (1 + 0.00530248 \sin^2 \varphi - 0.00000585 \sin^2 2\varphi),$$

where, φ – latitude of stations.

3. Results

We calculated dry tropospheric delay at zenith and at different zenith angles using new Eq. (16). The performances of new equation were determined by comparing their results with those obtained from highly accurate numerical integration model at three stations of Egypt at January, July and average data of year. The difference is shown in Table 2.

By analyzing these results, it can be seen that for zenith angles lower than 60° new eq. are represent high accuracy in tropospheric delay prediction because they are more closely to NIM. At 60° the mean difference between new model and NIM is about 7.14 mm with rms of 10.08 mm.

But for zenith angle more than 60°, new model gave high errors by comparing with NIM. At 70° zenith angle (20° elevation angle) the mean difference between new model and NIM is about 27.89 mm with rms of 31.73 mm, at 80° zenith angle it is about –281.37 mm with rms of 283.01 mm, at 83° zenith angle it is about –801.75 mm with rms 803.12 mm and

Table 2. Mean tropospheric delay difference (mm) between new equations and NIM

Zenith angle	Mean	RMS	Max.	Zenith angle	Mean	RMS	Max.
0°	4.88	5.23	7.11	55°	6.27	7.67	15.67
5°	4.66	4.96	6.62	60°	7.14	10.08	21.20
10°	4.70	5.01	6.65	65°	12.11	16.02	31.40
15°	4.76	5.08	6.70	70°	27.89	31.73	53.07
20°	4.86	5.20	6.78	75°	77.64	80.18	110.22
25°	4.97	5.34	6.87	80°	281.37	283.01	327.35
30°	5.00	5.42	7.05	81°	386.21	387.72	436.22
35°	5.05	5.54	7.78	82°	547.72	549.09	601.03
40°	5.08	5.73	8.79	83°	801.75	803.12	864.12
45°	5.21	6.07	10.23	84°	1232.45	1233.83	1320.49
50°	5.63	6.62	12.36	85°	2008.56	2010.05	2139.66

at 85° zenith angle (5° elevation angle) the mean difference between new model and NIM is about 2008.56 mm with rms of 2010.05 mm.

For reducing errors by new Eq. (16) at zenith angle more than 60° we can increase the value of $\boldsymbol{z_h}$ by multiplying it in factor K, then zenith dry delay can be written as:

$$\Delta S_{dtrop} = 22.281969 \frac{P_0 - P_a}{g_{h0} Q} \sec K z_h . \qquad (17)$$

Values of the factor K can be calculated by formula:

$$K = \frac{\arccos\ K z_h}{\arcsin z_h} , \qquad (18)$$

$$\text{since } \cos K z_h = \frac{\Delta S_{dtrop}}{\Delta S_{dNIM}} \cos z_h \qquad (19)$$

and z_h is determined by Eq. (13) and (14). ΔS_{dtrop} which used in Eq. (19), determined by Eq. (16), ΔS_{dNIM} – by numerical integration models Eq. (5) and (6). At atmospheric conditions of Egypt, Table 3 has the values of factor K at different zenith angles more than 60°. In order to estimate the values of factor K we applied equations (18) and (19) for each station in (January, July and average data for one year) for zenith angles from 60° to 85°. The least square estimated values for the factor K for Aswan station, for Helwan station and for Mersa Matrouh station. Then the mean values are taken as average values from three stations.

By using the least square theory, the value of K factor can be calculated by eq. of the best line of second degree polynomial as:

$$K_0 = -1.403 \sec z_0^2 + 67.99 \sec z_0 - 65.77 , \qquad (20)$$

since $K = 1 + 10^{-5} K_0$.

At observation out of atmosphere for heights more than 100 km, value of pressure is very small and can be neglected ($P_a = 0$).

With Eq. (17) zenith dry delay can be written as:

$$\Delta S_{dtrop} = 22.38458 \frac{P_0}{g_{h0}} \sec K z_h . \qquad (21)$$

3.1. Assessment of new model

In order to assess the performance of new model (Eq. (20) and (21)), we have compared it with various common models such as Saastamoinen model, Hopfield model, Niell-MF, B&E-MF, UNB3 model and VMF at different zenith angles. The performances were determined by comparing the dry tropospheric delay predicted by models with those obtained from highly accurate numerical integration model as presented in Tables 4–7 and in Figures 1–3.

Table 3. Mean values of the factor K for Egypt at different elevation angles

Zenith angle	Mean value	RMS	Zenith angle	Mean value	RMS
60°	1.000573862	0.001122	81°	1.003110190	0.000285
65°	1.000884343	0.000875	82°	1.003490867	0.000257
70°	1.001243930	0.000712	83°	1.003944597	0.000242
75°	1.001819860	0.000491	84°	1.004538184	0.000230
80°	1.002804542	0.000314	85°	1.005326503	0.000230

Table 4. Tropospheric delay difference (in mm) between different models and NIM

Models	60°			65°			70°		
	Mean (mm)	RMS (mm)	Max (mm)	Mean (mm)	RMS (mm)	Max (mm)	Mean (mm)	RMS (mm)	Max (mm)
Saastamoinen	14.98	17.60	30.64	22.08	25.46	43.26	39.48	43.30	69.44
Hopfield	10.36	13.59	28.31	16.04	19.43	38.90	29.55	33.85	60.25
Niell-mf	17.32	20.05	35.03	27.73	30.45	49.23	51.15	53.52	78.24
VMF	15.59	18.19	32.71	23.74	26.85	45.06	43.16	45.93	69.89
B&E-mf	14.74	17.32	31.64	21.86	25.20	43.21	39.64	42.63	66.44
UNB3m	45.27	51.45	83.17	63.52	73.06	111.35	82.80	94.67	146.75
new model	9.64	11.00	–20.24	11.45	13.13	–22.68	14.82	17.30	–26.44

Table 5. Tropospheric delay difference (in mm) between different models and NIM

Models	75°			80°			81°		
	Mean (mm)	RMS (mm)	Max (mm)	Mean (mm)	RMS (mm)	Max (mm)	Mean (mm)	RMS (mm)	Max (mm)
Saastamoinen	87.48	91.90	137.60	275.67	284.66	402.03	319.58	344.84	539.35
Hopfield	72.52	75.70	113.78	242.16	244.89	309.05	271.29	277.80	379.26
Niell-mf	113.99	115.99	151.23	349.75	351.47	411.07	465.05	466.76	535.68
VMF	95.05	97.41	131.44	289.12	291.16	347.77	383.97	386.00	451.07
B&E-mf	87.90	90.44	124.45	275.81	277.94	335.01	370.99	373.08	438.83
UNB3m	240.02	254.12	360.22	398.84	413.08	527.25	441.73	466.98	658.50
new model	19.41	22.74	34.78	31.29	34.99	–53.94	36.10	39.84	–62.46

Table 6. Tropospheric delay difference (in mm) between different models and NIM

Models	82°			83°			84°		
	Mean (mm)	RMS (mm)	Max (mm)	Mean (mm)	RMS (mm)	Max (mm)	Mean (mm)	RMS (mm)	Max (mm)
Saastamoinen	389.84	451.09	753.36	957.03	960.56	1107.32	2396.03	2453.21	2912.50
Hopfield	317.13	338.29	520.15	675.32	677.92	781.82	1473.22	1507.62	1864.20
Niell-mf	637.76	642.21	753.79	900.80	902.61	1002.00	1328.90	1330.91	1457.07
VMF	526.35	531.79	646.88	742.61	744.77	837.09	1095.35	1097.73	1213.79
B&E-mf	517.17	522.69	636.38	746.08	748.21	842.06	1134.19	1136.47	1254.89
UNB3m	505.63	556.18	861.54	968.40	980.12	1154.21	1897.53	1922.78	2419.60
new model	41.09	46.36	–73.87	51.29	56.69	–88.63	63.65	71.56	–105.06

Table 7. Tropospheric delay difference (in mm) between different models and NIM

Models	85°		
	Mean (mm)	RMS (mm)	Max (mm)
Saastamoinen	2804.61	2806.68	2993.45
Hopfield	1689.75	1692.85	1864.20
Niell-mf	2061.62	2064.04	2233.4
VMF	1700.02	1702.89	1857.2
B&E-mf	1834.97	1837.62	1995.7
UNB3m	2151.13	2161.23	2419.60
new model	83.23	96.42	186.73

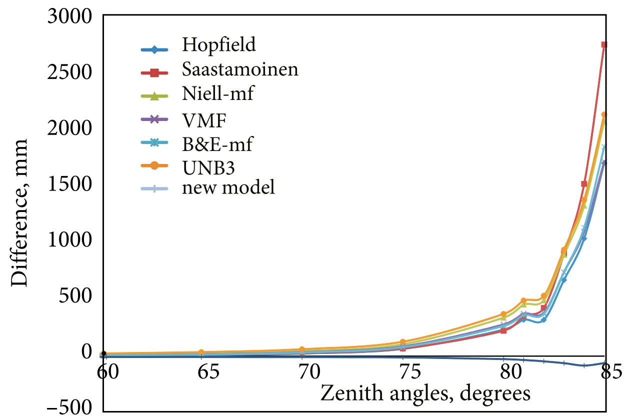

Fig. 2. Difference in mm for Helwan station, January

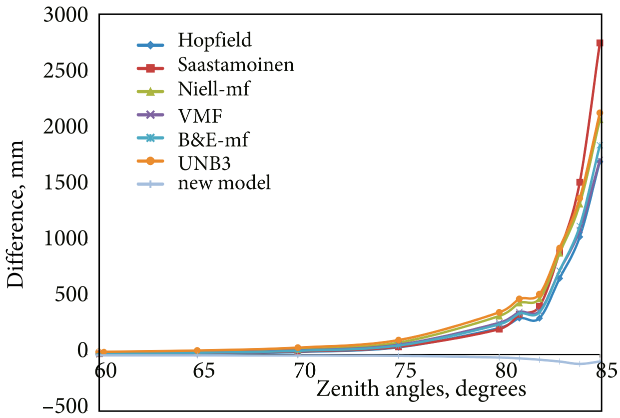

Fig. 1. Difference in mm for Aswan station, January

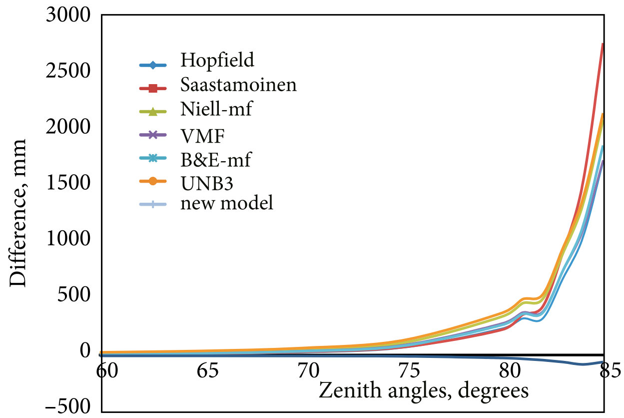

Fig. 3. Difference in mm for Mersa-Matrouh station, January

3.2. Discussion

By analyzing these results, it can be seen that new model presents high accuracy in dry tropospheric delay prediction especially for zenith angles above 60 degree. At 60° mean difference of new model and NIM is about 9.64 mm with rms of 11 mm comparing with Hopfield model which gives mean difference about 10.36 mm with rms of 13.59 mm and B&E-MF which gives mean error about 14.74 mm with rms of 17.32 mm. At 80° mean difference of new model and NIM is about 31.29 mm with rms of 34.99 mm comparing with Hopfield model which gives mean difference about 242.16 mm with rms of 244.89 mm and B&E-MF which gives mean error about 275.81 mm with rms of 277.94 mm. At 83° mean difference of new model and NIM is about 51.29 mm with rms of 56.69 mm comparing with Hopfield model which gives mean difference about 675.32 mm with rms of 677.92 mm and VMF which gives mean error about 746.08 mm with rms of 748.21 mm. At 85° mean difference of new model and NIM is about 83.23 mm with rms of 96.42 mm comparing with Hopfield model which gives mean difference about 1689.75 mm with rms of 1692.85 mm and VMF which gives mean error about 1700.02 mm with rms of 1702.89 mm.

From results it can be seen that, the Hopfield model is offering the second best solution for the delay correction with the condition of availability of surface meteorological data in Egypt. B & E – MF will be the solution with not much degraded accuracy when there is no surface meteorological data for zenith angle up to 80°. For small elevation angle Vienna – MF is the best to estimate tropospheric delay without needing to surface meteorological data.

Conclusions

The new tropospheric correction model has shown acceptable level of accuracy in estimation the tropospheric delay in south, center and north Egypt regions as it agrees reasonably well with the numerical integration model. So this model is recommended for tropospheric correction in this area with the condational availability of surface meteorological data.

Saastamoinen model will be the second solution with not much degraded accuracy for small zenith angle up to 30°, and Hopfield model will be the best solution for delay correction at small elevation angle up to 5°. If there is no surface meteorological data, B&E–MF will be the solution with acceptable level of accuracy.

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