Estimation of New Atmospheric Delay Correction Models in Egypt for Measurement of Vertical Distances

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Abstract: It is generally known that the atmospheric effects to the GPS signals are the most dominant spatially correlated biases. The atmosphere causing the delay in GPS signals consists of two main layers, ionosphere and troposphere. The ionospheric bias can be mitigated using duel frequency receivers. Unlike the ionospheric bias, the tropospheric bias cannot be removed using the same procedure. Compensation for the tropospheric bias is often carried out using a standard troposphere model. Most standard tropospheric models were experimentally derived using available radiosonde data, which were mostly observed on the European and North American continents. In this study, complex theoretical researches for estimation new tropospheric formulas, which are using at minimal surface meteorological data about the atmosphere of Egypt, were carried out. This paper aims to compare the results of new models with the results derived from the use of forth different standard tropospheric models, namely the Saastamoinen model, Hopfield model, Simplified Hopfield model and Black model. Overall results indicate that new model is the best-fit standard tropospheric model with the GPS data collected in Egypt with errors no more than 1 mm.

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1. Introduction

One of the factors limiting the GPS baseline accuracy is due to the atmospheric delay. The atmosphere causing the delay in GPS signals consists of two main layers, ionosphere and troposphere. The ionosphere is the band of the atmosphere from around 50 km to 1000 km above the earth's surface (Hofmann-Wellenhof, et al, 1997). The ionospheric delay is a function of the total electron content along the signal path, and the frequency of the propagation. With regard to duel-frequency user, the ionospheric delay is frequency-dependent and the ionosphere-free combination can be formed in order to eliminate this delay (Rizos, 1997). The troposphere is the band of the atmosphere from the earth's surface to about 8 km over the poles and 16 km over the equator (Langley, 1998). The tropospheric delay is a function of elevation and altitude of the receiver, and is dependent on many factors such as atmospheric pressure, temperature and relative humidity. Unlike the ionospheric delay, the tropospheric delay is not frequency-dependent. It cannot therefore be eliminated through linear combinations of L1 and L2 observations. Several standard tropospheric models are generally used to correct for the tropospheric delay.

All standard tropospheric models are empirically derived from available radiosonde data, which were mostly obtained in the European and North American continents. Global constants within some standard models take no account of latitudinal and seasonal variations of parameters in the atmosphere (Roberts and Rizos, 2001). Furthermore, daily variations of temperature and humidity may cause the tropospheric effects derived from standard models to be in error especially in the height component. High and variable water vapor content, particularly in equatorial regions, may exaggerate this effect further (Mends, 1999).

In Egypt, an investigation on the impact of tropospheric delay is still very limited. What is of particular interest to the GPS surveyors in Egypt is which standard tropospheric model should be used in the base line processing. In order to determine the best-fit tropospheric model for processing of the data collected in Egypt, investigations on the impact of different global tropospheric models on GPS baseline accuracy were therefore computed (Younes et al, 2012). Study of Younes, 2012 was recommended Hopfield model for prediction of tropospheric dry delay at zenith for south Egypt and Saastamoinen model for north Egypt. But, these models have errors to 14 mm by comparing with results derived by numerical integration models. In this paper investigations will be computed to estimate a new tropospheric model more available at all conditions of atmosphere of Egypt. This paper aims to emphasis an impact of the new tropospheric delay model on GPS baseline accuracy by comparing it with results derived from the use of the different models, namely the Saastamoinen model (Saastamoinen, 1973), Hopfield model (Hopfield, 1969), Simplified

Hopfield model (Wells, 1977) and Black model (Torben, 2000).

2. Data and models used in this study

In the present analysis we use radiosonde observations from Egyptian Meteorological Authority (EMA) as average values between 1990 and 2005 which is derived for three stations (Aswan, Helwan, and Mersa-Matrouh). Data is available twice daily (day and night) in two months of the year (January and July).

Table 1. Stations coordinate

Station	Latitude	Longitude	H(m)
Mersa-matrouh	31°52`	32°47`	38
Helwan	29°52`	31°20`	139.26
Aswan	23°58`	32°47`	192

2.1. Radiosonde data

Ray tracing technique assumes a spherically stratified and homogeneous atmosphere. In order to calculate the delay at GPS permanent station the pressure, temperature, and dew point temperature from each sonde is used. To estimate the tropospheric delay we use numerical integration models as the equation:

$$\Delta S_{zd} = \frac{1}{6}\sum_{i=1}^{i=\frac{n}{2}}(H_{2i} - H_{2i-2})\,(N_{d\,2i-2} + 4N_{d\,2i-1} + N_{d\,2i}),$$

(1)

and double exponential transform for the arithmetic integration (Nakamura, 1991).

3. Methodology

The methodologies given here describe a processing technique to estimate delay correction models from GPS data. Tropospheric delay can be obtained directly by integrating the refractivity along the path of the GPS signal through the neutral atmosphere using following expression (Mendes, 1998):

$$\Delta D = \int_0^s (n-1)ds = -10^{-6}\int_0^s N\, ds$$

The tropospheric delay is therefore often represented as a linear combination of the hydrostatic and wet components:

$$\Delta D = -10^{-6}\int_0^s N_d\, ds - 10^{-6}\int_0^s N_w\, ds = \qquad (2)$$

$$-10^{-6}\int_{H_g}^{Ha} N_d \sec Z\, dH - 10^{-6}\int_{H_g}^{H_a} N_w \sec Z\, dH$$

where N_d, N_w – dry and wet refractivity; Z - zenith angle in degree in the current point of the trajectory of the signal; H_g, H_a - Heights in initial G and final A points of a way of a signal.

For the gas environment having density ρ, pressure p and absolute temperature T, the refractivity N for the dry component atmospheric delay:

$$N_d = \frac{N_{0d}T_0}{P_0}\cdot\frac{P}{T} = \frac{N_{0d}}{\rho_0}\rho\ , \qquad (3)$$

where N_0 - the refractivity of the gas environment that is having density ρ_0, pressure p_0 and Absolute temperature T_0.

Taking into account the formula (3) instead of (2), for dry atmospheric delay:

$$\Delta D_d = -10^{-6}\frac{N_{0d}}{\rho_0}\sec Z\int_{H_g}^{Ha}\rho\, dH\ . \qquad (4)$$

Using the basic equation of the static of atmosphere and hydrosphere (Wallace and Hobbs, 1977):

$$-dP = g\rho\, dH\ ,$$

where g – the acceleration due to the gravity in m/s^2, instead of (4) we will receive

$$\Delta D_d = -10^{-6}\frac{N_{0d}}{\rho_0}\sec Z_0\int_{P_g}^{Pa}\frac{dP}{g} = -10^{-6}\frac{N_{0d}}{\rho_0 g}\sec Z\left(P_g - p_a\right)\cdot \qquad (5)$$

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

$$P = R_d\,\rho T\ ,$$

where R_d – gas constant for dry air, we have

$$\rho_0 = \frac{P_0}{R_d T_0}\ .$$

Substituting ρ_0 in the formula (5), we have

$$\Delta D_d = -10^{-6}\frac{N_{0d}T_0R_d}{P_0 g}\sec Z\left(P_g - P_a\right). \qquad (6)$$

For radio waves refraction indices N define under the formula K. Froome – L. Essen:

$$N = 77.624\frac{P}{T} - 12.924\frac{e}{T} + 371896\frac{e}{T^2}\ , \qquad (7)$$

where P and e are expressed in hPa (mb). Considering $P = P_d + e$, we have

$$N = 77.624\frac{P_d}{T} + 64.700\frac{e}{T} + 371896\frac{e}{T^2}\ , \qquad (8)$$

and $N_{0d} = 77.624\dfrac{P_0}{T_0}$.

Taking into account this value instead of (6), will receive

$$\Delta D_d = -77.624 * 10^{-6} \frac{R_d}{g} \sec Z \left(P_g - P_a\right). \quad (9)$$

We consider **values of the acceleration** due to the gravity are expressed by:

$$g = Q \cdot g_g . \qquad (10)$$

where g_g - the gravity in the see level; and value Q for various heights H are received by empirical methods for conditions of atmosphere of Egypt.

The final expression of total zenith tropospheric delay is given as:

$$\Delta H_d = -77.624 * 10^{-6} \frac{R_d}{g_g Q} \left(P_g - P_a\right). \qquad (11)$$

Is known, then

$$Q = -77.624 * 10^{-6} \frac{R_d}{g_g \, \Delta H_d} \left(P_g - P_a\right), \quad (12)$$

where P_g, P_a – in mb; ΔH_d – in mm; values R_d = 287.05287±0.01 J Kg^{-1} K^{-1} is constant and does not change up to heights 90 km (Lide, 1997); g_g - acceleration of a normal gravity on a sea level are received under the formula:

$$g_g = 9.7803266 \left(1 + 0.00530248 \sin^2 \beta - 0.00000585 \sin^2 2\beta\right)$$

,

where , β – latitude of stations.

Values ΔH_d in formula (12) were calculated by method of numerical integration of the formula (9) at z = 0.0 and values g defined as an average from values g on the bottom and top borders of a layer under the known formula:

$$g = g_g \left(\frac{r_s}{r_s + H}\right)^2 , \qquad (13)$$

where, r_s – mean geocentric radius of the station; H - Height for which define g.

In table 2 for conditions of atmosphere of Egypt (station Helwan - city of Cairo) for various heights H are resulted pressure in mb and values of ΔH_d for the dry component atmospheric delay defined by a method of numerical integration under the formula of **Thomas Simpson**. At H to 26.0 km integration knots settled down through 0.5 km, from 26.0 to 40.0 km - through 1.0 km, from 40.0 to 60.0 km - through 2.0 km, from 60.0 to 100.0 km - through 10.0 km. Definition error ΔH_d, calculated by a method of doubling of a step of integration used the formula:

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

where I_1, I_2 - values of the integrals calculated at a step H and $2H$ accordingly, does not exceed 0.01 mm.

In Egypt at geodetic and cartographical works used ellipsoid WGS 84, for which: a = 6 378 137 m and f = 1/ 298.25722101. For the station Helwan at latitude β = 29° 52', have g_g = 9.793144542 m / c^2, r_s = 6 374 743.798 m.

The analysis of values (1-Q).10^5 has shown that they can be approximated expression:

$$q = (1 - Q)10^5 = \frac{H}{aH^2 + bH + c}, \qquad (14)$$

whence we receive the equation

$$H^2 a + Hb + c - \frac{H}{q} = v .$$

By data of table 2 of such equations will be 39. Solving these equations by a method of the least squares, we will receive three normal equations:

$$\left[H^4\right]a + \left[H^3\right]b + \left[H^2\right]c - \left[\frac{H^3}{q}\right] = 0,$$

$$\left[H^3\right]a + \left[H^2\right]b + \left[H\right]c - \left[\frac{H^2}{q}\right] = 0,$$

$$\left[H^2\right]a + \left[H\right]b + nc - \left[\frac{H}{q}\right] = 0.$$

Substituting in these equations numerical values, we will receive:

$$75917565.0\, a + 1480753.0\, b + 32985.0\, c = 3482.292373,$$

$$1480753.0\, a + 32985.0\, b + 919.0\, c = 80.61688962,$$

$$32985.0\, a + 919.0\, b + 39\, c = 2.65233438.$$

The solving of these equations leads to:

$$a = 0.0000263, \quad b = -0.00003398, \quad c = 0.0465653,$$

Substituting the received values in the formula (14), we have:

$$q = \frac{1000\, H}{0.0263\, H^2 - 0.03398\, H + 46.5653} \qquad (15)$$

Then

$$Q = 1 - \frac{0.01\, H}{0.0263\, H^2 - 0.03398\, H + 46.5653} \qquad (16)$$

From table 2 it is visible that the formula (15) for determination values q and the formula (16) for calculation values Q it is expedient to use to height of 44.0 km, as at heights more than 44.0 km the value q, defined under the formula (15), quickly decrease with heights, therefore for heights more than 44.0 km it is possible to consider values q as the constants equal q = 458 and $\boldsymbol{Q}$ **= 0.995416.** From the table it is shown that the differences δ between values ΔH_d, calculated by a method of numerical integration under Simpson's formula, and $\Delta H_d'$, calculated under formulas (11) and (16) don’t exceed 0.70 mm.

When observing objects that are outside the atmosphere, located at altitudes above 100 km, it is possible to consider that values Q as the constants equal 0.995416 and P_a = 0 then The final expression of total zenith tropospheric delay for Egypt is given as:

$$\Delta H_d = -0.00223848 \frac{p_{dg}}{g_g} \qquad (17)$$

Table 2: Determination values of the factor *Q* for calculation values of the acceleration of a gravity for conditions of atmosphere of Egypt

H, км	*P*, mb	ΔH_d, mm	*Q* form. (12)	$q = (1-Q).10^5$	*q* form.(15)	*Q*′ form.(16)	$\Delta H_d'$, mm	δ, mm
0.0	1019.4	0.0	1	0	0	1	0	0
1.0	902.71	265.55	0.99985	15	21	0.999785	265.56	0.01
2.0	798.45	502.85	0.99973	27	43	0.999571	502.93	0.08
3.0	704.93	715.91	0.99943	57	64	0.999358	715.96	0.05
4.0	620.96	907.37	0.99912	88	85	0.999146	907.34	-0.03
5.0	545.46	1079.61	0.99883	117	106	0.998937	1079.50	-0.11
6.0	477.6	1234.51	0.99857	143	127	0.998732	1234.31	-0.20
7.0	416.66	1373.71	0.99833	167	147	0.998530	1373.43	-0.28
8.0	362.07	1498.48	0.99809	191	167	0.998333	1498.11	-0.37
9.0	313.35	1609.88	0.99787	213	186	0.998140	1609.45	-0.43
10.0	270.09	1708.88	0.99767	233	205	0.997953	1708.39	-0.49
11.0	231.98	1796.19	0.99745	255	223	0.997772	1795.61	-0.58
12.0	198.7	1872.42	0.99728	272	240	0.997597	1871.82	-0.60
13.0	169.9	1938.47	0.99711	289	257	0.997429	1937.84	-0.63
14.0	145.1	1995.36	0.99696	304	273	0.997268	1994.74	-0.62
15.0	123.75	2044.36	0.99682	318	289	0.997114	2043.76	-0.60
16.0	105.39	2086.52	0.99670	330	303	0.996967	2085.96	-0.56
17.0	89.651	2122.69	0.99659	341	317	0.996828	2122.18	-0.51
18.0	76.223	2153.57	0.99648	352	331	0.996696	2153.11	-0.46
19.0	64.79	2179.88	0.99639	361	343	0.996571	2179.48	-0.40
20.0	55.118	2202.16	0.99630	370	355	0.996454	2201.82	-0.33
21.0	46.934	2221.01	0.99623	377	366	0.996345	2220.76	-0.25
22.0	39.965	2237.08	0.99616	384	377	0.996242	2236.90	-0.18
23.0	34.062	2250.70	0.99610	390	386	0.996147	2250.60	-0.10
24.0	29.084	2262.19	0.99605	395	394	0.996059	2262.17	-0.02
25.0	24.872	2271.91	0.99600	400	402	0.995978	2271.97	0.06
26.0	21.300	2280.17	0.99596	404	410	0.995903	2280.31	0.14
28.0	15.691	2293.14	0.99589	411	423	0.995773	2293.42	0.28
30.0	11.623	2302.56	0.99584	416	434	0.995666	2302.96	0.40
32.0	8.6566	2309.42	0.99580	420	442	0.995581	2309.94	0.52
34.0	6.807	2314.46	0.99545	455	449	0.995515	2314.32	-0.14
36.0	4.8761	2318.18	0.99575	425	453	0.995468	2318.84	0.66
38.0	3.6866	2320.94	0.99573	427	456	0.995436	2321.63	0.69
40.0	2.8004	2323.00	0.99572	428	458	0.995417	2323.70	0.70
44.0	1.6464	2325.69	0.99570	430	458	0.995416	2326.34	0.65
48.0	0.9885	2327.23	0.99568	432	455	0.995416	2327.85	0.62
52.0	0.6004	2328.14	0.99567	433	449	0.995416	2328.73	0.59
56.0	0.3604	2328.70	0.99566	434	440	0.995416	2329.28	0.58
60.0	0.2117	2329.05	0.99566	434	431	0.995416	2329.62	0.57
70.0	0.0503	2329.43	0.99565	435	404	0.995416	2329.99	0.56

4. Verification New Formulas

The first step we compare zenith tropospheric delay resulted from the new model for Egypt to those resulted from numerical integration model (NIM). In addition, tropospheric delay estimated using known models used to improve the accuracy of the new model.

Table3. Differences in mm between zenith delay resulting from delay models and numerical integration model

Station	Models	Max (mm)	Mean (mm)	RMS (mm)
Aswan	Saastamoinen	11.21	6.81	7.50
	Hopfield	9.19	3.77	5.39
	Simplified Hopfield	10.39	4.96	6.29
	Black	10.62	5.19	6.47
	New Model for Egypt	**5.52**	**1.16**	**3.33**
Helwan	Saastamoinen	10.15	5.23	6.58
	Hopfield	14.40	6.35	8.52
	Simplified Hopfield	13.21	5.96	7.91
	Black	-11.61	-3.03	7.04
	New Model for Egypt	**-5.38**	**-3.45**	**4.04**
Mersa-Matrouh	Saastamoinen	10.27	5.24	6.69
	Hopfield	13.55	6.29	8.22
	Simplified Hopfield	12.36	5.9	7.47
	Black	-12.12	-4.13	7.33
	New Model for Egypt	**-6.05**	**-4.04**	**4.79**

It can be seen from this table that the estimated new model is the most precise model to predict zenith dry delay for all area of Egypt. The mean rms for estimated model (4.05 mm) is smaller than the mean rms for all other models (7.12mm) by almost 43%. The mean difference between Hopfield and NIM is 3.77 mm with rms of 5.39 mm at station Aswan and reach to 6.81 mm with rms of 7.50 mm for Saastamoinen model but for new model the mean difference no more than 1.33 mm with rms 3.33 mm for same station. For station Helwan, the mean difference exceeds from 3.03 mm for Black model to 6.35mm for Hopfield model with rms do 8.52 mm but for new model rms reach 4 mm only. This model gives rms no more than 5 mm for Mersa-Matrouh station with mean difference do 4 mm only comparing with rms equal 6.69 mm for Saastamoinen model with mean difference 5.24 mm for same station.

The second step we compare tropospheric delay resulted from estimated models and other models at zenith with numerical integration model for extreme temperature models of atmospheres of Egypt (for an absolute minimum and an absolute maximum temperatures). For this purpose we collected temperature at various heights for these models (Tab. 4), obtained from Egyptian meteorological authority.

Table 4: Temperature of air for an absolute minimum and maximum of temperature models of atmosphere of Egypt

Absolute maximum model				Absolute minimum model			
H, км	$T_{max.}$(˚C)	Place	Month	*H*, км	$T_{min.}$(˚C)	Place	Month
0.0	48.5	El - Kharga	June	0.0	-1.60	El - Dakhla	December
1.324	33.0	Helwan	May	1.518	-3.3	Mersa - Matruh	March
3.164	19.4	Хелуан	July	3.089	-13.7	Mersa - Matruh	March
4.448	12.0	Aswan	July	4.292	-23.7	Mersa - Matruh	March
5.931	6.9	Helwan	July	5.672	-33.7	Mersa - Matruh	March
7.692	-0.1	Helwan	July	7.294	-42.3	Mersa - Matruh	March
9.866	-15.0	Helwan	July	9.199	-51.2	Mersa - Matruh	December
11.190	-22.8	Helwan	July	10.476	-60.1	Mersa - Matruh	March
12.753	-32.7	Helwan	July	11.604	-65.1	Mersa - Matruh	January
14.501	-44.7	Helwan	July	14.010	-72.4	Aswan	March
16.527	-42.3	Mersa - Matruh	May	16.458	-78.0	Aswan	February
18.715	-38.3	Mersa - Matruh	May	18.459	-84.3	Aswan	January
19.769	-36.4	Mersa - Matruh	May	19.420	-74.3	Helwan	January
20.914	-35.0	Mersa - Matruh	May	20.482	-73.8	Helwan	January
22.918	-33.6	Helwan	May	22.005	-72.9	Helwan	January
24.600	-27.6	Helwan	June	23.768	-67.4	Helwan	December
27.495	-26.6	Helwan	June	26.107	-63.2	Helwan	December

Table 5. Difference in mm between zenith delays resulted from tropospheric delay models and numerical integration model

Temperature	Saastamoinen	Hopfield	M-Hopfield	Black	New model
Absolute Max.	5.25	6.03	5.76	8.25	**0.47**
Absolute Min.	5.8	4.94	6.22	6.46	**1.03**

As shown in this table New model is the most precise model to predict tropospheric delay for condition atmosphere of Egypt. This model gives an error no more than millimeters in absolute Max temperature comparing with 5.25 mm using Saastamoinen models. At absolute Min. temperature, the difference between new model and NIM is 1.03 mm but for Hopfield model, it is 4.94 mm.

5. Conclusions

By analyzing data used in this study for three meteorological stations (Aswan , Helwan and Mersa-Matrouh) , it can be concluded that New model, resulted in this study, for atmospheric conditions of Egypt , is more precise for prediction of zenith tropospheric dry delay with accuracy to millimeters with the advantage that it needs only surface pressure in observation point.

So, new model is recommended for prediction of tropospheric dry delay for atmospheric conditions of different geographic regions in Egypt.

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