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Research Article

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Studying and Assessment the Tropospheric Delay at Different Weather Conditions in Egypt

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Abstract One of the most significant error sources which affect GPS signal propagation time is the zenith tropospheric delay (ZTD). Estimating ZTD is very useful for meteorological applications and weather prediction. ZTD computation is also very important in geodetic studies to improve position accuracy. Many precise point positioning (PPP) online services were developed during the past years to support positioning and, in parallel deliver estimates of the tropospheric delay. In this paper, firstly, an assessment of estimated ZTD in Europe from four PPP online services is presented. Observation data of four whole days from eight IGS stations in Europe are used in this study. Observation time was chosen to cover the weather conditions through the four seasons of the year in Europe. Four online precise point positioning services APPS, CSRS-PPP, GAPS, and MagicGNSS were used in this study and the ZTD value estimates delivered by these services were compared with the ZTD values provided by the International GNSS Service (IGS) troposphere product. The results show a good RMSE agreement (<17 mm) for APPS, CSRS-PPP, and MagicGNSS services. On the other hand GAPS delivers a weak accuracy with RMSE values of up to 38 mm. The APPS service provides ZTD values closest to the IGS Troposphere product along the four seasons of the year.

Secondly, the performance of the online PPP services for estimating the ZTD in Egypt has been tested by using observation data of four days from six stations in Egypt. Observation time was chosen to cover the weather conditions through the four seasons of the year in Egypt. Based on the first part of the study about Europe, the APPS service was taken as a reference to which the other online services were compared. The GAPS service was not used in this part because it gave the weakest accuracy for ZTD value. The results show a good RMSE agreement (<12 mm) for the both the CSRS-PPP and MagicGNSS services along the four seasons of the year.

Keywords GPS, Zenith Tropospheric Delay (ZTD), Precise Point Positioning (PPP) Online Services

1. Introduction

The GPS signal is refracted when it moves along the Earth's atmosphere. The signal bends from the original directions as it moves through different refractive indices regions in the troposphere and the ionosphere layers. The troposphere layer contains 75 % of the mass of the atmosphere and most of its water vapor. The tropospheric delay is caused by two reasons, the delay of the signal excess path and the bending effects on the radio signal. The excess delay of the GPS signal occurs because the troposphere refractive index is greater than unity, and the bending of the GPS signal is caused by the change of the refractive index with height. The tropospheric delay is divided into two components, hydrostatic delay, and wet delay. The hydrostatic delay is caused by the dry gases in the troposphere layer and the non-dipole component of water vapor refractivity. The wet delay is caused by water vapor. Estimating the total zenith tropospheric delay is very important for positioning, for weather prediction, and it also provides relevant information about climate change [1-2].

In geodesy, the total zenith tropospheric delay (ZTD) is usually estimated within the routine analysis of a network of ground-based GPS receivers [3-4]. Thus, ZTD computation needs scientific software packages that are not usual to unprofessional users in general or commercial software packages that are costly. But, the PPP free online services developed to estimate the ZTD. With these services, the unprofessional user does not need to use scientific or commercial software on his computer. All the processing achieved by dedicated computers at operations centers of the PPP online services organizations [5].

This paper presents an assessment of the performance of online PPP services in estimating The ZTD in Egypt along the four seasons of the year passing through a preceding study about Europe. Four online PPP services are used in this study. These services are the Canadian Spatial Reference System precise point positioning service (CSRS-PPP), The Automatic Precise Positioning Service (APPS), the GNSS Analysis and Positioning Software (GAPS), and the Magic-PPP online PPP software.

1.1. Tropospheric Delay Models

The GPS signals which propagate through the atmosphere are affected by the free electron content in the ionosphere layer and by the density of the air in the troposphere layer. These effects cause a delay in the GPS signals. The refractive index N of the troposphere layer can be expressed by:

$$\mathrm{N} = 10^{6}(n-1) \tag{1}$$

The refractivity is described by the following equation [6]:

$$\mathrm{N} = \mathrm{N_{Dry}} + \mathrm{N_{Wet}} = \mathrm{K_1}\frac{\mathrm{P_d}}{\mathrm{T}} + \mathrm{K_2}\frac{\mathrm{e}}{\mathrm{T}} + \mathrm{K_3}\frac{\mathrm{e}}{\mathrm{T^2}} \tag{2}$$

Where:

P_d is the partial pressure due to dry gases,

K_i are the refractivity constants,

e is the partial pressure of water vapor, and

T is the absolute temperature.

The tropospheric delay can be derived by integration along the path of the signal through the troposphere layer using the following equation:

$$\mathrm{d_{trop}} = 10^{-6}\int_{path}^{\infty}\mathrm{N}\,ds \tag{3}$$

The tropospheric delay is usually divided into two components, the hydrostatic delay and the wet delay. The hydrostatic delay occurs due to the dry gases in the troposphere layer and is usually derived by introducing the meteorological data gathered close to the ground-based receiver. The wet delay is usually estimated by eliminating the hydrostatic delay from the total tropospheric delay. The wet delay occurs by the water vapor in the troposphere layer.

Hence, the tropospheric delay can be expressed by the summation of the hydrostatic and wet components:

$$\mathrm{d_{trop}} = 10^{-6}\int_{path}^{\infty}\mathrm{N_h}\,ds + 10^{-6}\int_{path}^{\infty}\mathrm{N_w}\,ds \tag{4}$$

The following form can be used to describe the zenith tropospheric delay components:

$$\mathrm{d^z_{trop}} = \mathrm{d^z_h} + \mathrm{d^z_w} \tag{5}$$

The slant tropospheric delay at a certain elevation angle is derived by the zenith delay and mapping functions values. This expression includes separate mapping functions for the hydrostatic and wet delay:

$$\mathrm{d^s_{trop}} = \mathrm{m_h}(\varepsilon)\times\mathrm{d^z_h} + \mathrm{m_w}(\varepsilon)\times\mathrm{d^z_w} \tag{6}$$

Where:

$m_h(\varepsilon)$ The hydrostatic mapping function, and

$m_w(\varepsilon)$ The wet mapping function.

Generally, the value of total zenith tropospheric delay is about 2.50 m. The zenith hydrostatic delay is about 90% of this value, and the zenith wet delay is the rest 10% of it. As satellites decrease in elevation toward the horizon, the slant hydrostatic delay and the slant wet delay values increase [7].

Equations (1-6) show that the ZTD value depends on refractivity of the troposphere layer. The refractivity is calculated from meteorological parameters along the path of the signal, so, the zenith tropospheric delay also counts on these parameters [1].

Many different troposphere models created to estimate the tropospheric delay. In general, meteorological data like temperature and pressure are main components of these models forms. Hopfield [8], Saastamoinen [9], Davis et al. [10] and Baby et al. [11] considered the most famous models in this field [12]. The zenith tropospheric delay derived using the PPP technique.

1.2. Precise Point Positioning (PPP) Services

In last years, many organizations have developed and improved PPP online services to offer GNSS positioning services without need of reference stations. Moreover estimates of the ZTD can be obtained in parallel. Users can use most of these services by a free registration to be able to submit the data and then get the products of these services via the internet [13]. In this study, four PPP online services are used.

The Canadian Spatial Reference System (CSRS-PPP service) is an online service which is operated by Natural Resources Canada (NRCan). Users can use this service to estimate the position and can also get extra products such as the local tropospheric zenith delays, the station-clock states, and the carrier-phase ambiguities. Users need to free register to get its products. The CSRS-PPP service bases all calculations on available ephemeris and clock corrections obtained from IGS and Natural Resources Canada (NRCan) organizations. Data can be processed in static or kinematic mode, this service also can process the data observed by a single or dual frequency receiver [14].

The Automatic Precise Positioning Service (APPS) is an online service operated by The Jet Propulsion Lab (JPL).APPS can process static and kinematic GPS data. Users need to free register to estimate coordinates and also to retrieve estimates of the ZTD. The user can't process single frequency observations by this service but may choose between Rapid, Ultra-rapid and Final type products from the Jet Propulsion Lab (JPL) to correct orbits and clocks of satellites [15].

The GNSS Analysis and Positioning Software (GAPS) is an online service operated by the University of New Brunswick (UNB) to provide users with a free online PPP tool for estimating positions and other parameters of interest. This service allows the user to choose between Rapid, Ultra-rapid and Final products from IGS and Natural Resources Canada (NRCan) as a source to correct orbits and clocks of satellites [16].

The MagicGNSS is an online service developed by the company GMV Aerospace and Defense. Users can process data using MagicGNSS service by emailing data or by free registration. By MagicGNSS, data in static mode or kinematic mode can be processed. The user can also choose between final and rapid products for clocks and orbits corrections which are accessible by the GMV or IGS [17].

Figure 1: Europe IGS Stations

2. Practical Study and Results Analysis

2.1. First Study Area

Used data in this part of study are collected from eight IGS stations in Europe shown in Figure (1). Eight IGS stations GENO, GRAZ, FFMJ, BRUX, GANP, MEDI, OPMT and ZIM2 are used. The observation time for the above IGS stations is chosen to cover the weather conditions through the four seasons of the year in Europe. The observation periods are selected in four days, the 22th of March, June, September and December of year 2017.

2.1.1. Data processing

The used GPS data in this part of study are processed using the four PPP services APPS, CSRS-PPP, GAPS and MagicGNSS that previously described .In this part of the study, a package of processing parameters are applied in all processing strategies as shown in table (1):

Table 1: Used processing parameters in different online PPP services

Parameter	CSRS-PPP	APPS	GAPS	MagicGNSS
Mode of calculation	Static	Static	Static	Static
Constellation	GPS	GPS	GPS	GPS
Frequency	Dual	Dual	Dual	Dual
Observation type	Code and phase	Code and phase	Code and phase	Code and phase
The reference frame	ITRF14	ITRF14	ITRF14	ITRF14
Orbits/Clocks used	IGS Final	JPL Final	IGS Final	IGS Final
Cut-off angle	7.5°	7.5°	7.5°	7.5°
Mapping Function	VMF1	GMF	VMF1	GPT2
Output data rate	300 sec	300 sec	300 sec	300 sec

2.1.2. Results and Discussion

The following Figure (2) illustrates the ZTD values for GENO station along DOY 81/2017 by using the IGS troposphere product and the four online PPP services.

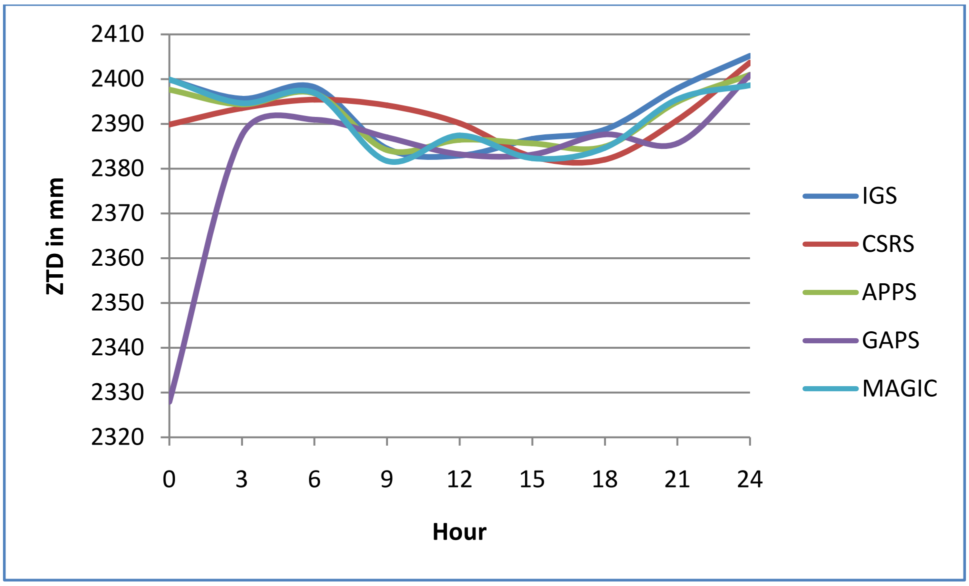

Figure 2: ZTD values in mm along DOY 81/2017 for GENO station

The above figure is a selected example from 32 figures that illustrate the eight IGS stations results in the four chosen days shown in details in the main thesis of this study.

The following Figure (3) shows the average value of ZTD in contour map from IGS product for Europe stations area in DOY 81/2017.Figure (3) is a selected example from 20 figures shown in details the main thesis of this study that illustrate the average value of ZTD in contour maps from IGS product and the four online PPP services for Europe stations area in the four chosen days

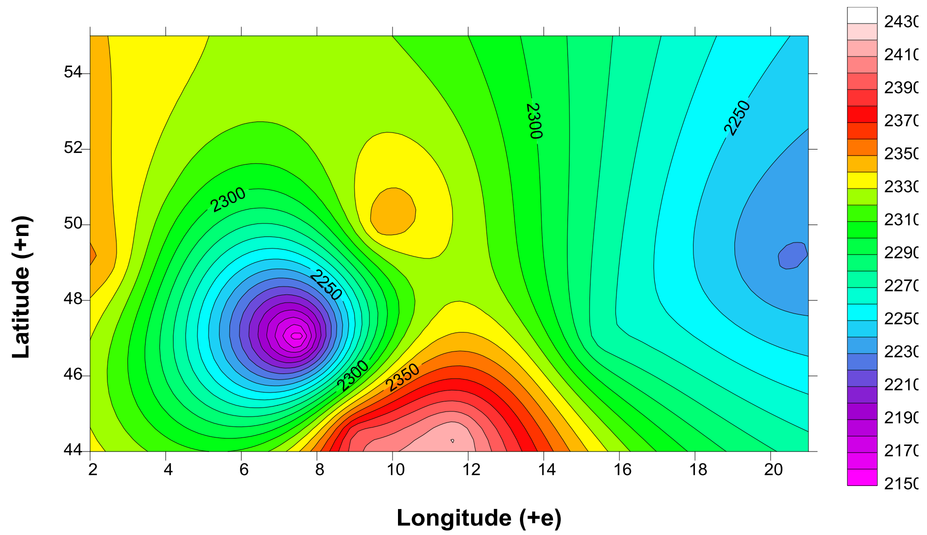

Figure 3: Contour map for ZTD from IGS product for Europe stations area in DOY 81/2017

The relationship between the ZTD values obtained by the above mentioned online PPP services and the IGS tropospheric product values is investigated by error calculation which is performed to determine how much the average ZTD values along the day, obtained from the PPP services, differed from the IGS product average values along the day. The following equation is used to calculate this deviation:

$$\text{Error }\% = \frac{(ZTD_{PPPService} - ZTD_{IGS})}{ZTD_{IGS}} \times 100 \quad (7)$$

The following Figures (4-7) illustrate the deviation of the PPP services average ZTD values from the IGS product values:

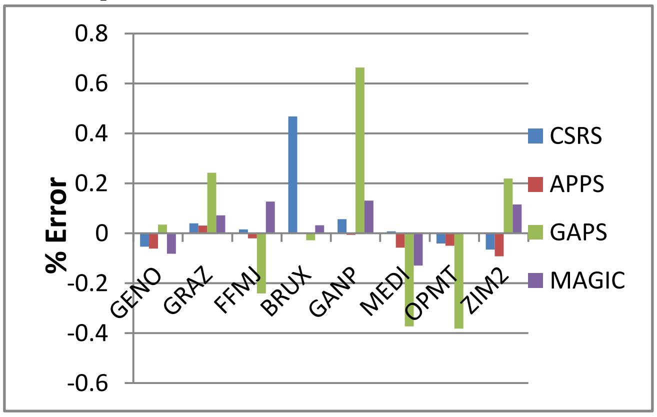

Figure 4: Error% values for day 81/2017

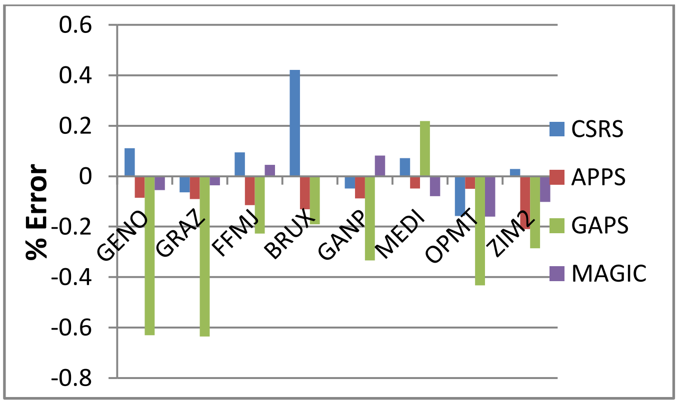

Figure 5: Error% values for day 173/2017

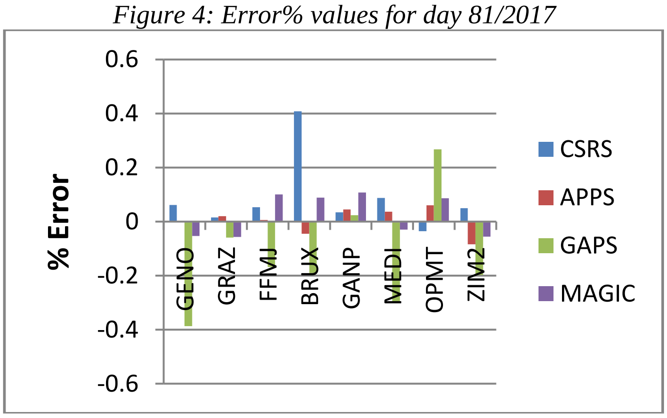

Figure 6: Error% values for day 265/2017

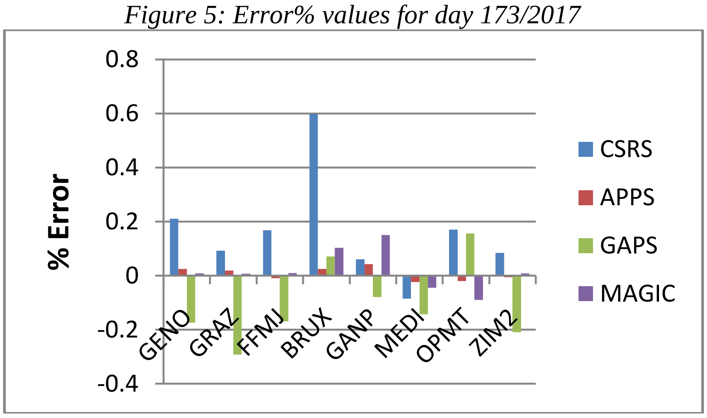

Figure 7: Error% values for day 356/2017

To evaluate the estimated ZTD from the four online services previously described, The Root Mean Square Error (RMSE) value is used in this evaluation as an accuracy indication, and it is calculated by the following equation:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}(ZTD_{estimated}-ZTD_{IGS})^2}{n}} \quad (8)$$

Where n is the total number of the available estimated ZTD values. The RMSE is calculated using Equation (8) for each IGS station and each online service per day. The following Tables (2-5) and Figures (8-11) illustrate the RMSE of ZTD values estimated with each online PPP service.

Table 2: RMSE in mm for day 81/2017

Station	RMSE in mm.			
	CSRS	APPS	GAPS	MAGIC
GENO	6.52	3.65	35.34	4.42
GRAZ	4.9	2.55	29.59	3.37
FFMJ	3.24	2.16	13.96	4.15
BRUX	11.31	2.05	9.29	2.39
GANP	3.86	2.37	87.77	3.98
MEDI	3.29	2.93	28.29	4.28
OPMT	4.7	3.86	16.89	2.9
ZIM2	5.16	2.97	34.33	3.74

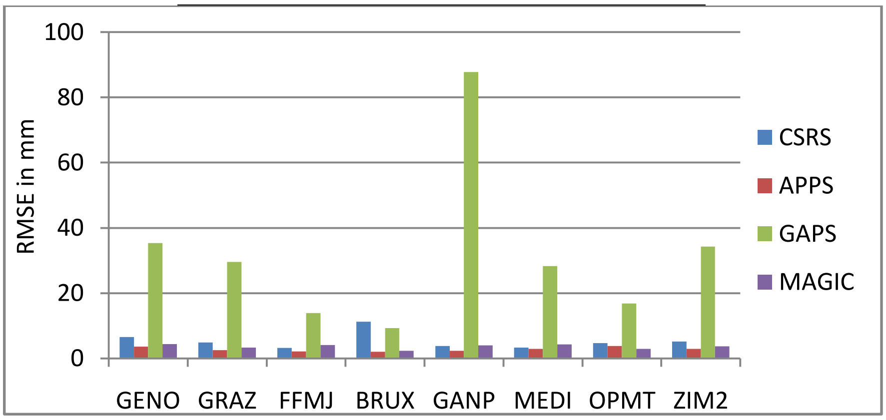

Figure 8: RMSE in mm for day 81/2017

Table 3: RMSE in mm for day 173/2017

Station	RMSE in mm.			
	CSRS	APPS	GAPS	MAGIC
GENO	10.1	3.9	28.08	5.43
GRAZ	6.35	4.45	33.95	4.8
FFMJ	9.47	4.99	37.59	5.72
BRUX	14.72	4.35	15.41	6.32
GANP	5.86	4.13	21.34	4.2
MEDI	6.93	4.73	57.5	4.72
OPMT	16.37	4.31	22.04	6.57
ZIM2	6.31	6.18	23.62	5.97

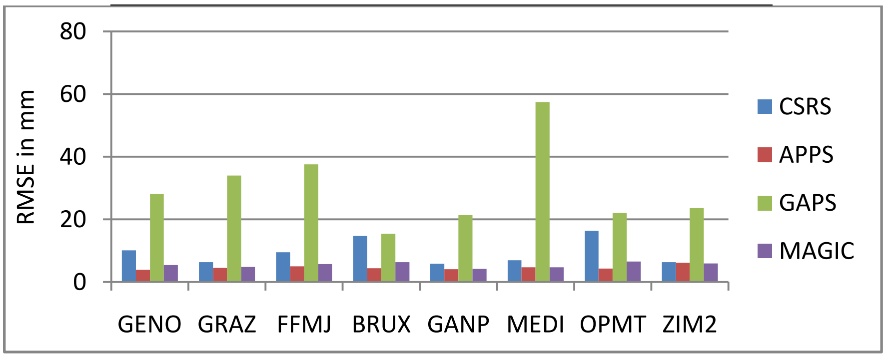

Figure 9: RMSE in mm for day 173/2017

Table 4: RMSE in mm for day 265/2017

Station	RMSE in mm.			
	CSRS	APPS	GAPS	MAGIC
GENO	4.79	2.52	28.97	3.48
GRAZ	4.11	3.46	7.63	3.65
FFMJ	3.81	3.15	12.28	3.89
BRUX	12.04	3.51	16.21	4.81
GANP	3.33	2.87	14.51	5.54
MEDI	4.8	3.97	25.45	4.12
OPMT	9.39	4.97	23.65	6.25
ZIM2	5.84	4.31	11.93	3.39

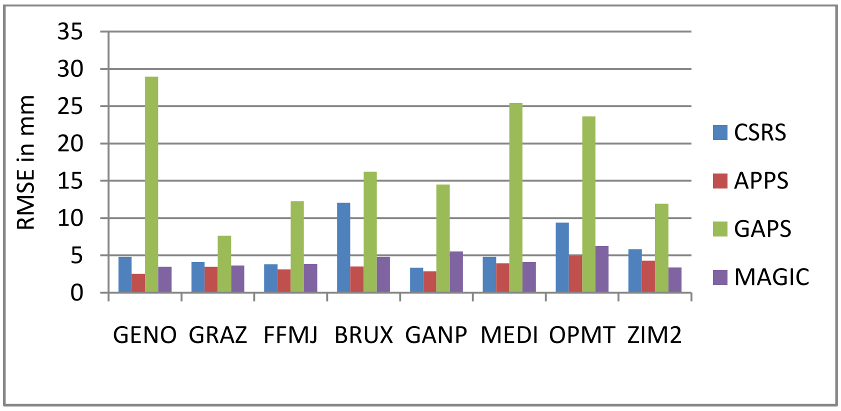

Figure 10: RMSE in mm for day 265/2017

Table 5: RMSE in mm for day 356/2017

Station	RMSE in mm.			
	CSRS	APPS	GAPS	MAGIC
GENO	8.05	2.59	25.65	4.36
GRAZ	4.89	2.23	21.48	3.1
FFMJ	5.95	2.34	19.42	3.21
BRUX	15.23	2.08	12.79	4.15
GANP	3.48	3.08	15.31	5.03
MEDI	4.94	3.49	25.52	3.85
OPMT	10.32	3.34	16.82	11.26
ZIM2	3.69	2.4	22.76	2.58

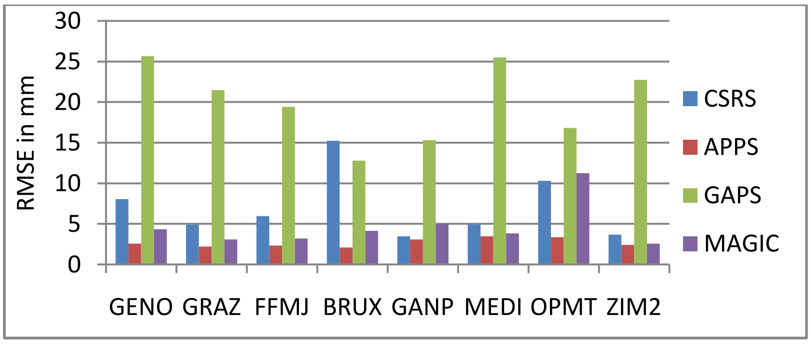

Figure 11: RMSE in mm for day 356/2017

Based on Table (2) it noticed that APPS service provides the most reliable results for ZTD values for the most of the used IGS stations during spring season where RMSE varied from about 2.05 mm to 6.06 mm, then MagicGNSS service where RMSE varied from about 2.39 mm to 5.43 mm, then CSRS service where RMSE varied from about 3.24 mm to 11.31 mm, then GAPS service with the weakest accuracy where RMSE varied from about 9.29 mm to 87.77 mm.

Based on Table (3) it noticed that APPS service provides the most reliable results the most reliable results for ZTD values for the most of the used IGS stations during summer season where RMSE varied from about 3.9 mm to 6.18 mm, then MagicGNSS service where RMSE varied from about 4.2 mm to 6.57 mm, then CSRS service where RMSE varied from about 5.86 mm to 16.37 mm, then GAPS service with the weakest accuracy where RMSE varied from about 15.41 mm to 57.5 mm.

Based on Table (4) it noticed that APPS service provides the most reliable results the most reliable results for ZTD values for the most of the used IGS stations during autumn season where RMSE varied from about 2.52 mm to 4.97 mm, then MagicGNSS service where RMSE varied from about 3.39 mm to 6.25 mm, then CSRS service where RMSE varied from about 3.33 mm to 12.04 mm, then GAPS service with the weakest accuracy where RMSE varied from about 7.63 mm to 28.97 mm.

Based on Table (5) it noticed that APPS service provides the most reliable results the most reliable results for ZTD values for the most of the used IGS stations during winter season where RMSE varied from about 2.08 mm to 3.49 mm, then MagicGNSS service where RMSE varied from about 2.58 mm to 11.26 mm, then CSRS service where RMSE varied from about 3.48 mm to 15.23 mm, then GAPS service with the weakest accuracy where RMSE varied from about 12.79 mm to 25.65 mm.

2.2. Second Study Area

Used data in this part of study are collected from six stations in Egypt shown in Figure (12). Six stations ALAM, ASWN, BORG, MNSR, MTRH, and SAID are used. The observation time for the above stations is chosen to cover the weather conditions through the four seasons in Egypt. The observation periods are selected in four days, the 26th of January, the 20th of March, the 1st of June and the 21th of September of the year 2014. Based on the first part of the study about Europe, the APPS service is taken as a reference to which the other online services were compared. The GAPS service is not used in this part because it gave the weakest accuracy for ZTD value.

Figure 12: Egypt stations

2.2.1. Data Processing

The used GPS data in this part of study are processed using APPS, CSRS-PPP and MagicGNSS services. In this part of the study, a package of processing parameters are applied in all processing strategies as shown in table (1).

2.2.2. Results and Discussion

The following Figure (13) illustrates the ZTD values for ASWN station along DOY 26/2014 by using APPS, CSRS-PPP and MagicGNSS services.

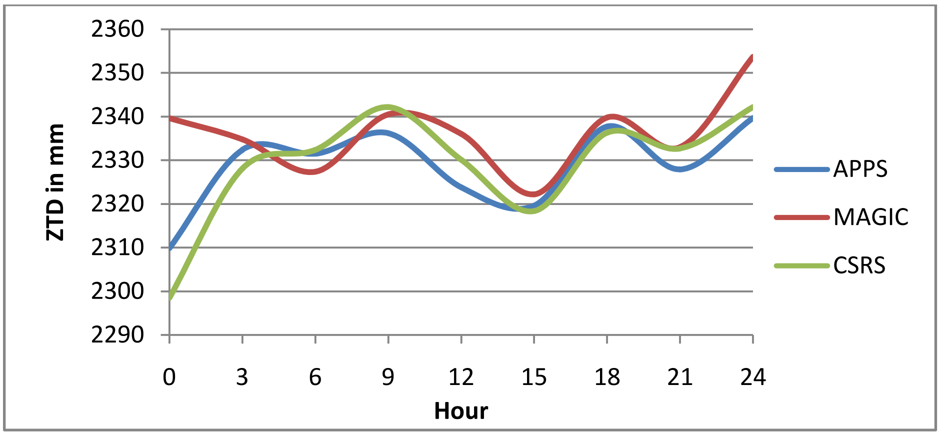

Figure 13: ZTD values in mm in DOY 26/2014 for ASWN station

The above figure is a selected example from 24 figures that illustrate the six stations results in the four chosen days shown in details in the main thesis of this study.

The following Figure (14) shows the average value of ZTD in contour map from APPS service for Egypt stations area in DOY 26/2014. Figure (14) is a selected example from 12 figures shown in details in the main thesis of this study which illustrate the average value of ZTD in contour maps from APPS, CSRS-PPP and MagicGNSS services for Egypt stations area in the four chosen days.

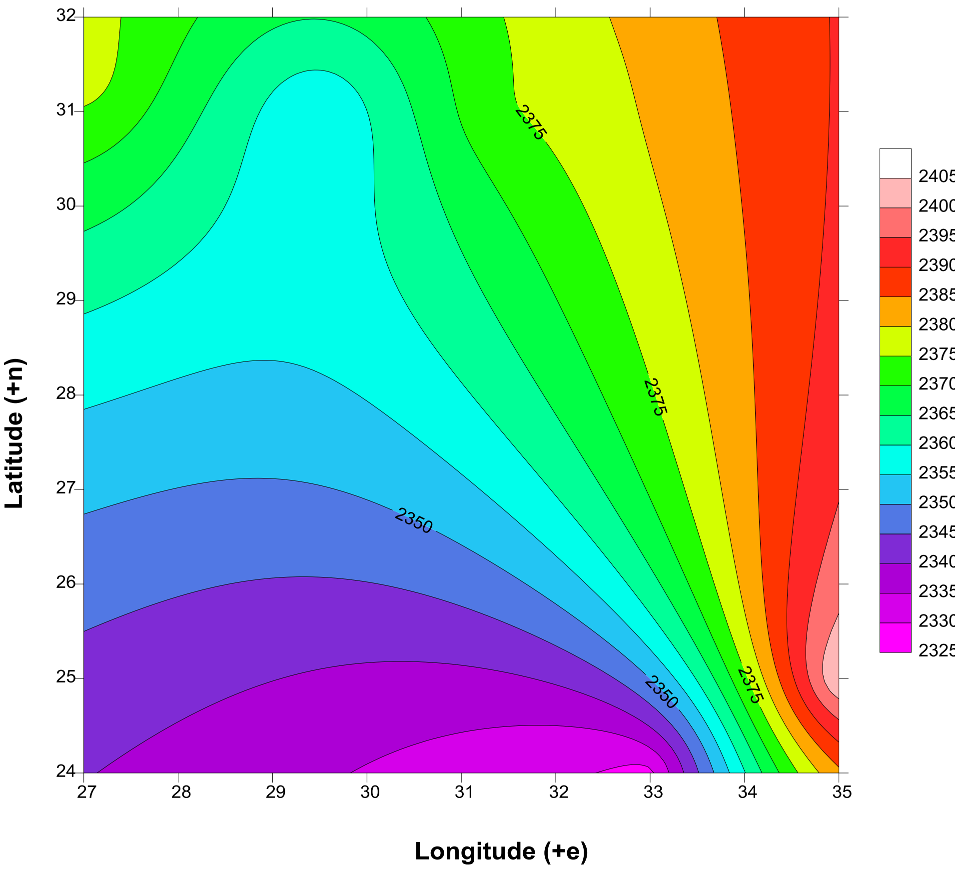

Figure 14: Contour map for ZTD from APPS service for Egypt stations area in DOY 26/2014

The relationship between the ZTD values obtained by APPS, CSRS-PPP and MagicGNSS services is investigated by error calculation which is performed to determine how much the average ZTD values in the day, obtained from CSRS-PPP and MagicGNSS services, differed from APPS service average values along the day. The following equation is used to calculate this deviation:

$$\text{Error \%} = \frac{(ZTD_{CSRS\ or\ MagicGNSS} - ZTD_{APPS})}{ZTD_{APPS}} \times 100 \qquad (9)$$

The following Figures (14-17) illustrate the deviation of CSRS-PPP and MagicGNSS average ZTD values from APPS service values:

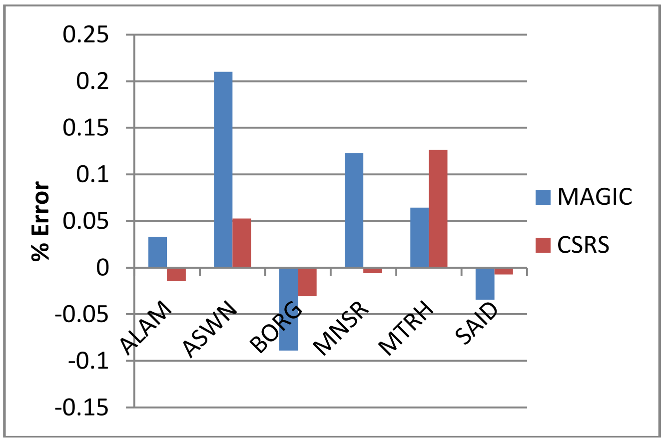

Figure 15: Error% values for day 26/2014

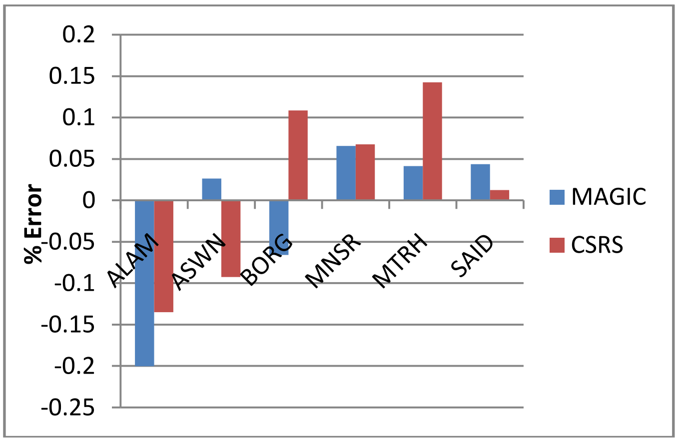

Figure 16: Error% values for day 79/2014

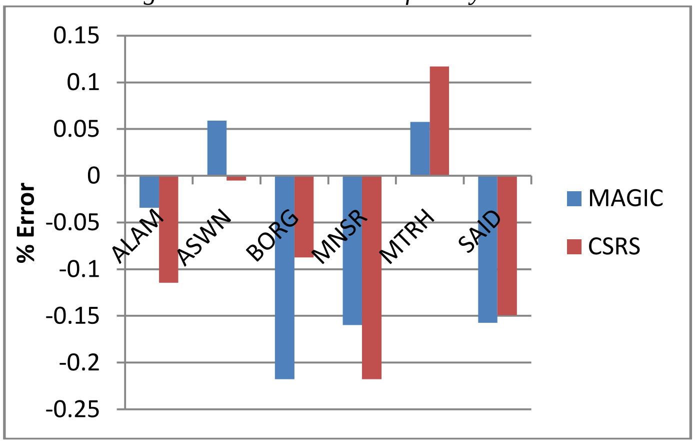

Figure 17: Error% values for day 152/2014

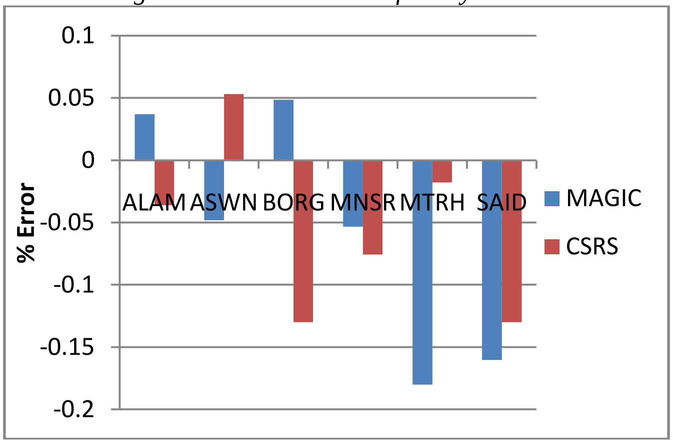

Figure 18: Error% values for day 264/2014

To evaluate the estimated ZTD from the CSRS-PPP and MagicGNSS services, The Root Mean Square Error (RMSE) value is used in this evaluation as an accuracy indication, and it is calculated by the following equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(ZTD_{CSRS\ or\ MagicGNSS} - ZTD_{APPS})^2}{n}} \qquad (10)$$

Where n is the total number of the available estimated ZTD values. The RMSE is calculated using Equation (10) for each station and each online service per day. The following Tables (6-9) and Figures (18-21) illustrate the RMSE of ZTD values estimated with CSRS-PPP and MagicGNSS services.

Table 7: RMSE in mm for day 79/2014

Station	**RMSE in mm.**	
	CSRS	**MAGIC**
ALAM	6.02	3.91
ASWN	5.65	10.14
BORG	9.96	6.03
MNSR	7.4	5.39
MTRH	6.39	2.99
SAID	7.51	7.01

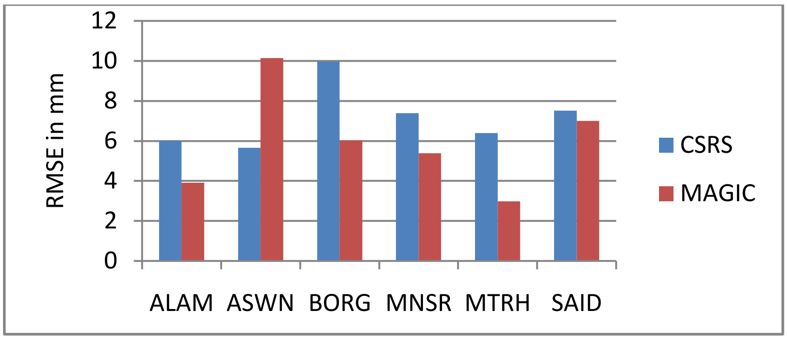

Figure 19: RMSE in mm for day 26/2017

Table 7: RMSE in mm for day 79/2014

Stations	RMSE in mm.	
	CSRS	**MAGIC**
ALAM	6.85	11.52
ASWN	3.14	4.27
BORG	4.26	2.98
MNSR	2.96	4.36
MTRH	7.1	4.37
SAID	2.81	3.47

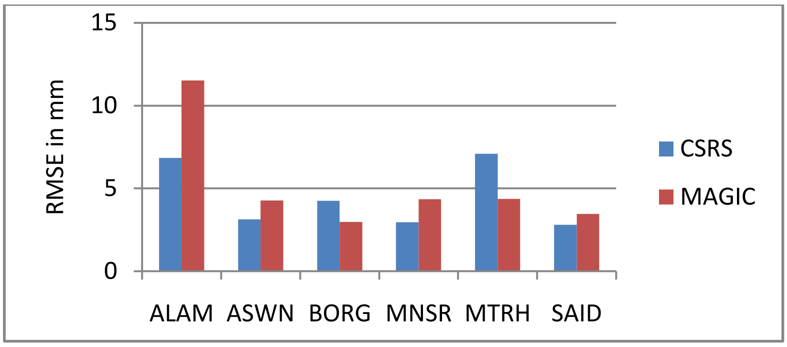

Figure 20: RMSE in mm for day 79/2014

Table 8: RMSE in mm for day 152/2014

Stations	RMSE in mm.	
	CSRS	**MAGIC**
ALAM	5.78	4.41
ASWN	3.1	3.56
BORG	5.68	6.21
MNSR	6.01	4.21
MTRH	4.54	3.67
SAID	6.51	5.13

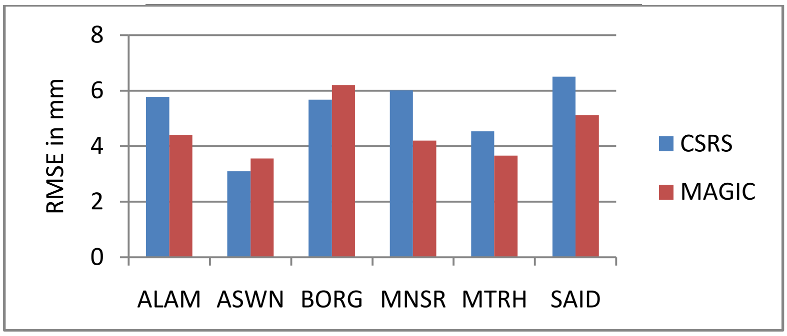

Figure 21: RMSE in mm for day 152/2014

Table 9: RMSE in mm for day 264/2014

Stations	RMSE in mm.	
	CSRS	MAGIC
ALAM	6.65	5.97
ASWN	2.58	3.85
BORG	5.37	5.77
MNSR	5.98	3.57
MTRH	7.21	6.02
SAID	6.16	4.92

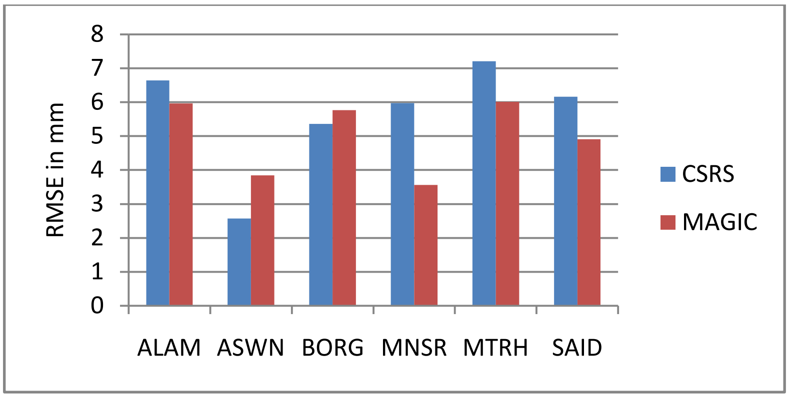

Figure 22: RMSE in mm for day 264/2014

Based on Table (6) it noticed that MagicGNSS service provides the closest ZTD values to APPS service for the most of Egypt stations during winter season where RMSE varied from about 2.99 mm to 10.14 mm, then CSRS service where RMSE varied from about 5.56 mm to 9.96 mm.

Based on Table (7) it noticed that CSRS service provides the closest ZTD values to APPS service for the most of Egypt stations during spring season where RMSE varied from about 2.81 mm to 7.1 mm, then MagicGNSS service where RMSE varied from about 2.98 mm to 11.52 mm.

Based on Table (8) it noticed that MagicGNSS service provides the closest ZTD values to APPS service for the most of Egypt stations during summer season where RMSE varied from about 3.56 mm to 6.21 mm, then CSRS service where RMSE varied from about 3.1 mm to 6.51 mm.

Based on Table (9) it noticed that MagicGNSS service provides the closest ZTD values to APPS service for the most of Egypt stations during autumn season where RMSE varied from about 3.57 mm to 6.02 mm, then CSRS service where RMSE varied from about 2.58 mm to 7.21 mm.

3. Conclusions

Based on the practical results and analysis, the following conclusions summarized:

1. The troposphere delay irregularity is a difficult phenomenon because of the rapid change in metrological parameters at weather conditions. So, the tropospheric delay remains one of the major error sources in high precision GNSS positioning. But, it is workable to establish a local interpolation a precise ZTD value for tropospheric delay mitigation using online service for fitting a local model.

2. For first study area (Europe):
   a. The results showed a good RMSE agreement (<17 mm) for APPS, CSRS-PPP and MagicGNSS services, and showed also that GAPS gives a weak accuracy where RMSE values up to 38 mm.
   b. It was found that APPS service provides the closest ZTD values to the IGS Troposheric product along the four seasons of the year.
3. For second study area (Egypt):
   a. The results showed a good RMSE agreement (<12 mm) for the both of CSRS-PPP and MagicGNSS services.

   b. It was found that MagicGNSS service provides the closest ZTD values to APPS service along winter, summer and autumn seasons, and CSRS-PPP service provides the closest ZTD values to APPS service along spring season.
4. To get a precise ZTD value for geodetical and meteorological studies in Europe or Egypt using PPP technique, it is recommended to use APPS service followed by MagicGNSS service, then CSRS-PPP service.

4. Recommendation

To get the best results in future studies, we recommend using more data from more observation sites with different conditions.

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