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Tropospheric wet delay estimation using GNSS: Case study of a permanent network in Egypt

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KEYWORDS

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Abstract The tropospheric delay is a serious error source for positioning using Global Navigation Satellite Systems (GNSS). Since the scientific applications of GNSS positioning such as crustal deformation studies and earthquakes prediction require high accuracy in positioning, analysis of tropospheric delay calculation is necessary to improve GNSS positioning accuracy.

In this study data from ground based GNSS receivers are used to evaluate effect of the tropospheric delay in position determination accuracy. These data are also used to study the tropospheric delay characteristics. The collected GNSS data are for the year 2013, taken from 8 stations from Egypt Permanent GNSS Network (EPGN) and 13 IGS stations. The GNSS data were processed using advanced GNSS software called Bernese V 5.0.

The results show that the RMS of the coordinates is better in case of making estimation for the troposphere ZWD and bad in case of ignoring the troposphere. Also there is a correlation between the troposphere and the height component. The troposphere ZWD values have daily, temporal and spatial variation, depending on time in the day, day in the year, geographic location of the station and how near it to water. The ZWD values also go upward from the start to the end of the year, and also it shows high correlation with the water vapor content in the troposphere.

1. Introduction

The troposphere is the lower part of earth's atmosphere, and its height varies from 9 to 16 km (Lutgens and Tarbuck, 1989). It is non-ionized and non-dispersive medium with respect to radio waves up to 15 GHz. The troposphere affects the GNSS signals since the signals are both delayed and refracted (e.g. Mousa and El-Fiky, 2005). The tropospheric delay is divided, based on physical parameters, into hydrostatic delay (dry) and wet delay. The hydrostatic delay is caused by dry gases and particles in the troposphere, and it

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is about 80–90% of the total tropospheric delay (e.g. Abdelfatah et al., 2009). Hydrostatic delay can be precisely determined from surface pressure measurements using empirical models (Saastamoinen, 1973; Hopfield, 1971). The tropospheric wet delay is due to water vapor content in the troposphere, and it is difficult to be precisely modeled, because the water vapor in the troposphere is not well mixed. The determination of the tropospheric zenith wet delay (ZWD) can't be consistently modeled with millimeter precision by any existing empirical model. So the ZWD is one of the accuracy limiting factors in GNSS positioning (Boehm et al., 2007). The ZWD precise estimation is important for high precision applications, such as Network Real Time Kinematic (RTK) and precise point positioning (PPP). In addition, the ZWD values calculated from GNSS measurements can be used in Numerical weather prediction (El-Mowafy and Lo, 2013).

In the present study, several processing strategies for the troposphere available in Bernese software were applied and tested. This is to illustrate the effect of the troposphere in the precision of positioning using GNSS. Also estimation of the ZWD values was made to study its temporal and spatial variations, beside that illustrating the yearly profiles of the ZWD for our EPGN stations. Furthermore a correlation was made between ZWD and perceptible water vapor (PWV).

2. Study area and data

Data used in our research were collected from eight GNSS stations (Arish – Asuoit – Aswan – Helwan – Kharga – Mansoura – Marsa Alam and Matrouh) of the Egyptian Permanent GNSS Network (EPGN) (Fig. 1), and EPGN was established by National Research Institute of Astronomy and Geophysics (NRIAG) in 2006 (Saleh and Becker, 2013). These stations represent different environments in Egypt, Coast line, Desert, Nile Valley and Delta to be representative for different climate conditions.

Thirteen (13) IGS stations with a good configuration around the EPGN stations were used for datum definition. These IGS stations are shown in Fig. 2. IGS stations belong to 3 different plates, African plate, Arabian plate, and Eurasian plate. There are 8 stations of the selected IGS stations included in the ITRF2008 datum. Being part of ITRF2008, the 8 stations were used as datum points to establish the ITRF2008 datum for the whole network used in the study.

Definite strategy was followed in data acquisition according to the purpose of our study. Data of five (5) days in or near the middle of every month over the year 2013 are collected, from all used EPGN stations and all used IGS stations according to the availability of data. This makes sixty (60) days all over the year to represent all weather conditions in the year as listed in Table 1.

3. Data processing

The used GNSS data were processed using Bernese GNSS software Version 5.0, that is sophisticated, high accuracy, high performance GNSS data post-processing package, developed by Astronomical Institute, University of Bern, Switzerland. This package can run under both Microsoft Windows and UNIX operating systems and is based on Least Squares fit technique (Dach et al., 2007). Bernese software is capable of

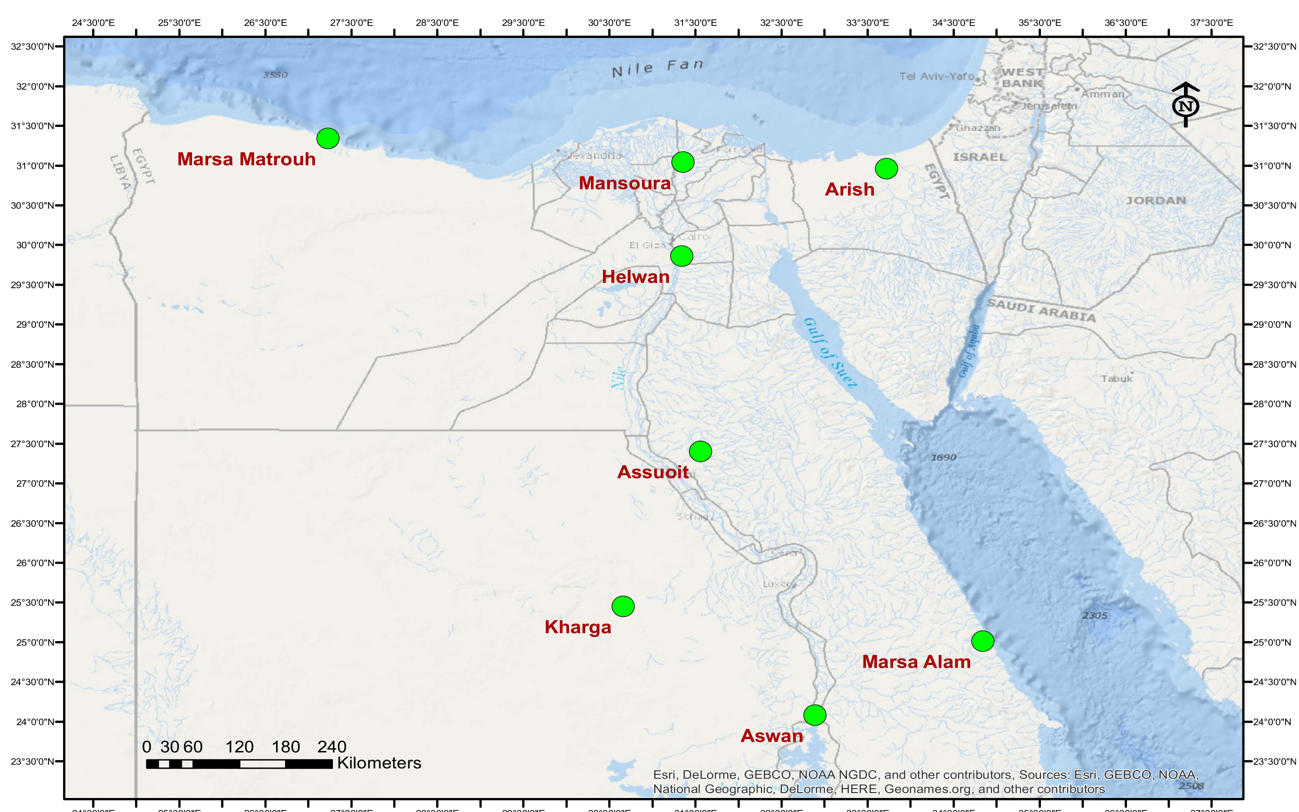

Figure 1 Geographic distribution of EPGN stations used in this study.

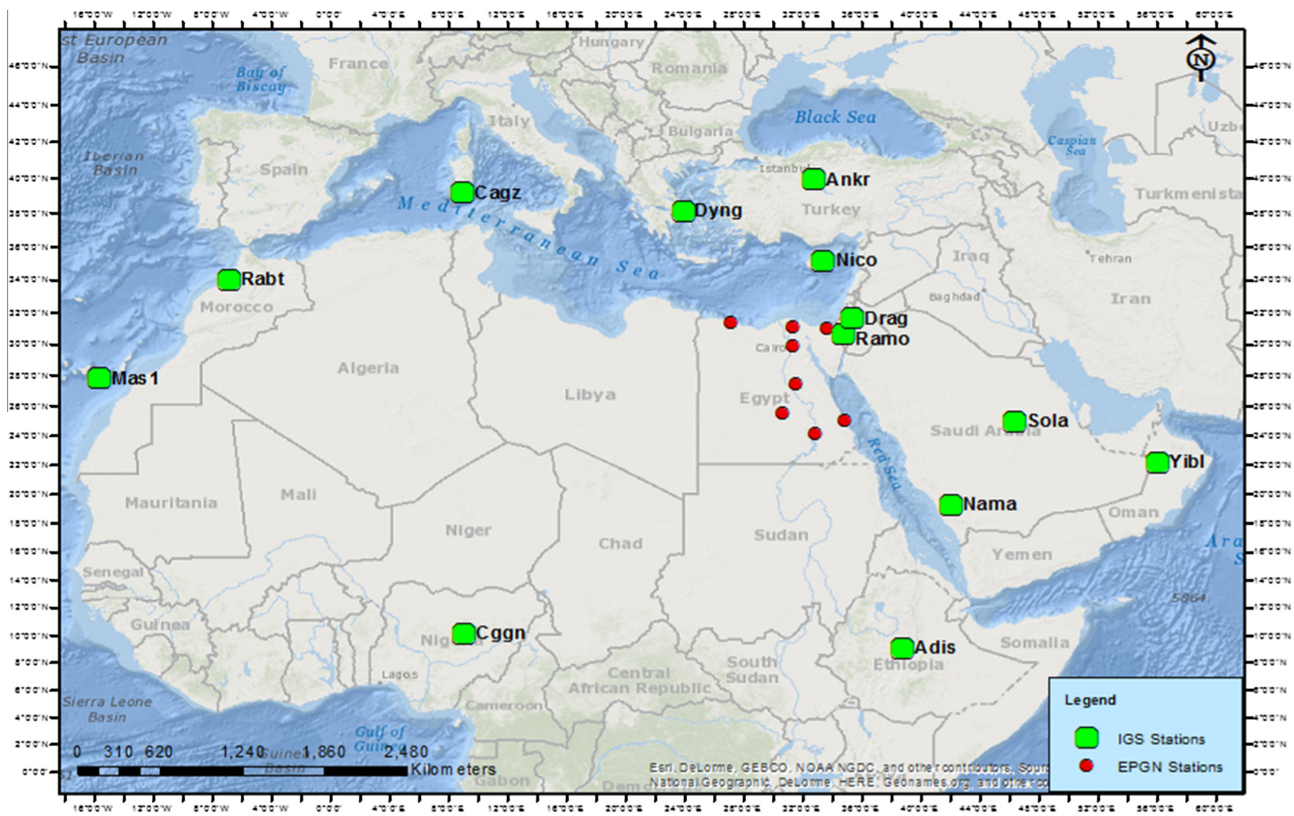

Figure 2 Geographic distribution of used IGS stations with EPGN stations.

Table 1 The selected days from every month in year 2013.

Month	Days in the month
January	17–21
February	13–17
March	16–20
April	26–30
May	16–20
June	14–18
July	13–17
August	15–19
September	13–17
October	13–17
November	4–8
December	8–12

handling both the precise point positioning and the network processing strategies.

Steps of GNSS observations processing using Bernese V5.0 can be summarized as a block diagram (Fig. 3). These raw data (GNSS data) are obtained in Receiver Independent Exchange (RINEX) format. These data are then processed using GNSS processing software packages to have the needed output in a form of coordinates and tropospheric delay. Raw data firstly undergo editing and decimation. In addition to editing the raw data, information about satellite positions in orbits, satellite clocks, a priori coordinates of the ground receiver and values from geophysical models are obtained from various sources, for example: International GNSS Service (IGS) or a previous work. All these data are then fed to the processing engine of the software package which is based on Kalman filter and Least Squares Method (LSM). User manages the processing stage by setup of a group of parameters, geophysical models and type of solution needed. The obtained output is coordinates, clock bias and tropospheric delay components (Dach et al., 2007).

3.1. Processing parameters

All data used from EPGN and IGS stations are from dual frequency receivers. In this study a group of processing parameters are applied in all processing strategies as follows:

- Sampling rate – 30 s
- Elevation cutoff angle – 3°
- Number of iterations – 6
- Horizontal atmosphere gradient – Non
- Ambiguity Fixing – QIF (Quasi Ionosphere Free)
- Datum – ITRF2008
- Ionosphere – Free linear combination L3
- Type of solution – Daily network solution
- Solution constrain – Minimum constraint
- Receivers types in EPGN:

Receiver Type	Station
Trimble 5700	Asuoit – Helwan – Kharga
Trimble NetR5	Aswan – Mansoura – Matrouh – Marsa Alam

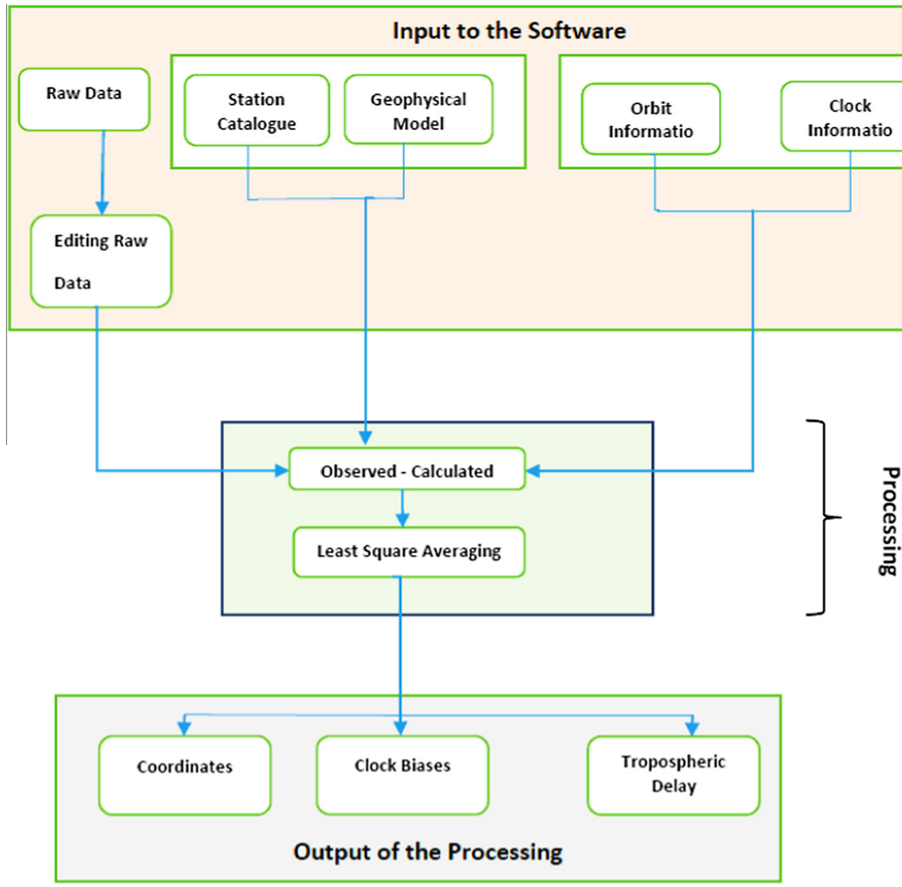

Figure 3 General block diagram of GNSS data processing.

3.2. Processing strategies

Performing GNSS data processing, three different processing strategies are followed, because the main interest in this study is to evaluate the effect of the troposphere parameters on GNSS accuracy. Besides the variation of the tropospheric wet delay over the study area, is discussed. These processing strategies are as follows: using a complete model to correct the tropospheric error, estimation of the tropospheric zenith wet delay (ZWD) and ignoring the troposphere totally.

3.2.1. Using a complete model to correct the tropospheric error

In this strategy, all a priori troposphere models in Bernese V5.0 (Saastamoinen, dry Saastamoinen, Neill, dry Neill, Hopfield and dry Hopfield) are firstly tested. Every model with all available troposphere mapping functions in the software (dry Neill, wet Neill, Hopfield and 1/Cos mapping functions) decides which is the best to be used in this strategy. The best results for the coordinates Root Mean Square (RMS) are in case of using the complete Neill model with the dry Neill mapping function. Hence for this strategy, we will use Neill model as a complete model with the dry Neill mapping function to correct the troposphere.

3.2.2. Estimation of the tropospheric zenith wet delay (ZWD)

In this strategy, as recommended in Bernese V 0.5 (Dach et al., 2007) user manual, a priori models and mapping functions are used as input in the processing. For estimating the site-specific troposphere parameters, the tropospheric dry part (ZHD) was accounted for by using the dry Niell model and then the remaining wet part (ZWD) was estimated and mapped with the corresponding wet Niell mapping function with one-hour time resolution. This is reasonable for standard analysis. The estimated site specific troposphere parameters besides refining the accuracy of the coordinate parameters, also have an advantage because this strategy gives the values of the estimated ZWD which is useful in the weather forecasting and climatology.

3.2.3. Ignore the troposphere totally

In this strategy the troposphere parameters are neglected and this strategy is expected to be the worst one in processing, as the troposphere is a systematic error in positioning using GNSS and must be solved by estimation of the troposphere parameters or by using a model.

4. Results and discussion

4.1. Coordinates RMS results for the used strategies

Here the results of the coordinates RMS for different seasons of the year are shown. Every RMS value for any station is the mean of RMS values for the selected days in this season, this is presented for all processing strategies, and the shaded cells represent the absence of data.

4.1.1. The RMS of stations coordinates for winter

Applying the three processing strategies, the coordinates RMS results are obtained in meter, as shown in the following Tables 2–4.

The RMS of coordinates (latitude, longitude, height) in winter is low in case of using a model and in case of estimation of the troposphere. For the horizontal coordinates (latitude, longitude) it varies from 0.0015 to 0.0018 m while for the vertical coordinates (height component), it is from 0.0032 to 0.0036 m. In case of ignoring the troposphere the RMS becomes high, for the horizontal coordinates. It is from 0.0029 to 0.0036 m and for the height component, it is in the range of 0.0059–0.0066 m.

4.1.2. The RMS of stations coordinates for spring

The following three Tables 5–7, represent the results of the RMS of the coordinates for the used three different ways of processing in spring.

The RMS of coordinates in spring becomes higher than that in winter in case of using a model and in case of estimation of the troposphere. For the horizontal coordinates it takes the values from 0.0022 to 0.0027 m and for the height component, it reaches about 0.00420.005 m. In case of ignoring the troposphere, the RMS becomes higher, for the horizontal coordinates it is from 0.0031 to 0.0039 m and for the height component, it is from 0.0061 to 0.007 m.

Table 2 Latitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Latitude RMS for winter			
Arish	0.0016	0.0016	0.0031
Asuoit	0.0016	0.0016	0.0030
Aswan	0.0015	0.0015	0.0029
Helwan	0.0016	0.0016	0.0030
Kharga			
Mansoura	0.0016	0.0016	0.0031
Marsa Alam	0.0015	0.0015	0.0029
Matrouh	0.0017	0.0016	0.0032

Table 3 Longitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Longitude RMS for winter			
Arish	0.0017	0.0017	0.0032
Asuoit	0.0018	0.0018	0.0035
Aswan	0.0017	0.0017	0.0032
Helwan	0.0017	0.0017	0.0032
Kharga			
Mansoura	0.0017	0.0017	0.0033
Marsa Alam	0.0017	0.0017	0.0033
Matrouh	0.0018	0.0018	0.0036

Table 4 Height RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Height RMS for winter			
Arish	0.0033	0.0032	0.0060
Asuoit	0.0036	0.0035	0.0066
Aswan	0.0034	0.0033	0.0061
Helwan	0.0032	0.0032	0.0059
Kharga			
Mansoura	0.0032	0.0032	0.0059
Marsa Alam	0.0033	0.0032	0.0061
Matrouh	0.0034	0.0033	0.0062

Table 5 Latitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Latitude RMS for spring			
Arish	0.0024	0.0024	0.0034
Asuoit	0.0023	0.0023	0.0033
Aswan	0.0022	0.0022	0.0031
Helwan	0.0023	0.0023	0.0033
Kharga	0.0022	0.0022	0.0032
Mansoura	0.0023	0.0024	0.0034
Marsa Alam	0.0022	0.0022	0.0031
Matrouh	0.0024	0.0024	0.0034

Table 6 Longitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Longitude RMS for spring			
Arish	0.0026	0.0026	0.0038
Asuoit	0.0026	0.0026	0.0038
Aswan	0.0026	0.0026	0.0037
Helwan	0.0026	0.0026	0.0037
Kharga	0.0026	0.0026	0.0038
Mansoura	0.0026	0.0026	0.0038
Marsa Alam	0.0025	0.0025	0.0037
Matrouh	0.0027	0.0027	0.0039

Table 7 Height RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Height RMS for spring			
Arish	0.0045	0.0045	0.0064
Asuoit	0.0050	0.0049	0.0070
Aswan	0.0045	0.0045	0.0064
Helwan	0.0043	0.0043	0.0061
Kharga	0.0045	0.0044	0.0063
Mansoura	0.0043	0.0042	0.0062
Marsa Alam	0.0045	0.0044	0.0064
Matrouh	0.0043	0.0042	0.0061

4.1.3. The RMS of stations coordinates for summer

Tables 8–10, represent the results of the RMS of the coordinates for the used three different ways of processing in summer.

The RMS of coordinates in summer is high in case of using a model and in case of estimation of the troposphere. For the horizontal coordinates it assumes the values from 0.0035 to 0.0048 m and for the height component, it is from 0.005 to 0.0066 m. In case of ignoring the troposphere, the RMS becomes higher. The horizontal coordinate changes are from 0.0047 to 0.0065 m and from 0.0059 to 0.0081 m for the height component.

Table 8 Latitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Latitude RMS for summer			
Arish	0.0036	0.0036	0.0047
Asuoit			
Aswan	0.0036	0.0036	0.054
Helwan	0.0047	0.0047	0.0065
Kharga	0.0036	0.0036	0.0049
Mansoura	0.0036	0.0036	0.0049
Marsa Alam	0.0035	0.0036	0.0047
Matrouh	0.0036	0.0036	0.0048

Table 9 Longitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Longitude RMS for summer			
Arish	0.0043	0.0043	0.0054
Asuoit			
Aswan	0.0044	0.0044	0.0054
Helwan	0.0047	0.0048	0.0055
Kharga	0.0044	0.0044	0.0055
Mansoura	0.0043	0.0043	0.0054
Marsa Alam	0.0042	0.0042	0.0052
Matrouh	0.0044	0.0044	0.0055

Table 10 Height RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Height RMS for summer			
Arish	0.0065	0.0065	0.0080
Asuoit			
Aswan	0.0066	0.0065	0.0081
Helwan	0.0050	0.0050	0.0059
Kharga	0.0065	0.0065	0.0080
Mansoura	0.0062	0.0061	0.0076
Marsa Alam	0.0061	0.0061	0.0075
Matrouh	0.0061	0.0060	0.0076

4.1.4. The RMS of stations coordinates for autumn

Tables 11–13, represent the results of the RMS of the coordinates for the used three different ways of processing in autumn.

The RMS of coordinates in autumn is high in case of using a model and in case of estimation of the troposphere. For the horizontal coordinates it is from 0.0023 to 0.0063 m and for the height component from 0.0047 to 0.0076 m. In case of ignoring the troposphere the RMS becomes higher, for the horizontal coordinates it is from 0.0032 to 0.01 m and it is from 0.0067 to 0.011 m for the height component.

The troposphere error is a systematic error which affects the RMS of the coordinates. As clear in the previous tables, in both cases, case of using a model and case of making estimation of the ZWD, there are no significant differences in the horizontal coordinate RMS values. Usually it is the same in

Table 11 Latitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Latitude RMS for autumn			
Arish	0.0029	0.0029	0.0039
Asuoit	0.0023	0.0023	0.0032
Aswan	0.0026	0.0026	0.0035
Helwan	0.0027	0.0026	0.0037
Kharga	0.0061	0.0060	0.010
Mansoura	0.0028	0.0027	0.0038
Marsa Alam	0.0026	0.0026	0.0037
Matrouh	0.0029	0.0028	0.0039

Table 12 Longitude RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Longitude RMS for autumn			
Arish	0.0035	0.0035	0.0047
Asuoit	0.0028	0.0027	0.0038
Aswan	0.0033	0.0033	0.0045
Helwan	0.0033	0.0033	0.0044
Kharga	0.0063	0.0062	0.010
Mansoura	0.0033	0.0030	0.0044
Marsa Alam	0.0032	0.0032	0.0043
Matrouh	0.0035	0.0033	0.0046

Table 13 Height RMS for the three used strategies.

Station	Strategy 1	Strategy 2	Strategy 3
Height RMS for autumn			
Arish	0.0061	0.0061	0.0081
Asuoit	0.0049	0.0048	0.0067
Aswan	0.0058	0.0058	0.0077
Helwan	0.0055	0.0055	0.0074
Kharga	0.0076	0.0075	0.011
Mansoura	0.0055	0.0047	0.0074
Marsa Alam	0.0055	0.0055	0.0072
Matrouh	0.0057	0.0055	0.0075

most of stations and different times all over the year. It ranges from 0.0015 to 0.0063 m. If there are differences, it will be few parts of millimeter. In case of the vertical coordinates the RMS became higher than that of the horizontal coordinates, and it ranges from 0.0032 to 0.0076 m with few parts of millimeter differences between the two strategies. It is obvious that the height RMS most of time is better in case of using estimated ZWD than in case of using a model, usually by part of millimeter difference but in some cases the difference is high reaching 0.0008 m like in case of Mansoura station (Table 13).

In the third strategy of ignoring the troposphere totally in processing, the RMS of the horizontal coordinates became higher in comparison with the other two strategies. It ranges from 0.0029 to 0.01 m. while, for the RMS of the vertical coordinates, it ranges from 0.0059 to 0.011 m. It is clear that the RMS of the height component in this strategy is bad in comparison with the other strategies.

From the previous results of the RMS of the coordinates in the different processing strategies, it is clear that estimation of the tropospheric ZWD is the best strategy in the processing of data and it is important to have more precise solution. If data are not processed with making estimation of the tropospheric ZWD, it should be processed using a model to correct the troposphere and don't ignore it totally as the RMS of the coordinates will be bad.

There is high correlation between the height component and the troposphere estimation. So for more precession in network solution for the scientific studies such as the geodynamical studies, it is important to make estimation of the tropospheric wet delay to have the best needed RMS for investigating the micro changes in the dynamics of the earth and studying the geoid more precisely.

4.2. Verification of the troposphere zenith total delay (ZTD) from estimation strategy against IGS products

A comparison was established between the tropospheric ZTD values from IGS station products and the estimated ZTD values, to make assessment of the calculated ZTD. The IGS troposphere products are available on IGS web (2014). This shows the quality of the solution in comparison with IGS solution. The plotted ZTD values for every day are the mean of the ZTD values in this day, for the estimated ZTD values is 1 h resolution, and for the IGS solution the ZTD was estimated every 5 min with high temporal resolution. Figs. 4 and 5 are examples for the comparison of ZTD estimated here and IGS solution for Ankr and Cagz stations.

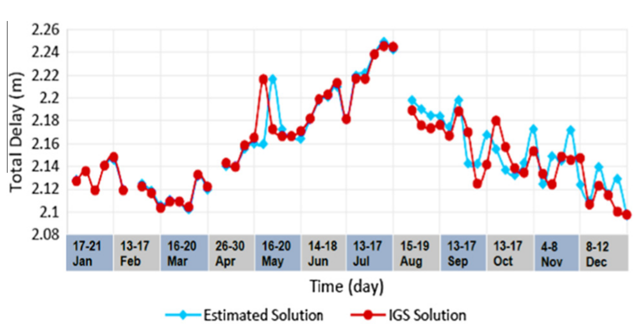

Figure 4 ZTD for Ankr station from estimated values and IGS solution.

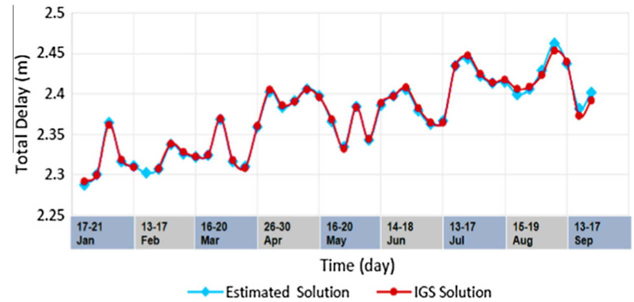

Figure 5 ZTD for Cagz station from estimated values and IGS solution.

It is clear in Fig. 4 for Ankr station that the ZTD shows good agreement between estimated ZTD values and the IGS solution. The mean difference is 0.17 cm and its RMS differences is 1.4 cm. For Cagz station (Fig. 5) the ZTD values show high agreement in the two solutions, the mean differences is 0.015 cm and its RMS difference is 0.34 cm. These figures show the good quality of the solution method.

4.3. The variation of the estimated tropospheric zenith wet delay

The values of the ZWD vary with time, location and local conditions. Its values are important to be studied to make interpretation of the positioning accuracy. The ZWD also has many usefulness's in meteorology like near real-time estimation of perceptible water vapor (PWV). The ZWD values were derived from the ZTD and the zenith hydrostatic delay (ZHD). The ZHD can easily calculated from the surface pressure measurements, and then the ZWD can be calculated as follows:

$$ZWD = ZTD - ZHD$$

A group of daily ZWD profiles are shown in Figs. 6–17. As examples, day from every month illustrates the daily, spatial and temporal variations.

The ZWD values get higher from the start to the end of the year as in Figs. 6–17, and its daily variation is within 11 cm (Fig. 14). Also the ZWD profile fluctuations vary from smooth fluctuated as in Figs. 10 and 11 to high fluctuated as in Figs. 13 and 17. The spatial variation from station to another in the same day is within 15 cm as in Fig. 14. There is temporal variation for ZWD from day to another in the year, for example Arish station shows 13.5 cm, Kharga station shows 16 cm, Marsa Alam station shows 16.5 cm and Helwan station shows 20 cm temporal variation.

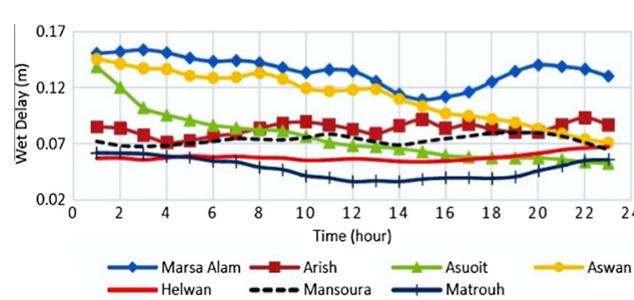

Figure 6 ZWD in 18 January – 2013.

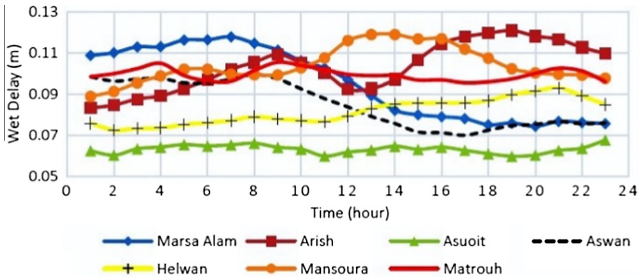

Figure 7 ZWD in 16 February – 2013.

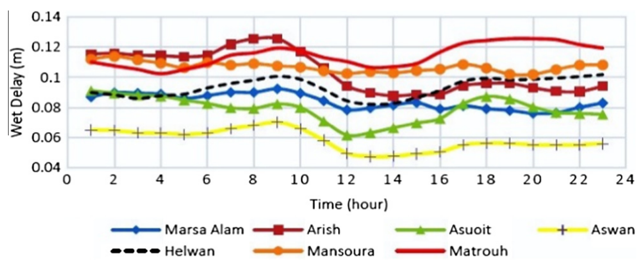

Figure 8 ZWD in 18 March – 2013.

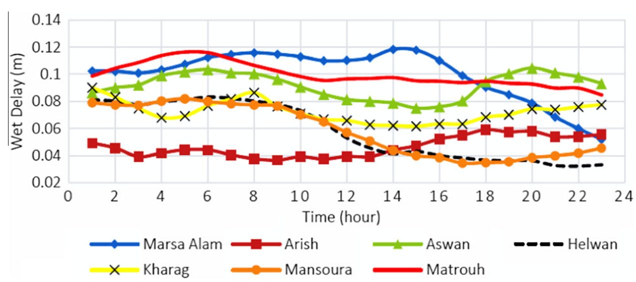

Figure 9 ZWD in 29 April – 2013.

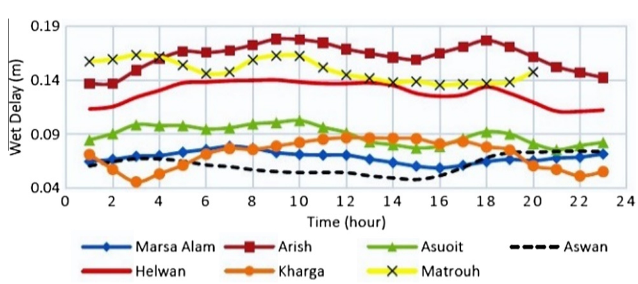

Figure 10 ZWD in 18 May – 2013.

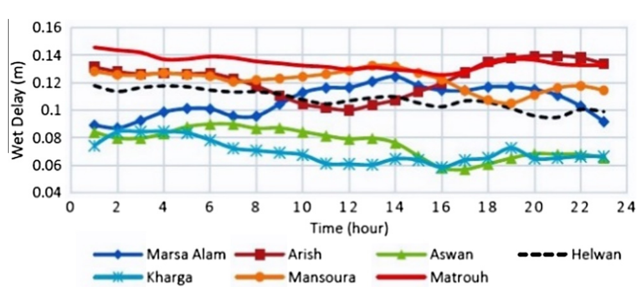

Figure 11 ZWD in 17 June – 2013.

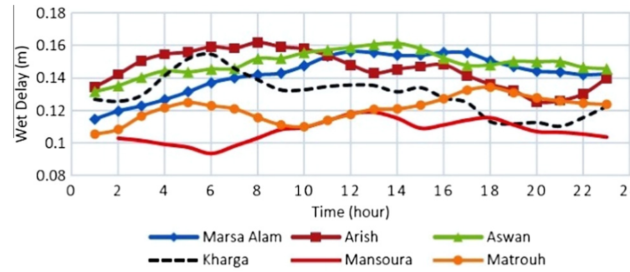

Figure 12 ZWD in 16 July – 2013.

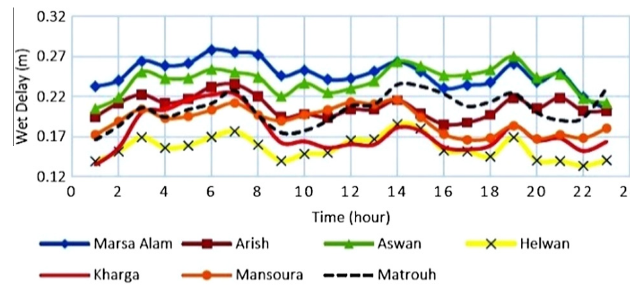

Figure 13 ZWD in 17 August – 2013.

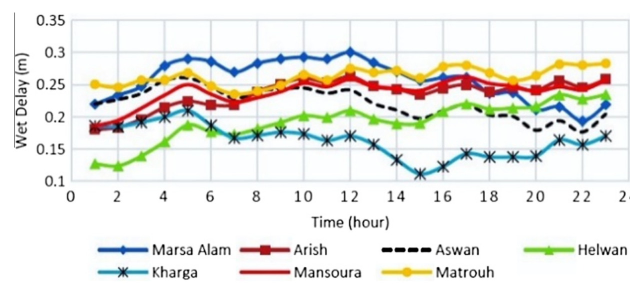

Figure 14 ZWD in 17 September – 2013.

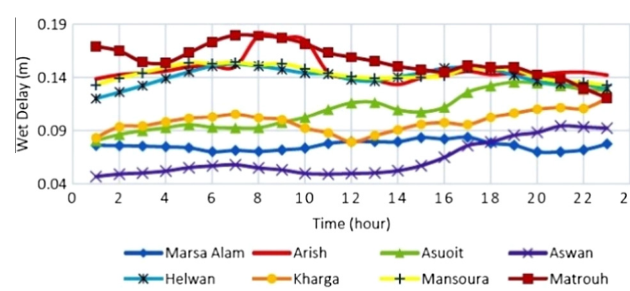

Figure 15 ZWD in 13 October – 2013.

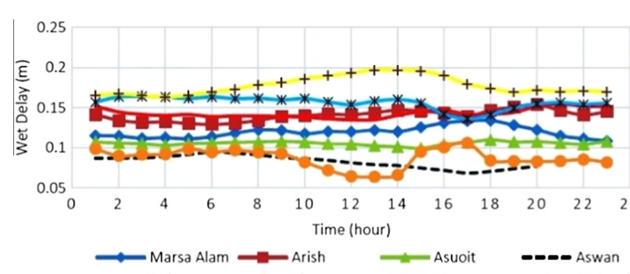

Figure 16 ZWD in 4 November – 2013.

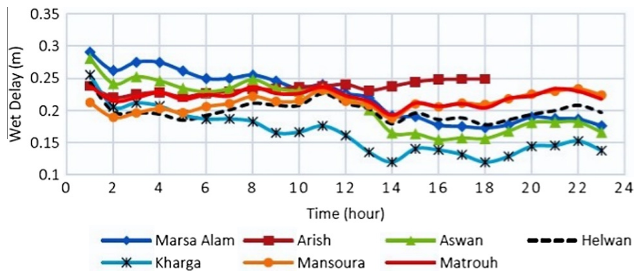

Figure 17 ZWD in 9 December – 2013.

4.4. Variation of ZWD in EPGN network during year 2013

In this part the variations of the ZWD values along the year 2013 for all used EPGN stations are shown in Figs. 18–25. The values of the ZWD, for selected days, shown in the figures are the mean of the hourly estimated ZWD for every day.

It is clear from the ZWD year profiles for EPGN stations that the ZWD values are low in winter and spring but get higher in summer and autumn at all stations. From station to another the spatial variation of ZWD is within 10.5 cm, and its highest values appear between Matrouh and Kharga stations. Also it is obvious that the variation of the ZWD val-

Figure 18 Year variations of ZWD at Arish station in 2013.

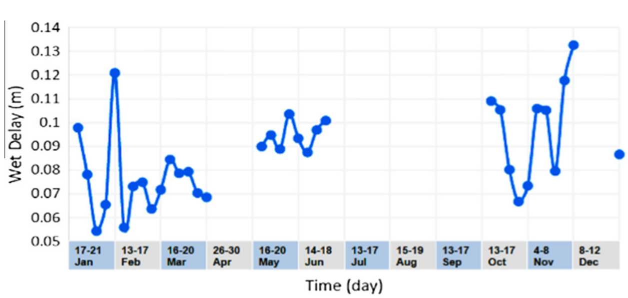

Figure 19 Year variations of ZWD at Asuoit station in 2013.

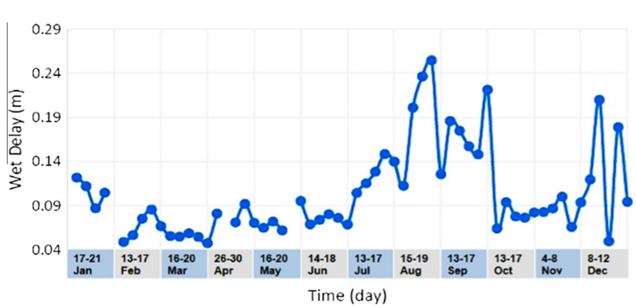

Figure 20 Year variations of ZWD at Aswan station in 2013.

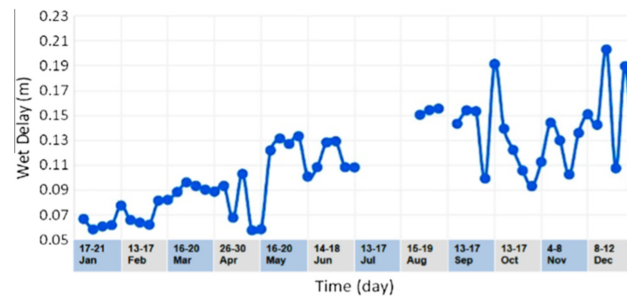

Figure 21 Year variations of ZWD at Helwan station in 2013.

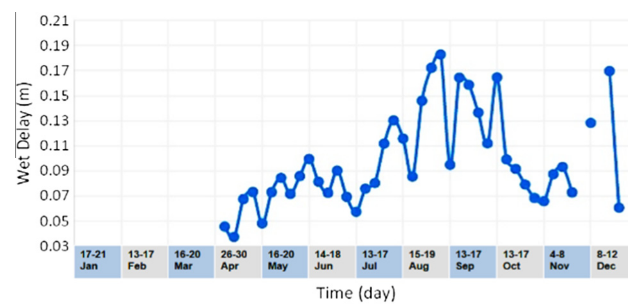

Figure 22 Year variations of ZWD at Kharga station in 2013.

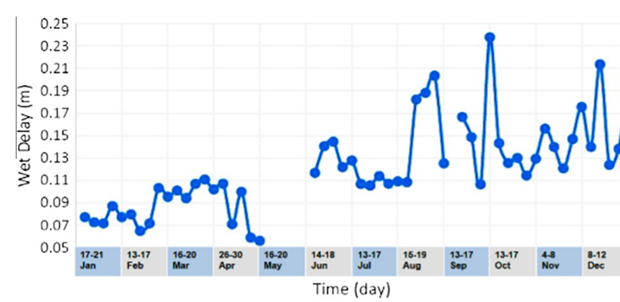

Figure 23 Year variations of ZWD at Mansoura station in 2013.

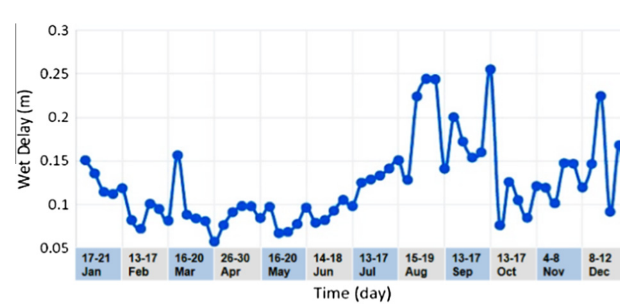

Figure 24 Year variations of ZWD at Marsa Alam station in 2013.

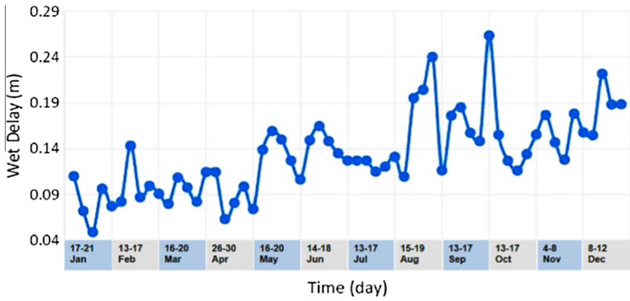

Figure 25 Year variations of ZWD at Matrouh station in 2013.

ues from location to another depends on how near the station to water is. Thus, the observed values at stations in coast line, Nile Valley and Delta show high ZWD. So all stations show high ZWD values along the year 2013 except Asuoit and Kharga stations which are far from water (Fig. 1). All stations show temporal variation or in another term seasonal variation from season to another. Asuoit station shows 8 cm, Helwan station shows 14.5 cm, Kharga station shows 15 cm, Mansoura station shows 18 cm, Arish station shows 19 cm, Marsa Alam station shows 20 cm, Aswan station shows 21.5 cm and Matrouh station shows 22 cm seasonal variation.

It is clearly observed that the general trend of ZWD profile values at all stations goes upward from the start of the year toward the end of the year. The same trend is assumed also for the RMS of the coordinate parameters in all previous processing strategies (Tables 2–13). So it is evident that the tropospheric ZWD is an important factor which affects the precession of the solutions strategy. It is important not to ignore the troposphere parameters in processing GNSS data for positioning.

4.5. Assessment and verification of ZWD with PWV

The ZWD values depend on the PWV i.e. water vapor content in the troposphere. To illustrate this relation between ZWD and PWV, a correlation was established between the ZWD values of Helwan and Matrouh GNSS stations with the PWV products of two Radiosonde stations near to our GNSS stations as in Fig. 26. The soundings are available on the site of Wyoming University department of Atmospheric Science (2014).

This correlation includes results of 12 day along the year 2013, day every month according to the availability of results. The following Figs. 27 and 28 show the profiles of the PWV and ZWD at Helwan and Matrouh stations.

The ZWD profiles of Helwan and Matrouh stations (Figs. 27 and 28) show high correlation with their equivalent PWV profiles from 0.83 to 0.84. This is in accordance with the theoretical fact that the tropospheric ZWD value depends on the amount of the water vapor content in the troposphere.

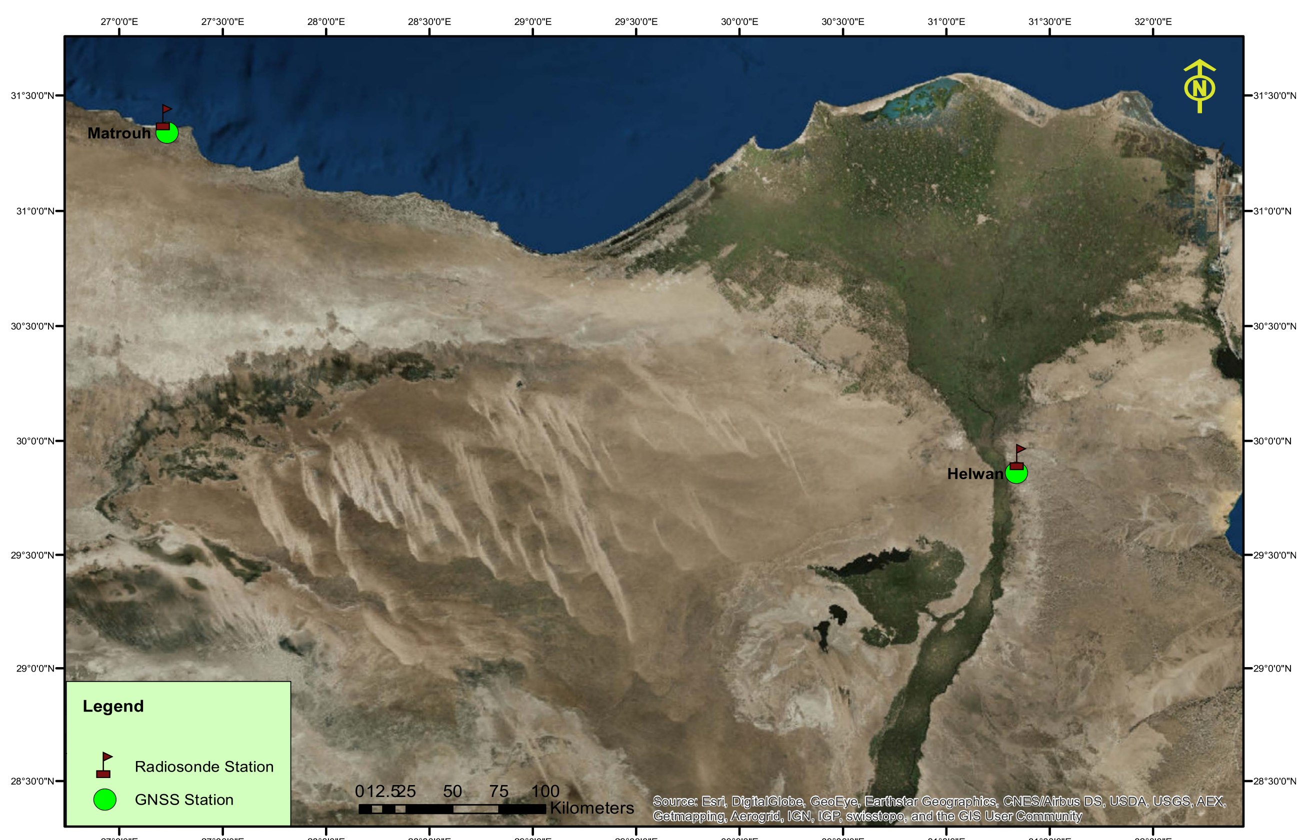

Figure 26 The geographic position of Radiosonde stations and GNSS stations.

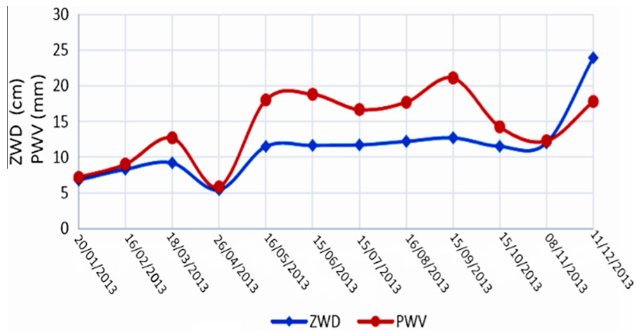

Figure 27 Helwan station ZWD and PWV values.

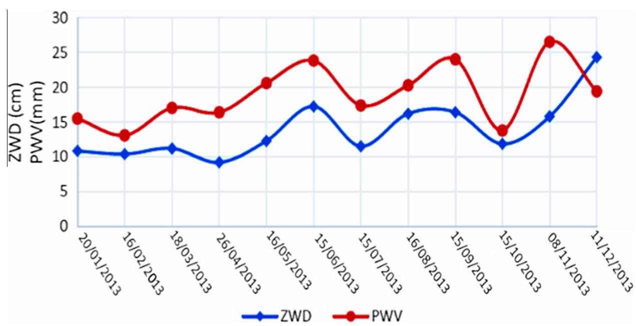

Figure 28 Matrouh station ZWD and PWV values.

5. Conclusion

In the present study, the GNSS estimated tropospheric ZWD values derived from observed data in the year 2013 at 8 EPGN stations were used to evaluate the impact of the troposphere on GNSS positioning accuracy. In addition, this study describes the best way in GNSS data network processing, besides illustrating the ZWD variations. Also this study clarifies the ZWD and PWV correlation.

There are no significant differences in the RMS for the horizontal coordinates in case of using a model and using estimated tropospheric ZWD. For the height component the RMS is better in case of using estimated tropospheric ZWD than using a model, and the differences are few parts of millimeter. Also there is a high correlation between the troposphere estimation and the RMS of the height component. In case of ignoring the troposphere in GNSS data processing the RMS for the horizontal and vertical coordinates becomes bad. So for more precise solution, it is better to make estimation of the troposphere or use a model in processing, not to ignore the troposphere totally.

The ZWD values show daily variation from the day time to the night within 11 cm. The spatial variation of the ZWD from station to another in the same day is within 15 cm and depends on how near the station to water. The ZWD temporal variation for any station from day to another along the year is within 20 cm. Also EPGN stations show ZWD variations along the year, and its values go upward from the start toward the end of the year, this is the same trend of the RMS values which also go upward from winter toward summer and autumn. In addition, there is high correlation between the ZWD values and its equivalent PWV values. The correlation coefficient between them is 0.83 and 0.84 for Matrouh and Helwan, respectively. From the present study the term of geo-meteorology is clear and useful.

Acknowledgments

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