

“ ESTIMATION OF GPS TROPOSPHERIC DELAYS USING DIFFERENT DATA PROCESSING STRATEGIES IN IRAN ”

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ABSTRACT

In this study, the performance of different processing software and strategies on the estimation of Zenith Wet Delay (ZWD) from Iran Permanent GPS Network (IPGN) was evaluated. For this purpose, GAMIT (version 10.4) and Bernese (version 5.0) software were used to estimate the ZWD values in baseline and Precise Point Positioning (PPP) mode, respectively. Then, the GPS ZWD time series in Tehran, which is the only International GNSS Service (IGS) station in Iran, were validated with the corresponding values derived from the measurements of the nearby radiosonde site at Mehrabad airport. Based on one year of estimates in both network (or baseline) and PPP mode, the GPS and radiosonde ZWD were consistent with a mean bias of 6 mm and standard deviation of 12 mm. Furthermore, the IGS final tropospheric products over 2011 were used to validate our GPS data processing in this study. The Results showed that there is a good agreement between our estimates and those obtained from IGS with a mean bias of less than 1 mm. Comparing PPP with the network GPS ZWD solutions in 15 stations of IPGN over one year, showed that two methods are consistent with mean bias and standard deviation of less than 2 and 5 mm. Finally, to examine the operational usage of IPGN tropospheric products, using the IGS ultra-rapid orbits the near real time ZTD were estimated and compared with final post processed solutions. For all stations, the near real time ZTD estimation results were comparable with the corresponding post processed estimates in terms of bias and standard deviation. The obtained correlation coefficient between final and near real time solutions was more than 0.95. These results suggest that ZTD derived from Iranian regional GPS network has the potential to incorporate in different meteorological applications.

1. INTRODUCTION

Water vapor is an important greenhouse gas of the atmosphere which plays a key role in many atmospheric processes such as cloud formation, the hydrological cycle and precipitation systems [Jacob, 2001]. The atmospheric water vapor is highly variable at different scales of time and space [Dai et al., 2002]. Therefore, high-resolution observations of this parameter are necessary to monitor the spatio-temporal variation of the atmospheric water vapor and use of this information in Numerical Weather Prediction (NWP) models [Zhang

and Zhan, 2007].

There are various techniques to measure the atmospheric water vapor content. Radiosonde as a conventional tool observes the atmospheric water vapor. However, due to the high cost for each launch, radiosondes often provide observations of the water vapor twice a day only. Low temporal and spatial heterogeneity of the radiosonde measurements is not suitable for studying the atmospheric water vapor variations at different scales of time and space. Microwave radiometers are not applicable at heavy rain conditions [Jade and Vijayan, 2008]. Satellite-based observations of at-

atmospheric water vapor provide good spatial but poor temporal resolution data [Bevis, 1992].

During the last decades, GPS technology has proved as a worthwhile approach for preparing atmospheric water vapor measurements. Compared with other methods, GPS operates under all weather conditions with high-temporal resolution and long-term stability [Bevis et al., 1994; Rocken et al., 1997]. Also, dense GPS receiver networks can be built at a low cost and it is one of the major benefits of GPS meteorology. The atmospheric column water vapor content which is named Precipitable Water Vapor (PWV) can be computed from GPS observations. Several studies have been conducted to assess the GPS derived PWV measurements. The reported results proved that GPS provide estimates of comparable accuracy [Rocken et al., 1993; Tregoning et al., 1998; Basili et al., 2001; Bocolari et al., 2002; Dietrich et al., 2004; Sibylle et al., 2010; Sadeghi et al., 2014].

Over the years, water vapor estimates from ground-based GPS receiver has been interested in a wide range of studies and applications such as investigating the variability of the atmospheric water vapor [e.g., Dai et al., 2002; Bruno et al., 2007; Suparta et al., 2013], examining the water vapor changes during rainfalls [e.g., Liou and Huang, 2000; Foster et al., 2003; Li and Deng, 2013; Choy et al., 2013], monitoring climate changes [e.g., Ware et al., 2000; Gradinarsky et al., 2002; Nilsson and Elgered, 2008] and numerical weather prediction [e.g., Gutman and Benjamin, 2001; Boniface et al., 2009; Suparta et al., 2014; Sharifi et al., 2016].

The total delay of GPS signals caused by the troposphere in the zenith direction known as Zenith Total Delay (ZTD). It is a basic variable in the estimation of PWV from ground based GPS observations. The ZTD has two components: the dry or hydrostatic delay (ZHD) and the Zenith Wet Delay (ZWD). The dry part can be precisely computed from surface meteorological measurements using empirical models such as Saastamoinen model [Saastamoinen, 1972]. The wet component of the tropospheric path delays is related to the amount of water vapor in the atmosphere. The ZTD can be estimated in the data processing along with other unknown parameters. Today, the analysis centers utilize advanced GPS processing techniques such as Precise Point Positioning (PPP) and network solution to provide near real time and real time tropospheric products which used in many applications [Guerova et al., 2016].

The Iranian Permanent GPS Network (IPGN) has been operated to study the tectonic deformation and also for

navigation and surveying purposes. Recently, continuous valuable observation from IPGN has been used in several meteorological applications over Iran [e.g., Adavi and Mashhadi-Hossainali, 2014; Sharifi et al., 2016]. However, no efforts have been made to compare different GPS ZTD estimation methods in the study region. So, the first aim of this study is to examine the effect of GPS processing strategies (PPP and network solutions) on ZTD estimations. On the other hand, the real time retrieval of ZTDs is very necessary in many time-critical meteorological applications such as severe weather monitoring and short-term forecasts. Therefore, the second objective is to evaluate the quality of near real time ZTD estimates from the Iranian network for operational meteorology.

In the next section, we describe the data used to estimate the tropospheric delays. The calculation of ZWD using radiosonde observations followed by different GPS data processing techniques for ZWD estimation is then presented in Sec. 3. Comparison results between our own GPS processing and the IGS final tropospheric products together with radiosonde measurements are given in Sec. 4. The summary and conclusions are drawn in the last section.

2. DATA

In this paper, the entire 2011 year was selected as the study period. An Iranian permanent GPS network consisting of more than 100 stations has been established by the National Cartographic Center of Iran (NCC) for both geodynamic and geodetic purposes. Here, continuous GPS observations of 15 stations of the IPGN network were utilized to study the effect of different GPS data processing on the ZTD estimation. The geographical distribution of the selected GPS sites with varying topography is depicted in Figure 1.

Among the all IPGN stations, only TEHN is included in the IGS stations. There is a radiosonde with co-located synoptic station located at Mehrabad airport in the vicinity of TEHN GPS station. Surface meteorological observations along with radiosonde data in the Tehran Mehrabad airport station were used to validate the GPS derived tropospheric delays. The synoptic data were collected from the Center of Iran Meteorological Organization (CIMO) and the radio sounding data was obtained from the web site of the department of atmospheric sciences of the University of Wyoming

<http://weather.uwyo.edu/upperair/sounding.html>.

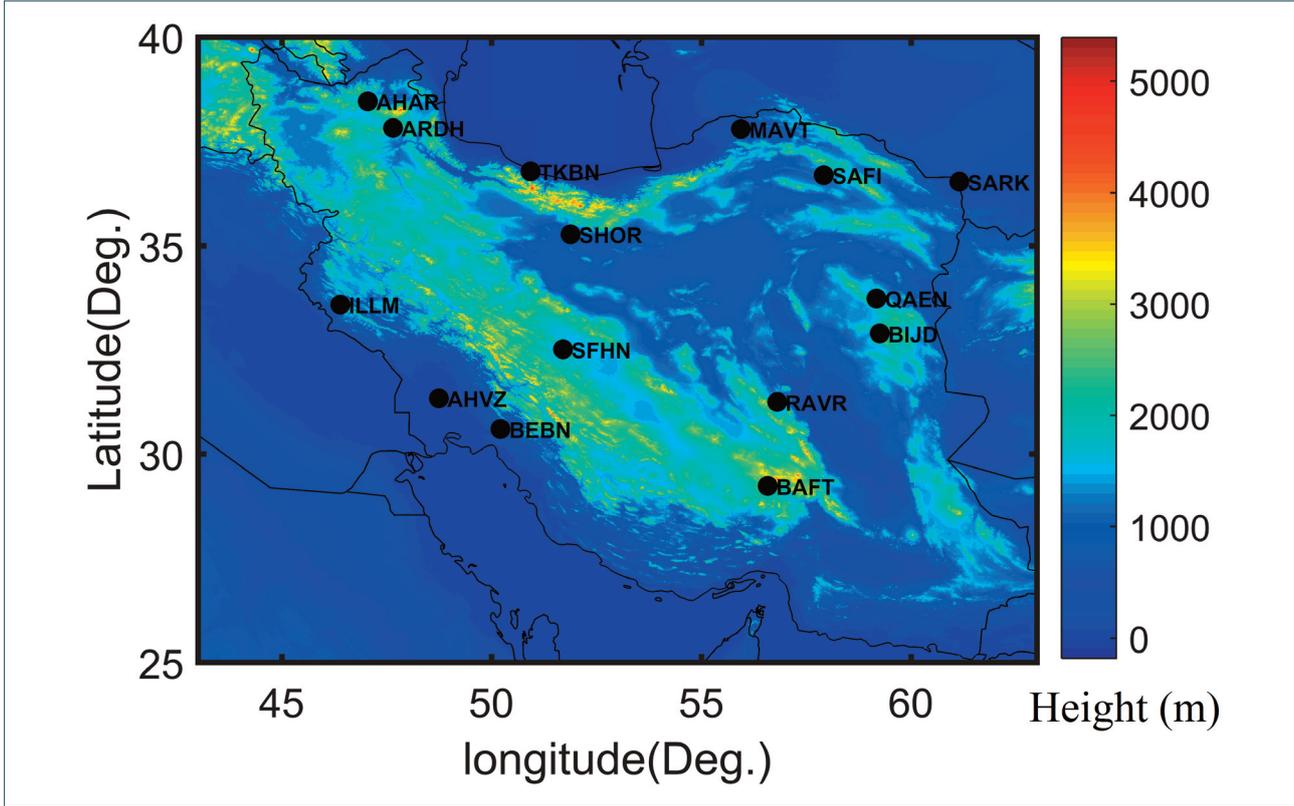


FIGURE 1. Geographic distribution of the selected GPS stations used in this study.

Also, IGS provides its final GPS tropospheric products with the highest quality and temporal resolution of 300 s. Therefore, ZTD values of the IGS final tropospheric products were used as a reference to verify our data processing in the present work. Besides the data mentioned above, accessory data required to process the GPS observations, including antenna phase center variations, earth orientation parameters, lunar and solar ephemerides, leap seconds and nutation tables. These ancillary data can be prepared from several active archives such as Scripps Orbit and Permanent Array Center (SOPAC).

3. ZENITH WET DELAY ESTIMATION

3.1 ZWD ESTIMATION USING RADIOSONDE DATA

The wet delay along the GPS signal path is related to the water vapor content which is mostly included in the troposphere. The amount of water vapor is decreased to almost zero from the surface up to about 10 km [Hopfield, 1971]. About 95% of the water vapor content is concentrated in the first 5 km above Earth's surface. The ZWD values can be estimated by numerical integration of radiosonde profiles available at the

Mehrabad station. Based on the following equation, The ZWD parameter is numerically computed [Schueler et al., 2000].

$$ZWD = 10^{-6} \int_{H_0}^{\infty} N_W(H) dH \approx 10^{-6} \sum_{i=1}^n \frac{N_W^i + N_W^{i+1}}{2} \Delta H_{i+1,i} \quad (1)$$

Where N_W is the wet refractivity and the index i and $i+1$ refer to the present point and the nearest upward point in the radiosonde profile, respectively. $\Delta H_{i+1,i}$ denotes the geopotential height difference between the current and the nearest upward point of the profile, and the geopotential height of surface point is expressed by H_0 . Therefore, according to the equation (1), ZWD is calculated from radiosonde observations, and its value is considered to be the reference value in the present study. The wet refractivity (N_W) can be obtained from the following equation [Thayer et al., 1974].

$$N_W = \left[k_2' \left(\frac{e}{T} \right) + k_3 \left(\frac{e}{T^2} \right) \right] Z_W^{-1} \quad (2)$$

where $k_3 = 377600 \pm 30000 \text{ K}^2/\text{mb}$, $k_2' = 16.5 \pm 10 \text{ K}/\text{mb}$ are the refractivity coefficients and Z_W^{-1} is the inverse compressibility factor of the moist atmosphere and is given by Owens, [1967] as

$$Z_w^{-1} = 1 + 1650 \left(\frac{e}{T^3} \right) \left[1 - 0.01317T_c + 1.75 \times 10^{-4} T_c^2 + 1.44 \times 10^{-6} T_c^3 \right] \quad (3)$$

In equation (3), T and T_c are the temperatures in Kelvin and Celsius, respectively, and e is the partial pressure of water vapor in units of mbar.

It is clear that the profile of partial pressure of water vapor is required to obtain the Z_w^{-1} values. Using the following equation, we can obtain e value from the radiosonde relative humidity (RH) and temperature observations [Godson, 1955]

$$e = RH \cdot \exp(-37.2465 + 0.213166 \cdot T - 2.56908 \cdot 10^{-4} \cdot T^2) \quad (4)$$

In addition, one can use an empirical model along with surface meteorological data to determine ZTD. For instance, the Saastamoinen model is one of the most widely used ZTD models and expressed as [Hofmann-Wellenhof, 2008]

$$ZTD = \frac{0.0022768}{\sin Z} \left[p_0 + \left(\frac{1255}{T} + 0.05 \right) e - 1.16 \times \cot^2 Z \right] \quad (5)$$

where, Z is the zenith angle of the GPS signal.

3.2 ZWD ESTIMATION USING GPS DATA

The tropospheric delay as a significant error source during the propagation of Global Positioning System (GPS) signals contains valuable information for various meteorological applications. The total tropospheric delay of GPS signals known as ZTD can be estimated for each ground based station in the data processing. This parameter is divided into the dry (ZHD) and the wet parts (ZWD). The latter is related to the amount of water vapor in the atmosphere (Davis et al., 1985).

$$ZTD = ZHD + ZWD \quad (6)$$

Using the Saastamoinen model, the ZHD can be calculated as a function of surface pressure measurements (P_0) at GPS station, site latitude and height [Saastamoinen, 1972]

$$ZTD = 0.0022768^{P_0[hPa]} / f(\varphi, H), \quad (7)$$

$$f(\varphi, H) = 1 - 0.00266 \cos(2\varphi) - 0.28 \cdot 10^{-6} H \quad (8)$$

where, φ is the latitude and H is the height from geoid in kilometers. In this study, we use different GPS software to estimate the ZTD of the GPS signals during the processing of IPGN observations. Then, by reducing ZHD from the estimated total zenith delay, the ZWD is achieved.

3.2.1 PROCESSING METHODS

The raw data at the GPS receiver is usually stored in Receiver Independent Exchange (RINEX) format. These observations can be processed using different software packages such as GAMIT, Bernese and GIPSY. There are two data processing modes for estimating ZTD from ground based GPS observations: 1- network processing using double difference observations [Rocken et al., 1993; Bai, 2004; Hugentobler et al., 2007], and 2- Precise Point Positioning (PPP) based on un-differenced observations [Zumberge et al., 1997; Rocken, 2005]. The differential processing method requires at least two GPS receiver observations at the same time. Most GPS analysis centers also exploit a differential method to eliminate receiver and satellite clock errors. However, the ZTD estimation in PPP mode is conducted separately for each station. It is notable that the availability of the precise clock and orbit corrections is very necessary in the PPP method. One of the disadvantages of a differential method in comparison with the PPP approach is the high volume of the normal matrix. Also, in the PPP approach the site dependent effects in one station do not impress the ZTD solution in the other stations [Guerova et al., 2016].

Finally, after data processing, the coordinate components of the GPS stations, receiver clock error and tropospheric delays are estimated. In the present study, the PPP processing was done in Bernese software while the GAMIT software was utilized to process the data in baseline mode. Moreover, the IGS tropospheric products are used as the "truth" to evaluate our own processing. The IGS final ZTD products were estimated by the GIPSY package in PPP mode [Zumberge et al., 1997].

3.2.2 PROCESSING PARAMETERS

The ZTD estimation based on the network and PPP solutions was conducted using elevation cutoff angle of 7 degrees, the Global Mapping Function (GMF) and the IGS final orbit and clock products. Also, the tropospheric parameters were estimated in one hour interval. In the other hand, the IGS final tropospheric products which used in this study are generated by the GIPSY software package in a PPP mode. The unknown parameters were estimated at 5 minute intervals with the GMF mapping function [Boehm et al., 2006] and the IGS final orbit and clock products. For each IGS station, the final ZTD products are available approximately three weeks following the observation day (Hackman et al., 2015).

3.3 EVALUATION PROCEDURE

As noted above, the ZTD of GPS signal is estimated along with the position coordinates using different processing techniques such as PPP and network solutions. In this work, GPS observations from the IPGN network are processed independently in both PPP and network modes to estimate tropospheric delays. We will evaluate our own GPS ZWD estimates by comparing them with the IGS final tropospheric product as well as with the ZWD derived from radiosonde observations. The IGS troposphere working group produces final ZTD estimates for nearly all the stations of the IGS network as a contribution to meteorology. Also, there is only one GPS station (TEHN) in IPGN network.

First, we compare our estimates of GPS ZWD with the corresponding estimates obtained from the IGS final products as well as radiosonde observations in Tehran station over 2011. IGS provides final ZTDs in Tehran GPS station. ZHD values can be calculated from surface pressure data observed at the GPS site (see equation 7). So, by subtracting the computed ZHD from the IGS ZTD, time series of ZWD is extracted from IGS final tropospheric products and used as a reference.

Statistical parameters such as Standard Deviation (STD), Mean Bias Error (MBE) and correlation coefficient (R^2) is used to assess the various solutions of GPS ZWD and Saastamoinen model in comparison with the corresponding ZWD values obtained from radiosonde measurements near the IGS station. Therefore, the performance of the results obtained from our GPS processing can be examined compared to IGS final tropospheric products in terms of statistical results. Also, seasonal and day-night behavior of the difference values between all ZWD solutions and radiosonde derived ZWDs will be examined.

After validating the GPS derived ZWDs obtained by GPS data processing in this work (GAMIT and Bernese solutions) against IGS results (GIPSY solution) and radiosonde ZWDs at TEHN GPS station, GPS ZTD estimates with network mode will be compared with the corresponding PPP solutions in 15 stations of IPGN over 2011.

Satellite orbit and clock information are essential inputs to estimate ZTD values from the GPS observation processing. Here, IGS orbit and clock products are used in GPS data processing. IGS analysis centers provide satellite ephemeris in three forms: final, rapid and ultra-rapid (<http://www.igs.org/products/data>). The final post-processed ephemeris are the highest quality IGS solutions and available at 12-18 days latency. The IGS

rapid orbit and clock products are available with approximately 17 hours latency. The ultra-rapid products are updated every 6 hour and available for real time and near real time use such as disaster monitoring. IGS final orbit and clock information are used to achieve ZWD from GPS observations at Tehran station.

In order to examine the near real time ZTDs derived from IPGN observations, the IGS ultra-rapid and final ephemeris independently will be used in GPS data processing to obtain near real time and final post-processed ZTD solutions, respectively. Then, near real time and final GPS ZTD time series in 15 IPGN sites are compared to each other.

4. RESULTS

4.1 COMPARISON OF DIFFERENT GPS PROCESSING WITH RADIOSONDE

According to the above mentioned equations, the time series of radiosonde ZWD were calculated at Tehran Mehrabad airport station over 2011. In order to investigate the effect of processing strategy on the estimation of tropospheric delay, the GPS data were processed using GAMIT version 10.4 and Bernese version 5.0 software in baseline and PPP processing mode, respectively. Additionally, the IGS final ZTD products at Tehran station were utilized to verify the GPS data processing in the present study.

Here, we used Saastamoinen model to calculate the ZHD values from surface meteorological observations and then, ZWD was obtained by removing the ZHD from ZTD over the study period. Also, the ZWD derived from the Saastamoinen model as a common troposphere delay correction model were compared with values determined by other methods. The ZWD estimates calculated by various GPS processing modes together with the corresponding values from radiosonde and Saastamoinen model for all days of 2011 are demonstrated in Figure 2. There is a good consistency between the GPS ZWD estimates with high temporal resolution and the corresponding radiosonde measurements (red squares).

Table 2 gives the minimum and maximum ZWD values obtained from different methods at Tehran station during 2011. As shown in Table 2, results from different GPS processing packages (GIPSY, GAMIT, and Bernese) are very close to each other and larger than the corresponding radiosonde values, while Saastamoinen model gives the delays less than those of ra-

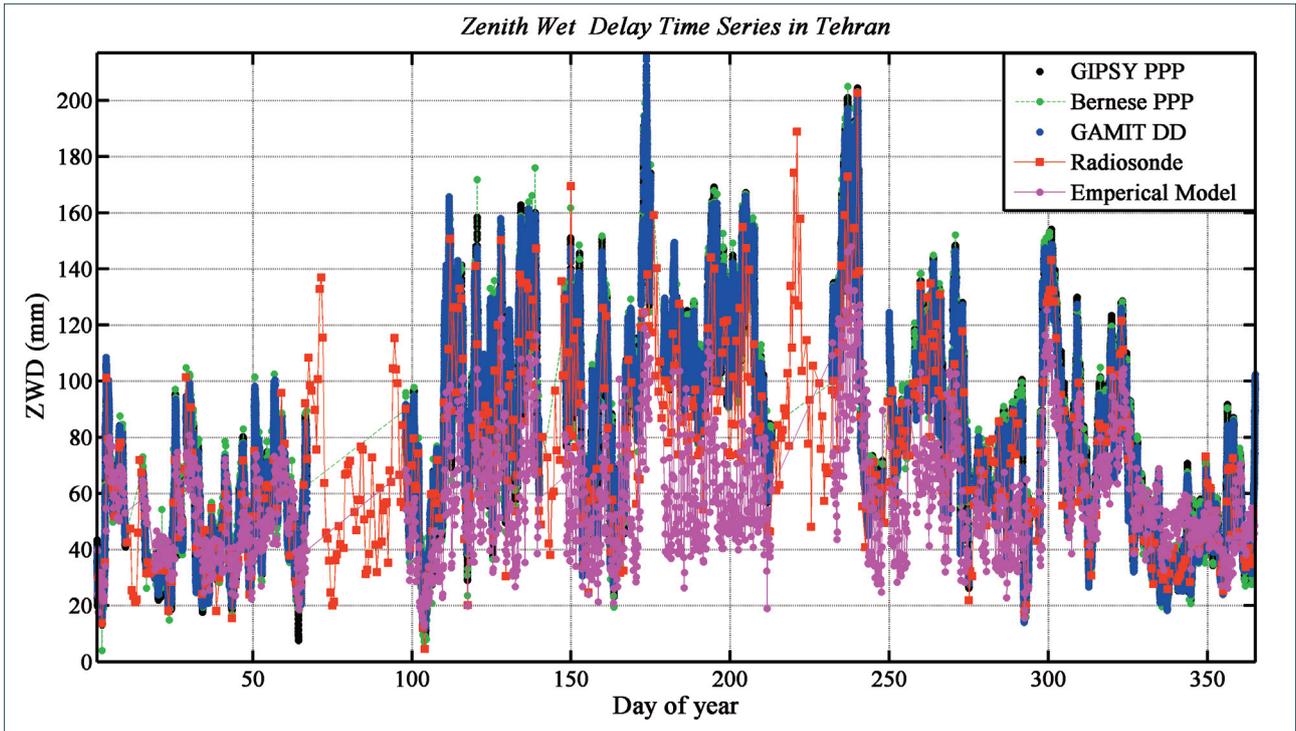


FIGURE 2. ZWD estimates calculated by various GPS processing mode together with the corresponding values from radiosonde and empirical Saastamoinen model in Tehran station.

diosonde observations. Statistical parameters of the ZWD comparisons between various GPS processing strategies

along with Saastamoinen model and the corresponding radiosonde derived values are summarized in Table 2.

	Bernese_PPP	GIPSY_PPP	GAMIT_DD	Radiosonde	Saastamoinen
Min Value	3.9	7.6	11.5	4.6	12.7
Max Value	217.1	212.2	215.6	202.6	147.9

TABLE 1. Min-max ZWD (mm) values from various GPS processing softwares, Radiosonde and the Saastamoinen model at Tehran station over 2011.

	Min Value	Max Value	MBE	STD	R ²
Bernese_PPP	-44.7	62.7	6.3	11.9	0.938
GIPSY_PPP	-46.1	60.1	6.8	12.1	0.939
GAMIT_DD	-45.5	62.3	5.6	11.8	0.942
Saastamoinen	-96.1	34.2	-18.1	22.9	0.717

TABLE 2. Evaluation of ZWD (mm) differences between various GPS processing softwares, Saastamoinen model with Radiosonde at Tehran station over 2011.

Station ID	Geodetic height (m)	MBE (mm)	STD (mm)	R ²
AHAR	1360.341	-2.0	4.6	0.994
AHVZ	5.746	-0.5	4.9	0.993
ARDH	1774.957	-1.4	6.7	0.979
BAFT	2276.141	-1.8	5.0	0.987
BEBN	302.324	-1.1	4.7	0.993
BIJD	1475.375	-2.1	4.6	0.986
ILLM	1327.223	-1.7	4.4	0.988
QAEN	1426.736	-2.1	4.3	0.987
SAFI	1213.267	-2.7	4.4	0.992
MAVT	442.213	-1.9	4.6	0.997
SARK	251.576	-2.8	4.6	0.994
RAVR	1179.058	-0.6	5.7	0.978
SFHN	1547.514	-1.8	4.3	0.987
SHOR	946.178	-0.7	4.8	0.991
TKBN	-20.665	-1.8	5.3	0.996

TABLE 3. Statistical results of the differences between the estimated tropospheric ZTD from PPP (Bernese) and Double Difference (GAMIT) processing methods.

The results show high correlation between the ZWD estimates from different GPS software with the radiosonde ones up to 0.94. As seen in Table 2, the maximum bias and standard deviation of ZWD estimates from GPS observations are 6.8 and 12.1 mm, respectively, while the Saastamoinen model has shown a bias of -18 and a standard deviation of 22 mm, relative to the radiosonde. Again, the maximum bias of about 1 mm between our data processing (with GAMIT and Bernese software) and GIPSY indicates that the results are comparable to that of the IGS final tropospheric products.

Although the GPS derived ZWDs from two processing techniques were validated against IGS final tropospheric products at Tehran station, but a more general comparison between PPP and network solutions is required in the study area. Therefore, the GPS observations from 15 IPGN stations were processed both with the PPP and baseline processing methods over 2011. The statistical results of the ZTD time series estimated from two different processing strategies for all stations are listed in Table 3.

It can be seen that the absolute mean bias and the

standard deviation of the differences between the estimated tropospheric ZTD from PPP and Double Difference (DD) processing methods are less than 3 and 7 mm, respectively. Moreover, the correlation coefficient between ZTD time series derived from these two methods for all GPS stations are higher than 0.97. This finding corresponds to the results obtained from the previous studies [e.g., Ning et al., 2012; choy et al., 2013; Morel et al., 2014]. There is no noticeable relation between the size of mean bias and the standard deviation of two methods with the height of the GPS stations. According to Table 3, the PPP derived ZTDs and the corresponding baseline solutions are well comparable and can be used alternatively to estimate the tropospheric delays from IPGN observations.

4.2 DAY-NIGHT AND SEASONAL DIFFERENCES

After validating the GPS ZWD values in pervious section, here we examine the temporal variations of ZTD differences between the various estimates of ZWD and the radiosonde measurements in the year 2011. The

	Spring		Summer		Autumn		Winter	
	MBE	STD	MBE	STD	MBE	STD	MBE	STD
Bernese_PPP	6.6	13.1	13.7	15.2	3.5	7.9	1.8	6.2
GIPSY_PPP	7.1	12.6	15.8	15.0	3.9	7.6	0.8	5.1
GAMIT_DD	7.3	12.9	13.7	14.8	1.5	7.3	0.3	4.7
Saastamoinen	-27.2	22.1	-32.7	21.1	-9.0	20.0	-4.9	14.6

TABLE 4. Seasonal statistical parameters of the ZWD (mm) comparisons between various GPS processing softwares, Saastamoinen model with radiosonde at Tehran station over 2011.

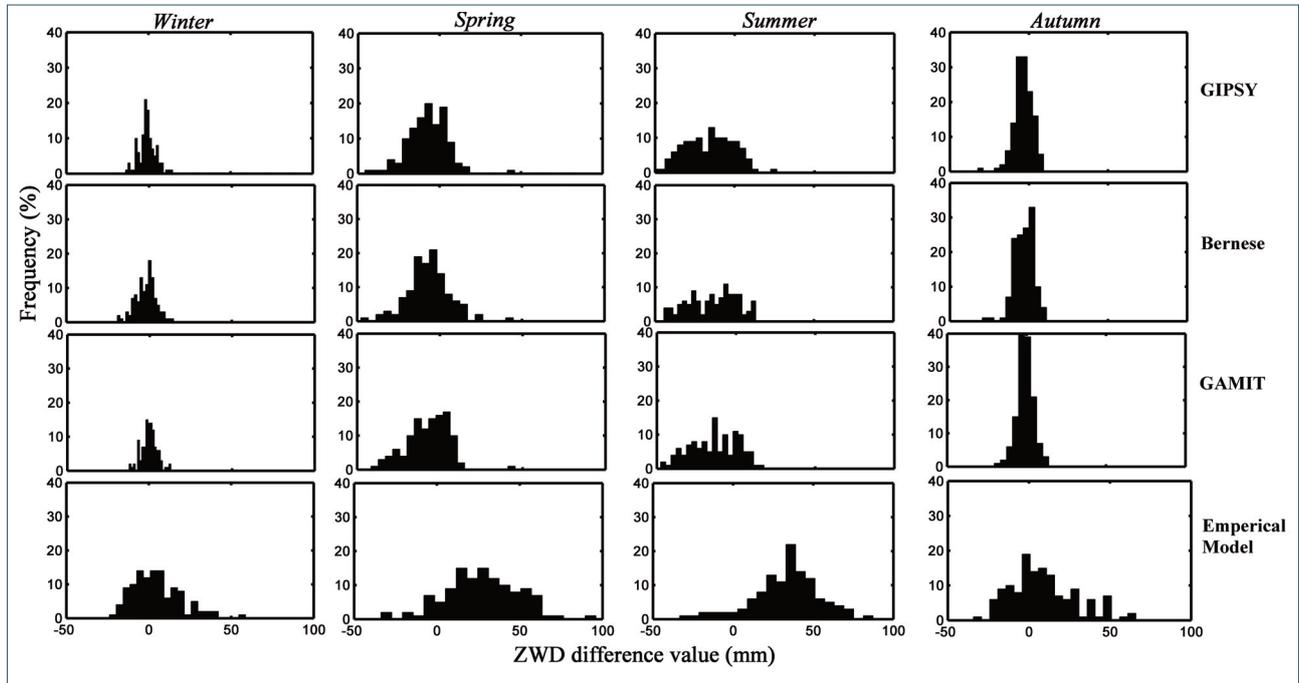


FIGURE 3. Frequency histograms of the ZWD differences of the Bernese, GIPSY (in PPP mode), GAMIT (in baseline mode) and Saastamoinen model estimates with respect to corresponding extracted values from radiosonde, during the 2011 seasons.

error statistics of the ZWDs derived from various GPS processing packages along with the Saastamoinen model in different seasons of 2011 are presented in Table 4. It can be shown that the GPS ZWD is greater than radiosonde ones for all seasons. Overall, the mean bias of the GPS ZWD estimates has a seasonal behavior and changes from 1mm in winter to 15 mm in summer. Figure 3 displays the seasonal frequency histograms of the ZWD differences between the different methods and radiosonde. As shown in Figure 3 and Table 3, the mean bias of the ZWD differences has a clear seasonal variation. Based on Hasse et al. [2003],

the seasonal biases in tropospheric delays derived from the GPS and radiosonde are probably due to the day-night moisture bias in the radiosonde measurements.

Also, the standard deviation of ZWD differences ranges from 5 mm in winter to 16 mm in summer. In fact, larger moisture content can lead to a greater standard deviation. It may be due to the heterogeneous water vapor distribution in warm seasons [Hasse et al., 2003]. Again, there is a high consistency between seasonal ZWD values obtained from our GPS processing and those of IGS. As shown in Table 4, the Saastamoinen model had the best estimates in winter, with a

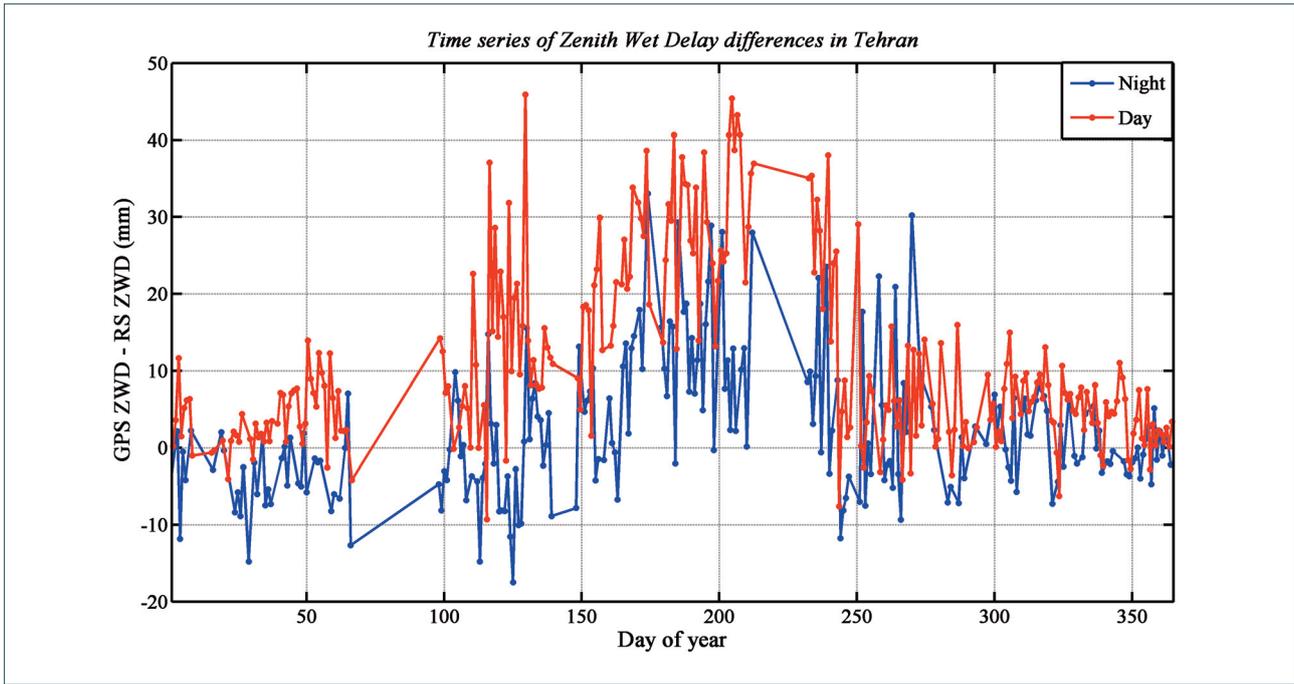


FIGURE 4. Day (red) and night (blue) differences between ZTD derived from ground based GPS and radiosounding measurements.

bias of 4.9 and a standard deviation of 14.6 mm.

Moreover, time series of the ZWD differences between GPS and radiosonde both for days (red spots) and nights (blue spots) are depicted in Figure 4. Comparing the time series of daily differences with the cor-

responding values throughout the night, it has shown the dry bias of radiosondes in daytime. These results are consistent with other previous studies [e.g., Kwon et al., 2007; Wang and Zhang, 2008].

	Bernese_PPP		GIPSY_PPP		GAMIT_DD	
	MBE	STD	MBE	STD	MBE	STD
Day	9.8	12.0	10.8	11.6	9.3	12.2
Night	2.1	10.5	2.1	10.9	1.6	10.1

TABLE 5. Day- night mean bias and standard deviation values of ZWD (mm) differences between various GPS processing software and radiosonde at Tehran station over 2011.

responding values throughout the night, it has shown the dry bias of radiosondes in daytime. These results are consistent with other previous studies [e.g., Kwon et al., 2007; Wang and Zhang, 2008].

Table 5, gives the yearly bias and standard deviation of ZWD values for each of the processing software packages for both day and night time at Tehran station. The standard deviation of daily values reaches its highest level in summer as well as those obtained

during night time. It can be seen that the ZWD values measured from the night time observations of radiosonde have a bias of 2 mm compared with the corresponding GPS estimates while the bias value reaches to 10 mm for daily launches. There is also no significant difference between the standard deviations during the day (12 mm) and night (10.5 mm). Once again, Table 5 shows that the day night results derived from our data processing in different modes are very close to the corresponding values obtained from the final IGS products. It should be noted that although the present study provides a comparison in TEHN GPS station, which included in the IGS stations, but the results are very consistent with previous works.

Station ID	MBE (mm)	STD (mm)	R ²
AHAR	0.4	8.2	0.982
AHVZ	0.1	8.6	0.979
ARDH	0.4	8.9	0.951
BAFT	-0.4	8.2	0.965
BEBN	-0.3	8.7	0.976
BIJD	0.05	8.5	0.959
ILLM	0.3	8.5	0.954
QAEN	-0.05	7.8	0.955
SAFI	0.2	7.9	0.975
MAVT	0.2	8.2	0.990
SARK	-0.1	8.0	0.983
RAVR	-0.1	8.8	0.932
SFHN	0.2	7.8	0.961
SHOR	0.2	9.1	0.964
TKBN	0.4	8.7	0.990

TABLE 6. Comparison of GPS ZTD estimates using different orbit and clock products (IGS ultra-rapid and final ephemeris) over 2011.

4.3 FINAL VS. NEAR REAL TIME ZTD

Throughout the GPS data processing with a particular software and strategy, the tropospheric delays can be estimated in different real time, near real time, and final post-processed modes. The post-processed ZTD values can be estimated with IGS precise orbit and clock products while IGS ultra-rapid ephemerides are used to estimate the GPS ZTDs in real time and near real time modes. However, we rely on near real time ZTD estimates for many meteorological applications such as severe weather forecasting. Therefore, IGS final and ultra-rapid orbit and clock products were used to process, one year GPS observations from 15 IPGN station. Then, different ZTD estimates generated from two different IGS ephemerides are compared to each other.

Table 6 summarizes the statistics of this comparison for all stations. The mean value of the correlation coefficient between the near real time ZTDs and the post-processed solutions over the study period was obtained around 0.97. Also, the average ZTD difference between the near real time and post-processed modes for all processed stations is about 0.5 mm with a standard deviation less than 9 mm. These analyses allow us to evaluate the potential of the IPGN observations in the operational applications. Based on previous studies [e.g., Gut-

man and Benjamin, 2001; Jarlemark et al., 2002; Dousa and Vaclavovic, 2014] the GPS ZTD estimates from the IPGN observations can be a useful data source for weather prediction applications.

5. CONCLUSIONS

Continuous GPS observations at permanent stations can be used to estimate high-precision tropospheric delays and its derivatives such as precipitated water vapor in Iran. By the processing of GPS data over 2011 for 15 IPGN permanent stations, we compared tropospheric delay values estimated by different software to evaluate the effect of processing methodology.

For this purpose, GAMIT software used to process the data in a double difference mode while PPP processing was conducted by using Bernese software. Among the stations used in this study, TEHN is the only IGS station located in the study area. On the other hand, there is also a radiosonde station located at Mehrabad Airport near TEHN GPS station. Therefore, GPS ZWD estimated from different types of software (GAMIT and Bernese) were compared with those derived from radiosonde data at Tehran over 2011. The

mean bias between the radiosonde estimated ZWD and the PPP solutions was 6.3 mm with a standard deviation of 11.9 mm while for the baseline processing it was found 5.6 and 11.8mm, respectively. So, there is a good agreement between the results from both methods of GPS data processing.

Also, IGS final tropospheric products as a standard reference were used to validate the estimated ZWD from our own GPS processing. The results showed that the estimated ZWD values from GPS data processing strategies in this study were consistent with those of IGS final products at Tehran station. For the other 15 IPGN stations, the statistical parameters of the ZTD comparisons between Bernese and GAMIT software indicate that both PPP and network solutions are comparable. For the most GPS stations, the agreement was about less than 2 and 5 mm in terms of mean yearly bias and standard deviation, respectively.

After calculating the ZWD differences between different GPS processing package (Bernese, GAMIT and Gipsy) estimation and corresponding radiosonde measurements, the seasonal dependency of the error statistics were investigated. Based on the results, the mean bias and standard deviation have a time dependent behavior and changes from 1 and 5 mm in winter to the 14 and 15 mm in summer. The higher order of the standard deviation in summer is most likely due to the inhomogeneous distribution of water vapor in the warm seasons. Furthermore, we compared the GPS derived ZWD values with the corresponding radiosonde measurements in the day (12 UTC) and night time (00 UTC) launch, separately. The mean bias of the differences between day time GPS and radiosonde ZWD estimates showed a dry bias of 10 mm while the radiosondes launched during night time have a smaller bias about 2 mm. It can be related to the higher dry bias of the radiosonde measurement during the day than at night. The difference between radiosonde and GPS ZWD showed a standard deviation of 12 mm and 10 mm at day and night time lunches, respectively. Also, the results of three GPS processing software have a good agreement with each other, both in day and night time.

Finally, we evaluate the accuracy of the near real time GPS ZTD derived from IPGN observations. Based on PPP technique and IGS ultra-rapid ephemerides information, the ZTD time series were estimated in 15 permanent stations and compared with those obtained from the post-processed solution which utilized the

final IGS products. The overall mean bias and standard deviation between the near real time ZTD and corresponding post processed estimates was found less than 0.5 and 10 mm. These results suggested that the near real time GPS ZTD derived from IPGN data processing can be used for numerous near real time meteorological applications in different regions of Iran.

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