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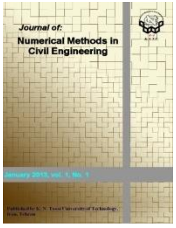

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Tropospheric delay efficiency from CSRS-PPP online service for meteorologists in Iran

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Abstract:

Earth's tropospheric delay is a valuable parameter in meteorological and climatic applications and studies such as short-term weather forecasting, monitoring of severe weather conditions, and long-term climate change. One of the methods for estimating the zenith delay of the Earth's atmosphere is the processing of the GNSS observations. In addition to estimating the station position as the main target of processing the observations, the Zenith Total Delay (ZTD) values of the signals received from the satellite are also estimated simultaneously. Processing GPS observations is complicated and costly for meteorologists other than geodesy professionals. Recently, free online GPS observation processing services have been developed. In this study, ZTD estimates of the CSRS-PPP online service in the Iranian region were evaluated to examine the potential of this data for use by meteorologists. For this purpose, 8-day observations from 46 permanent GPS stations distributed in different parts of Iran were used. Also, the ZTD values obtained from the GAMIT software with differential processing method were considered as trustworthy values. In general, the tropospheric delay estimates of the CSRS-PPP service showed high agreement with the corresponding values obtained from the GAMIT software. The mean correlation coefficient, RMSE, and bias of the online service estimates were 0.976, 3.38, and 0.42 mm, respectively, compared to the differential method. Based on the results of this research, it can be concluded that the ZTD products of the CSRS-PPP online service, which provide free processing for the general public, have acceptable accuracy and can be used for many studies.

1. Introduction

Measurement of troposphere delay is a valuable component of meteorological and climatic studies and is of interest to the meteorological community. The electromagnetic signal delay in the atmosphere caused by the troposphere and its changes over time can reflect the changes in the atmospheric conditions. Therefore, this quantity is used in many meteorological applications such as short-term weather forecasts, especially in severe conditions, as well as climate change monitoring in a region.

On the other hand, measuring or more accurately estimating this quantity continuously and in any weather conditions is very important because, in many cases, meteorologists need real-time or near-real-time values of the atmospheric tropospheric delay.

In recent decades, the Global Satellite Navigation System (GNSS) data has been used for positioning and navigation in various engineering and non-engineering applications [1-2]. In addition, GNSS observations can be used for atmospheric monitoring. GNSS satellite signals are affected by the presence of electrons and the density of air particles when passing through the ionized part of the atmosphere, the ionosphere, and the electrically neutral part of the troposphere. The tropospheric effect can be described by refractivity (N). This quantity depends on pressure, temperature, and water vapor pressure [3].

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An example of how GNSS data may be used in applications other than positioning and navigation is the simultaneous use of GNSS signal delay along with microwave radiometer measurements to accurately determine tropospheric correction for altimeter products [4]. Also, the use of GNSS data for remote sensing of the atmosphere can be mentioned, as GNSS signals in an inverse process can measure physical variables of the atmosphere such as temperature, pressure, refraction, and other information such as the height of the tropopause, which is required for climate monitoring and climate change [5]. In addition to these, measuring the amount of the atmospheric precipitation water vapor by GNSS observations under a method called ground-based GNSS meteorology is another use of GPS [6-7].

The amount of the precipitable water vapor can be obtained from the amount of vapor in the atmosphere. The latter quantity is proportional to the total zenith wet delay of the GPS signal (ZWD). ZWD values can be used in various studies, including weather forecasting and severe weather phenomena [8-10].

The total delay of the GPS signal in the zenith direction (ZTD) consists of two parts: wet (ZWD) and hydrostatic or dry (ZHD). This error is not easily calculated and cannot be eliminated due to its nature. However, its value can be estimated using the conventional relationships in ground-based GPS meteorology with synoptic pressure information, and finally, the amount of the precipitable water vapor can be achieved. The spatial structure and temporal behavior of water vapor can also be used in many fields of research and meteorological applications, such as weather forecasting, natural hazard reduction, and water resources management [11].

ZTD values can be estimated using accurate positioning methods. One method is the network processing of observations of dual-frequency GPS receivers, also known as the differential method or base-line processing. In this method, by the least-squares adjustment of the equation of double differential observations of phase observation formed between different base-lines, the coordinates of stations and tropospheric delay values are estimated simultaneously for all stations. One of the drawbacks of this method is the effectiveness of each station's observations in estimating the ZTD values of other stations. Also, the normal matrix in the least-squares method may increase as the number of stations increases, which can lead to increased processing time.

Another method of processing GPS observations to estimate the zenith delay of a signal is the precise point positioning (PPP) method. In this method, the tropospheric delay, position, and clock corrections are estimated with the help of precise ephemeris and ionospheric-free combinations. The ZTD estimates of each station using this method are not affected by the observations of other stations and the processing speed is higher than the differential method.

Recently, online GNSS observation processing services have received a great deal of attention because they are capable of determining the position and even the zenith of the receiver observations for free and with minimal time delay for those who do not need to engage in mathematical relationships and the complexity of estimating this quantity during processing. Meanwhile, the Canadian Spatial Reference System (CSRS) online software is one of the best examples for users and processes observations using the PPP technique. Several studies have examined the accuracy of positioning with this software using GNSS measurements and different observation conditions [12-16].

If the accuracy of the estimated ZTD values from these free online services is acceptable, researchers other than geodesists such as meteorologists can use the GPS meteorology technique in related fields with raw data. In 2017, Arabi and Nankeli reviewed and compared the accuracy of positioning of 4 famous online PPP services named GAPS, magicGNSS, CSRS-PPP, and APPS using the observations from February 1 to 15, 2015, at two IGS stations [17].

In addition to comparing the accuracy of estimating coordinate components, they compared the estimated ZTD values from the abovementioned four online services on February 1, 2015, with the reference values from the IGS site processing. Their results showed that online services could estimate the tropospheric delay with an average absolute value of ZTD difference of less than 5 mm compared to IGS products. However, ZTD estimation by the PPP method and through online services has not been well studied in Iran. In other words, the Arabi and Nankeli studies were conducted only in two IGS stations, only one of which was part of the network of permanent GPS stations in the country, and their comparison was made in just one day.

Given the time constraints and the number of stations in the abovementioned research, in this study, the authors reviewed the quality of the ZTD estimates from the Canadian online service CSRS-PPP at 46 stations of the Iranian permanent GPS network over eight days of 2014. The ZTD estimates from differential processing were used as reference values. In addition to extending the time period and the number of stations used, the relationship between the accuracy statistics of the tropospheric delay values of the CSRS-PPP service with the geographical location and topography of the region was also examined. Finally, the time evolution of ZTD values in four synoptic stations during precipitation was studied.

2. Study area and data

The network of permanent GPS stations in Iran, established by the National Cartographic Center of Iran, includes more than 100 stations. To evaluate the ZTD products of the CSRS-PPP online service, the observations of 46 stations of the country’s permanent GPS network were used. The geographical location of the selected GPS stations distributed in the area is shown in Figure 1.

Also, statistical evaluations were performed based on an observations period of eight days (days 30 to 37) in 2014. The list of these stations, along with their latitude and longitude and their four-character names, are given in Table 1.

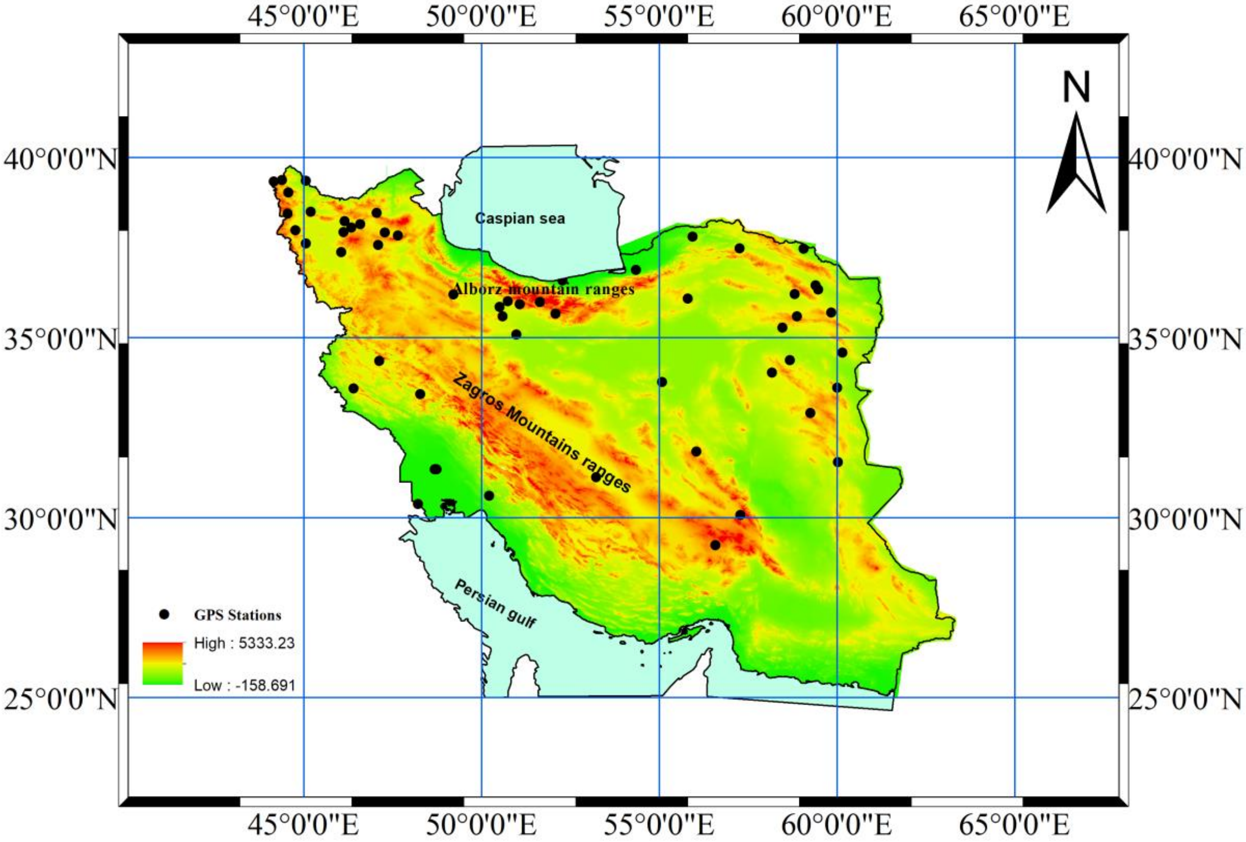

Fig. 1: Geographical location of the 46 GPS stations studied along with the topography of the area

Table. 1: Geodetic location of the GPS stations used in this study

Station name	Latitude (deg)	Longitude (deg)	Height (m)	Station name	Latitude (deg)	Longitude (deg)	Height (m)
abdn	30.37775	48.21349	-12.6021	**hstd**	37.57613	47.0942	1964.414
abrk	31.12039	53.22649	1535.35	**illm**	33.58858	46.39742	1327.276
absd	35.66112	52.09117	1972.673	**kadn**	35.59167	58.87826	1831.82
ahar	38.46807	47.04963	1360.382	**kblg**	39.03051	44.56471	1988.2
ahva	31.33956	48.68444	12.74875	**khje**	38.15163	46.59562	1514.56
ahvz	31.34378	48.74436	5.797895	**khur**	33.76924	55.08127	837.4174
akht	35.58823	50.60057	1278.948	**kkdy**	39.33224	44.15988	1954.667
amnd	38.2311	46.1552	1516.782	**kmsh**	34.35604	47.12466	1316.157
ardh	37.82875	47.65003	1775.003	**krmd**	36.19547	49.21072	1589.392
baft	29.2391	56.58003	2276.201	**kshm**	35.27051	58.473	1092.139

bahd	31.8406	56.04614	1428.903	**mavt**	37.80092	55.94384	442.2666
bebn	30.60557	50.21695	302.3776	**mhan**	30.07152	57.28838	1873.721
biaj	36.08602	55.80517	1091.071	**mmkn**	37.98502	44.77094	1869.371
bijd	32.90011	59.25527	1475.429	**mshn**	36.33467	59.47982	1087.434
bnab	37.36978	46.05188	1302.908	**nehb**	31.54196	60.03821	1172.979
brmn	37.91896	47.28837	1092.452	**nfrd**	36.45006	59.40127	1106.071
bojd	37.48027	57.27156	1661.339	**nish**	36.20699	58.82026	1194.994
bzgn	39.37912	44.39213	1434.74	**oryh**	37.61797	45.05695	1356.4
chsm	35.08752	50.98936	927.923	**pold**	39.35131	45.06151	815.603
farm	35.69606	59.84298	1395.231	**skoh**	37.93313	46.1229	1654.632
ferd	34.03059	58.18307	1283.979	**tabz**	38.05557	46.34325	1512.585
gona	34.37301	58.68354	1066.937	**vldn**	38.49143	45.19326	1307.25
grgn	36.87569	54.35326	4.093098	**zari**	38.44571	44.54981	1890.456

In addition to raw observations at GPS stations available in the RINEX format, other auxiliary data such as precise orbit data, antenna phase center changes, earth orientation parameters, moon and sun ephemerids, leap seconds, and nutation tables are required for processing observations in a differential manner using GAMIT software. Such data can be obtained from reputable archives such as SOPAC (http://sopac-csrc.ucsd.edu/index.php/sopac/).

3. Methodology

To determine ZTD, two processing methods can be used:

1- Solving the networks using dual differential observations [18-21] and,

2- Determining the exact position of the point with the PPP method, which uses zero-differenced observations [22-23].

The considered functional model in the PPP method is based on a combination of ionospheric-free observations to eliminate ionospheric error, which is formed for both types of phase and pseudo-interval observation. Also, in this method, researchers try to reduce or eliminate many errors, including satellite clock error, an error caused by phase center separation from the satellite mass center, error due to phase center receiver antenna separation, onshore tide effect, and relativity effect error, by using accurate models and orbital information. In addition, other major error sources such as troposphere effect and receiver clock error are considered as unknowns, along with estimating other unknowns.

Network solution is one of the most common methods of GPS observation processing. In this method, at least two or more receivers simultaneously observe GPS satellites. This method of processing provides high-precision estimates of ZTD. Many GPS observation processing centers use this method to eliminate receiver and satellite clock errors.

The PPP method, on the other hand, requires only one GPS receiver observation to provide accurate ZTD values. It is important to note that clock corrections and the precise orbit of satellites are required to process the observations in this method.

However, the ZTD estimation in PPP mode is done separately for each station, and a noteworthy point in the PPP method is needed for accurate clock and orbit access. One of the disadvantages of the network processing concerning the PPP mode is the high volume of the normal matrix in the least-square adjustment. Also, in the PPP method, the effects associated with each station will not affect the ZTD values of other stations [24]. Theoretically, there is no difference between these two methods. In network processing, dual differential residuals are generated from the signal path that must be converted to zero-differenced signal path residuals [25]. Finally, after processing the data by either method, the tropospheric delays of the GPS signal along with the position parameters are estimated.

In the present study, PPP processing was performed by the Canadian online service CSRS-PPP. Version 1.05 of the CSRS software has a variety of capabilities. For example, through this online service, observations can be processed in two different kinematic or static modes. Furthermore, in this service, processing GLONASS satellite observations is also possible in addition to GPS data.

Code and phase observations are used in two frequencies L1 and L2, and the antenna model is extracted through the station RINEX file and is included in the processing. In addition, the CSRS software is based on the ITRF2008 reference frame, and the satellite orbit and clocks data are

IGS Final. The cut-off angle during processing using the CSRS-PPP online service is 10 degrees, and the mapping function is GMF.

To use the CSRS-PPP International Absolute Positioning Service, developed by the Canadian Department of Natural Resources, one must first register using the link https://webapp.geod.nrcan.gc.ca/geod/account-compte/login.php. After registering on the desired website, you can enter the following link: https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php, and by selecting your favorite options, all you have to do is upload the RINEX file of the station. Finally, after a few minutes, the output of the PPP processing will be sent to the user's email. This online service can perform both static and kinematic GPS processing. Additional information such as the type of observations, the model and height of the antenna, and the initial coordinates of the receiver used to determine the exact absolute position are extracted and used from the observation file by the CSRS-PPP software.

Khaniani and Ghahremani, in 2018, showed that the tropospheric estimates obtained from the GAMIT software using differential processing mode are in high agreement with the corresponding estimates obtained from the IGS site processes at the Tehran station [26]. Here, the GAMIT software is used to process station networks, and these values are considered reliable values to evaluate the ZTD values obtained from the PPP online service. During processing with the GAMIT software, 10° cut-off angle value and GMF mapping function, the IGS Final orbital and clock products, the IERS 2010 earth orientation parameters, and the IGS08.atx antenna calibration model were used.

ZTD is divided into the dry component or Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD) or the wet component [27].

Having surface pressure measurements at the GPS station P_0 and by applying the Sasstamoinen model, the ZHD can be calculated with high accuracy using Eq. 1 [28].

$$\mathrm{ZHD} = \frac{0.0022768\,\mathrm{P_0}}{1-0.00265\cos(2\varphi)-0.000285\mathrm{h}} \tag{1}$$

where h is the station height from geoid in kilometer and φ is the geodetic latitude. By subtracting the hydrostatic delay from the estimated ZTD values, we obtain ZWD values that could be converted to PWV by the following equation [6].

$$\mathrm{PWV} = \frac{10^6 \times \mathrm{ZWD}}{\rho_w R_v\left[\left({k_3}/{T_m}\right)+k_2+k_1\left({M_w}/{M_d}\right)\right]} \tag{2}$$

where k_i are the physical constants of the refraction formula [29]. Also, in Eq. 2, M_d and M_w are the molecular mass of dry air and water vapor, respectively. The parameter T_m is the mean atmospheric temperature, which can be calculated using the vertical temperature profile or based on the linear experimental relationship of this parameter with the surface temperature T_0 [28,18].

According to 54330 radiosonde profiles from 11 stations distributed in Iran from 1996 to 2012, the coefficients of the linear model for T_m in the study area were obtained as follows:

$$T_m = 75.39 + 0.7103T_0 \tag{3}$$

It should be noted that the main purpose of this study was to evaluate the ZTD product of the online GPS processing service, and the focus of this research was not on the calculation of GPS PWV.

After processing the observations using both PPP and differential methods in all 46 stations from the 30th to the 37th day of 2014, 8-day time series of ZTD resulting from the two different methods were prepared in each station. Then for each station, the corresponding values were extracted at common times and using the statistical parameters of the correlation coefficient (R), mean bias error (MBE), root mean squares error (RMSE), and mean absolute error (MAE), the statistical quality of ZTD_PPP values were be examined. Eqs. 4 to 7 were used to calculate these statistical parameters.

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(ZTD_i^{PPP} - ZTD_i^{DD}) \tag{4}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (ZTD_i^{PPP} - ZTD_i^{DD})^2} \tag{5}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|(ZTD_i^{PPP} - ZTD_i^{DD})| \tag{6}$$

$$R = \frac{\sum_{i=1}^{N} (ZTD_i^{PPP} - ZTD_m^{PPP}) \sum_{i=1}^{N} (ZTD_i^{DD} - ZTD_m^{DD})}{\sqrt{\sum_{i=1}^{N} (ZTD_i^{PPP} - ZTD_m^{PPP})^2}\sqrt{\sum_{i=1}^{N} (ZTD_i^{DD} - ZTD_m^{DD})^2}} \tag{7}$$

In Eqs. 4 to 7, ZTD_i^{PPP} and ZTD_i^{DD} are the total zenith delay values obtained from the CSRS-PPP online service and the corresponding values obtained from the differential method in the GAMIT software, respectively. Also, N is the number of data pairs compared at each station and ZTD_m^{PPP} and ZTD_m^{DD} are the mean values of the zenith delay obtained from the online PPP and differential GPS processing methods at each station, respectively.

4. Results

4.1. Comparison of the CSRS-PPP and GAMIT ZTD values

As mentioned earlier, the accuracy of the Precipitable Water Vapor (PWV) obtained by GPS observations is highly dependent on the accuracy of the ZTD values. Therefore, by evaluating the ZTD values obtained from any GPS processing method, we can understand the efficiency of these products in meteorological and climatic applications. This section presents a comparison between the ZTD estimates from the differential processing and the corresponding estimates obtained by the PPP method through the CSRS online service. For this purpose, first, about 440 daily files of observations of 46 permanent GPS receivers in Iran, shown in Fig. 1, corresponding to eight days in 2014, separately by the online service CSRS-PPP was processed. Then, after archiving the processing outputs for each station in eight different days, the estimated ZTD values along with the corresponding time data were extracted from NNNNDDD0.pos format files, and the 8-day ZTD_PPP time series was formed in each station. For example, the file abdn0310.pos is related to the 31st day of 2014 of the Abadan permanent station, which includes valuable information such as GDOP, clock error, longitude, latitude, and the estimated geodetic height of the station. In addition to the variables mentioned, there are ZTD values in these files that interested users in meteorology could extract. For example, Fig. 2 shows the ZTD time series from the CSRS online service processing (blue graphs) and the GAMIT processing performed in this study (red graphs) for nine of the 46 stations studied. As can be seen from Fig. 2, the ZTD online service time series follows the estimated values of the differential method (red graphs) very well. According to the graphs in Fig. 2, it can be well seen that in both cases, when the value of the ZTD obtained from the GAMIT software reaches its peak and in the case where it decreases, the zenith delay values of the online service (red graphs) follows the blue graph (GAMIT estimates) well.

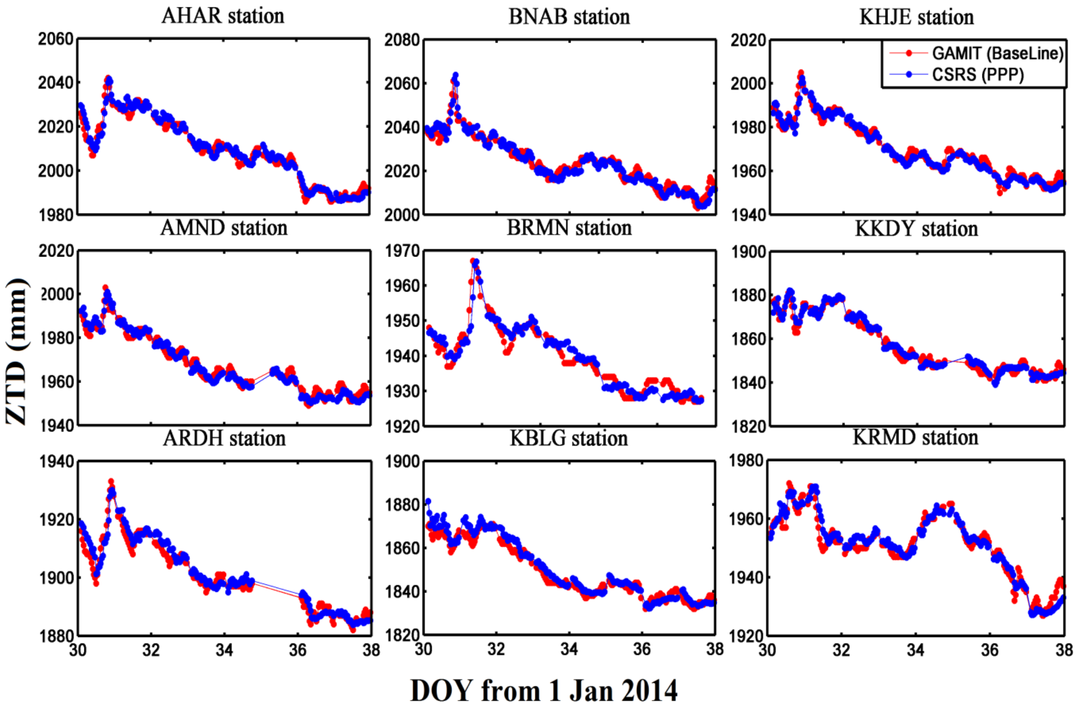

Fig. 2: Comparison of the ZTD time series obtained from PPP processing (using CSRS-PPP processing) and differential (using GAMIT processing) modes.

In addition to graphically examining the agreement between the two methods in estimating ZTD from GPS observations, it was necessary to compare them quantitatively with the help of standard statistics. Therefore, after preparing a pair of ZTD time series obtained from the online service and GAMIT software, these values were compared using Eqs. 1 to 4 for each station. The statistical results of this evaluation are given in Table 2.

Table. 2: Statistical comparison of the ZTD estimates obtained from the CSRS-PPP online service with the corresponding values obtained from the differential processing of the GAMIT software

Station name	MBE (mm)	MAE (mm)	RMSE (mm)	R	N
abdn	-1.595	4.222	5.200	0.983	1999
abrk	0.798	2.357	3.141	0.979	2093
absd	1.945	2.392	2.928	0.972	2087
ahar	-0.174	2.339	2.993	0.978	2218
ahva	1.261	3.976	5.011	0.9882	1673
ahvz	0.937	3.025	3.761	0.991	2001
akht	1.053	2.864	3.508	0.935	1271
amnd	0.621	2.556	3.189	0.974	2082
ardh	-0.576	2.585	3.417	0.960	1874
baft	0.574	3.02	3.749	0.980	1815
bahd	-0.207	2.260	2.907	0.976	1778
bebn	1.309	3.103	3.909	0.992	1946
biaj	1.212	2.438	3.029	0.976	2022
bijd	0.044	2.141	2.888	0.984	2038
bnab	0.439	2.398	3.156	0.964	2195
brmn	0.382	2.650	3.263	0.984	2086
bojd	-0.127	2.147	2.801	0.952	1330
bzgn	1.808	2.523	3.094	0.985	2077
chsm	1.262	3.148	3.876	0.964	2072
farm	0.335	3.027	3.840	0.9809	1877
ferd	-0.238	2.279	2.978	0.978	2090
gona	0.126	2.591	3.278	0.9801	2102
grgn	1.453	2.657	3.277	0.992	2123
hstd	1.214	2.384	3.021	0.979	1960
illm	1.591	2.658	3.326	0.983	2062
kadn	-0.112	3.207	4.208	0.954	1839
kblg	-1.482	2.652	3.457	0.979	2150
khje	0.548	2.027	2.723	0.978	2188
khur	1.291	2.617	3.275	0.973	2058
kkdy	-0.167	2.007	2.660	0.978	2064
kmsh	2.052	2.776	3.324	0.984	2062
krmd	-0.013	2.294	3.056	0.961	2191
kshm	0.437	2.224	2.798	0.981	2093
mavt	0.412	2.195	2.778	0.992	1925
mhan	0.717	3.227	4.070	0.959	1599
mmkn	-0.317	2.090	2.822	0.970	2169
mshn	-1.571	3.515	4.797	0.975	1596
nehb	0.913	5.043	6.735	0.935	1904
nfrd	1.184	2.672	3.212	0.991	2110
nish	-0.412	2.778	3.649	0.979	2112
oryh	-0.307	2.246	2.954	0.974	2182

pold	-0.757	2.456	3.085	0.985	2217
skoh	0.199	2.152	2.790	0.9725	2174
tabz	0.251	2.266	2.923	0.975	2197
vldn	0.758	1.730	2.311	0.989	1670
zari	0.642	2.024	2.561	0.9819	2184

Also, Table 2 summarizes the statistical evaluation of the ZTD estimates of the CSRS-PPP online service in this study. In general, the mean values of bias, MAE, RMSE, and R of the online service tropospheric delay products compared to the differential method were 0.42, 2.65, 3.38, and 0.976 mm, respectively. As shown in Table 2, there is a high agreement in the ZTD values from the online service and GAMIT processing.

According to the studies of Vey et al., if the accuracy of the ZTD parameter is about 4 to 10 mm and the pressure and temperature error are 2 mbar and 2 K, respectively, RMSE of the estimated PWV values using these parameters will be about 1.1 to 1.9 mm [30]. Therefore, according to Tables 2 and 3, we can expect an error of less than 2 mm in estimating PWV by using the PPP method in GPS data processing. According to the 2014 study by Yuan et al., the acceptable error thresholds for the GPS ZTD and PWV values in numerical weather prediction models are 15 mm and 3 mm, respectively[31].

Table. 3: General evaluation of the ZTD estimates of CSRS-PPP online service compared to the differential observation processing method.

Statistic	**Mean**	**MAX**	**MIN**
MBE	0.42	2.05	-1.595
MAE	2.65	5.04	1.73
RMSE	3.38	6.73	2.31
R	0.976	0.996	0.90

In other words, the average bias of the ZTD estimates obtained from PPP processing for all stations was 0.42 mm, and the maximum RMSE values did not exceed 7 mm. Therefore, in numerical weather forecasting, the PPP method can be used to generate ZTD and, ultimately, PWV values. It should be noted that estimating PWV values with an accuracy of less than 2 mm is very valuable for meteorologists.

Another objective of this study was to investigate the relationship between the efficiency of the ZTD online service estimates and the geographical location parameters of the studied station. For this purpose, the correlation of error statistics in Table 2 with the geographical coordinates of the stations was calculated and is presented in Table 4. From the values in Table 4, it can be inferred that in most cases, the performance of the tropospheric delay estimates of the CSRS-PPP online service is independent of the geographical location of the station. In other words, most correlation values are small and insignificant, and there is no strong statistical relationship between the accuracy of the ZTD estimates and the geodetic longitude, latitude, and height of the station.

Table. 4: Correlation of the statistical parameters of the ZTD estimates of the CSRS-PPP online service with the geographical parameters of the studied stations

Geodetic coordinate **Statistic**	**Latitude**	**Longitude**	**Height**
MBE	-0.18	-0.02	-0.10
MAE	-0.57	0.30	-0.39
RMSE	-0.55	0.32	-0.34
R	0.02	-0.16	-0.38

According to Table 4, MAE and RMSE statistics, which somehow indicate the precision of ZTD estimates, have a negative correlation of up to 57% with the latitude of the studied station. The reason for this can be attributed to the proximity of low latitudes to the tropics. As we get closer to the equator, the amount of water vapor in the atmosphere increases, increasing ZTD.

When the ZTD quantity values are higher, for example, in summer seasons or at lower latitudes, the estimation error will also increase. Therefore, by reducing the latitude of the stations, due to the natural conditions of the Earth's atmosphere at lower latitudes, the precision of the ZTD estimation may be relatively reduced. However, as mentioned in Table 3, the largest RMSE value of the ZTD obtained from the CSRS-PPP service was 6.73 mm, which is acceptable accuracy.

In addition, according to Table 4, it can be seen that there is a weak negative correlation of less than 40% between the station height and the precision of ZTD estimation. When the height of a station in a particular area is lower than other stations, GPS signals travel a longer path to reach the receiver, which leads to an increase in the amount of ZTD at the station compared to other stations. On the other hand, with increasing the ZTD values, the RMSE estimate will increase slightly. Therefore, we see that, inherently, decreasing the station height can have a small effect on increasing the RMSE estimate of the tropospheric delay. So, although there is a weak relative relationship between the ZTD precision and station latitude and height, this should not be attributed to an error in online service processing.

4.2. ZTD temporal evolutions during precipitation events

In Section 4.1, the CSRS-PPP online service ZTD estimates were statistically evaluated using the corresponding values obtained from the differential GPS observation processing method. According to the results, the quality of these values was confirmed. In other words, the CSRS-PPP online service tropospheric delay products can be suggested for meteorological studies.

In this section, the temporal variations of ZTD values obtained from the online service, generated with a temporal resolution of about 1 minute, are examined in 4 synoptic stations. For this purpose, the synoptic stations located at a short horizontal distance from GPS stations in which precipitation had occurred were considered. Table 5 presents the IDs of these synoptic stations, the name of their corresponding GPS stations, and their horizontal distance from each other.

To study the changes of the ZTD values before, during, and after the rainfall, the ZTD time series along with the bar graph of 6-hour rainfall measurements at the stations presented in Table 5 were prepared as shown in Fig. 3.

Table. 5: GPS and corresponding synoptic stations which were used to study the temporal evolution of the ZTD values during precipitation events

GPS station	Horizontal distance (km)	Synoptic station ID
AHAR	4.25	40704
ORYH	4.47	40712
BOJD	3.57	40723
MAVT	0.09	40721

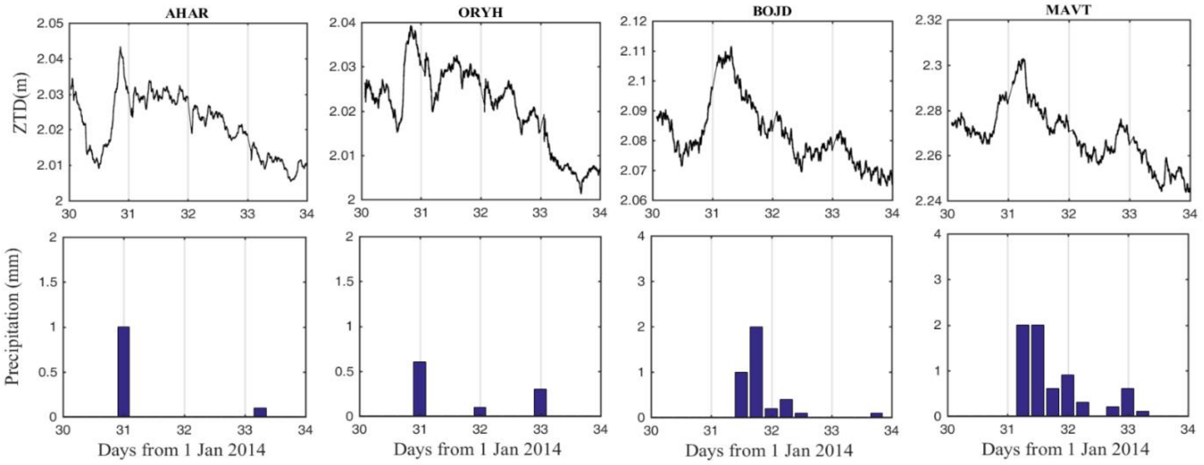

Fig. 3: ZTD time series from the CSRS-PPP service processing with precipitation values at AHAR, ORYH, BOJD, and MAVT stations from the 30th to 34th days of 2014

As GPS observations are measured continuously at a very high temporal resolution, the ZTD time series can be generated almost continuously by processing these observations, as shown in Fig. 3. According to the precipitation graphs for AHAR and ORYH stations, precipitation was reported on the 31st day. On the other hand, it can be easily observed that before the occurrence of precipitation on the 31st day, ZTD values in both stations showed an increase with a steep slope to the extent that precipitation occurred. When it rained, this quantity gradually began to decline. Such behavior can also be seen in BOJD and MAVT stations.

A few hours before the onset of precipitation, ZTD values typically began to rise and eventually reach their maximum, beginning to decline slowly during precipitation and peaking again until the next precipitation. What can be seen from the graphs in Fig. 3 is that the values of tropospheric delays in a region may reach their relative maximums with no precipitation occurring, but before precipitation, they will experience upward changes. Khaniani et al. in 2021 showed that the simultaneous use of the GPS PWV values along with other meteorological parameters in the Tehran station could help to predict short-term rainfall in the region. Given the potential of the GPS observations to detect atmospheric-influenced parameters such as ZTD values, using the ZTD values of online GPS processing services such as the CSRS-PPP can be very useful for meteorologists.

5. Conclusion

In recent decades, many meteorologists and climatologists have become interested in using GPS meteorology utilizing observations of ground-based GPS receivers. The reason for this is the ability to use GPS observations in all weather conditions continuously and for a long time without the need for calibration and also as a by-product next to its primary purpose, i.e., positioning.

However, using GPS observations for meteorological applications requires specialized processing knowledge of these observations, usually done by geodesy specialists. On the other hand, in recent years, online services have been able to process GPS observations for free and send the results to the user. One of the outputs of online services is the ZTD values of the signals recorded in the GPS receiver. In this study, the accuracy of ZTD values obtained from the processing of the CSRS-PPP online service in the region of Iran was evaluated. For this purpose, 8-day observations of 46 permanent stations were used. The ZTD values obtained from the differential processing of observations obtained from GAMIT software were used as reliable values. The results of this study showed that the tropospheric delay values of the online service are up to about 98% consistent with the corresponding GAMIT estimates. Also, the maximum estimated RMSE of the ZTD_PPP values obtained from the online service was close to 7 mm. This amount of error in ZTD estimation typically results in an error of less than 1.7 mm in the PWV calculation, which is acceptable in many meteorological applications. In addition, the study of the relationship between the accuracy of the ZTD estimates of online service with changing the geographical location of the GPS station showed that, in general, the performance of the ZTD estimates is not significantly related to the location of the station. Also, the study of the temporal evolution of the ZTD values obtained from the online service during rainfall at four synoptic stations showed that ZTD values increase significantly before precipitation events and begin to decrease during and after precipitation.

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