Impact of different sampling rates on precise point positioning performance using online processing service

Serdar Erol, Reha Metin Alkan, I. Murat Ozulu and Veli Ilçi

ABSTRACT
In this study, the effect of different sampling rates (i.e., observation recording interval) on the Precise Point Positioning (PPP) solutions in terms of accuracy was investigated. For this purpose, a field test was carried out in Corum province, Turkey, on 11 September 2019. Within this context, a Geodetic Point (GP) was established and precisely coordinated. A static GNSS measurement was occupied on the GP for about 4-hour time at 0.10 second (s)/10 Hz measurement intervals with the Trimble R10 geodetic grade GNSS receiver. The original observation file was converted to RINEX format and then decimated into the different data sampling rates as 0.2 s, 0.5 s, 1 s, 5 s, 10 s, 30 s, 60 s, and 120 s. All these RINEX observation files were submitted to the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) online processing service the day after the data collection date by choosing both static and kinematic processing options. In this way, PPP-derived static coordinates, and the kinematic coordinates of each measurement epoch were calculated. The PPP-derived coordinates obtained from each decimated sampling intervals were compared to known coordinates of the GP for northing, easting, 2D position, and height components. According to the static and kinematic processing results, high data sampling rates did not change the PPP solutions in terms of accuracy when compared to the results obtained using lower sampling rates. The results of this study imply that it was not necessary to collect GNSS data with high-rate intervals for many surveying projects requiring cm-level accuracy.

1. Introduction
The most common way for highly accurate positioning with satellite-based GNSS methods is using carrier phase observations with at least two receivers (one is at rover, and one is a reference with known coordinates) simultaneously. The collected data should then be processed with a proper GNSS processing software in an office. This procedure generally needs high capital and labor field and office work. Furthermore, it does not provide a solution for the applications that need real-time coordinates.

In order to make an accurate positioning in real-time, the Real-time Kinematic (RTK) method as Single-baseline RTK or Network RTK (NRTK) was introduced. On the other hand, Single-baseline RTK requires mainly a base station and radio-link whereas NRTK requires many reference stations, the control center(s), and a communication link (Internet, cellular) in order to transmit the corrections to the user. Furthermore, there is a distance limitation between the rover and its reference station, which typically restricts to about 10–20 km for Single-baseline RTK and 70–100 km interstation distances for NRTK methods (Hofmann-Wellenhof, Legat, and Wieser 2003; El-Mowafy 2012; Denys et al. 2017). However, it is underlined that these methods cannot be effectively used in some difficult terrain conditions, such as, urban canyons, gorges, high mountains/hills surrounded areas, etc. that restrict or limit radio connectivity or GSM usage.

More recently, the Precise Point Positioning (PPP), either post-processed or real-time, was suggested. This technique provides centimeter to decimeter level homogeneous accurate positioning within a consistent global reference frame anywhere in the world by using data collected by only one GNSS receiver with the help of the derived available or real-time streaming GNSS satellite products. International GNSS Service (IGS) has carried on the Real-time Service (RTS) for the real-time PPP on a global scale since 2013. In addition, some private companies have also started their own commercial global real-time PPP services as an alternative to IGS-RTS by the time. Besides, scientific/academic, commercial, in-house software, and free online services are available for post-processed PPP. Many researchers have been investigated the performance of the PPP technique with some theoretical background such as Zumberge et al. (1997), Héroux and Koubâ (2001), Rizos et al. (2012), Seepersad and Bisnath (2014), Choy, Bisnath, and Rizos (2017), Kiliszek, Szolucha, and Kosięczyński (2018), Choy and
Harima (2019) and DeSanto, Chadwell, and Sandwell (2019). These studies revealed that PPP is a robust cost-effective alternative to the traditional differential GNSS positioning by means of the obtained accuracy and operational simplicity since it does not need single/local or regional network reference station data. This is more important in some field conditions such as offshore marine applications, remote region studies that a nearby station is unavailable, or the establishment of a base station is difficult or not cost-effective (Martin et al. 2011). With many advantages, the PPP technique has been widely used in a wide range of applications like surveying, mapping, precise positioning, crustal deformation monitoring, weather forecasting, estimation of orbits, agriculture, construction, mining, unmanned aerial vehicle photogrammetry, and so on.

More recently, as a result of the improvements in GNSS hardware and data processing strategies, the data collection at a very high sampling rate has become possible (Xu et al. 2013). Depending on these developments, high-rate GNSS PPP has started to be used in seismology and many engineering projects including measuring the earthquake displacements, monitoring the health of engineering structures, measuring the vibration and displacement of civil engineering structures such as high-rise buildings, towers, long and short-span bridges, viaducts that under the effect of an earthquake, strong winds or traffic loads (Wang et al. 2012; Xu et al. 2013; Yigit 2016; Yigit and Erâp 2017; Kaloop, Yigit, and Hu 2018; Kudlačik et al. 2019).

2. Precise point positioning

The PPP, as one of the innovative techniques, uses the un-differenced carrier-phase and code observations by incorporating precise satellite orbits and clock corrections produced by mainly IGS and other organizations such as JPL, CODE, and Geodetic Survey Division of Natural Resources Canada (NRCan). Furthermore, in order to get cm-level accuracy in the PPP, additional biases and errors including sagnac effect, phase wind-up effect, relativistic effect, loading effects, satellite, and receiver antenna phase center offset and directional variation corrections should be considered.

The basic PPP solution equations are given below:

\[
P(L_i) = \rho + c(dt - dT) + d_{\text{orb}} + d_{\text{ion}} + d_{\text{trop}} + \varepsilon[P(L_i)]
\]

(1)

\[
\phi(L_i) = \rho + c(dt - dT) + d_{\text{orb}} - d_{\text{ion}} + d_{\text{trop}} + \lambda_iN_i + \varepsilon[\phi(L_i)]
\]

(2)

where;

\( P(L_i) \) and \( \phi(L_i) \): measured pseudorange and carrier-phase range on \( L_i \), respectively (m),

\( \rho \): true geometric range (m),

\( dt \) and \( dT \): receiver and satellite clock errors that absorbed code/phase biases, respectively (s),

\( d_{\text{orb}} \), \( d_{\text{ion}} \), \( d_{\text{trop}} \): orbital, ionospheric, and tropospheric errors, respectively (m),

\( N_i \): phase ambiguity on \( L_i \),

\( \lambda_i \): carrier phase \((L_i)\) wavelength (m),

\( \varepsilon[\cdot] \): un-modeled noise (m).

In order to eliminate the first-order ionospheric delay errors in the PPP technique, the ionosphere-free combined code and carrier-phase observables are used. In this case, the equations can be expressed as:

\[
P_{IF} = \frac{f_1^2P(L_1) - f_2^2P(L_2)}{f_1^2 - f_2^2} = \rho + c(dt - dT) + d_{\text{orb}} + M(E) \cdot \text{ZPD} + \varepsilon[P(L_{1,2})]
\]

(3)

\[
\phi_{IF} = \frac{f_1^2\phi(L_1) - f_2^2\phi(L_2)}{f_1^2 - f_2^2} = \rho + c(dt - dT) + d_{\text{orb}} + M(E) \cdot \text{ZPD} + \lambda_{IF}N_{IF} + \varepsilon[\phi(L_{1,2})]
\]

(4)

where;

\( P_{IF} \) and \( \phi_{IF} \): iono-free pseudorange and carrier-phase combination, respectively (m),

\( f_1 \) and \( f_2 \): \( L_1 \) and \( L_2 \) carrier frequencies,

\( M(E) \): elevation \((E)\) dependent tropospheric mapping function,

\( \text{ZPD} \): tropospheric zenith path delay (m).

Although the PPP has many advantages, it is worth mentioning that it has still a disadvantage of requiring a relatively long convergence time compared to the RTK technique. Typically it needs tens of minutes to several hours to solve the carrier-phase float/fixed ambiguities for centimeter-level positioning accuracy. This restricts the use of PPP in real-time GNSS applications (Choy, Bisnath, and Rizos 2017).

The PPP-derivated coordinates can be calculated with Scientific/Academic Software (e.g. Bernese, GipsyX, RTKLIB, and Net_Diff etc.), Commercial Software (e.g. GrafNav), and Online Processing GNSS platforms (e.g. CSRS-PPP, APPS, GAPS, magicGNSS, and Trimble CenterPoint RTX Post-Processing Service, etc.). Each of these platforms has advantages and shortcomings. For instance, scientific and academic software requires qualified and experienced personnel who have a GNSS theoretical background. At the same time, it generally needs to pay a license fee. Recently, many organizations, research institutes and universities have introduced their own online GNSS processing services. Through these services, the data collected in the field with only a single GNSS receiver is processed using PPP or relative method depending on the service used, and point
coordinates are calculated. These services are mostly free and provide unlimited service to their users worldwide. With having many advantages, the web-based online GNSS processing services have been widely used as an alternative to the traditional processing approaches. On the other hand, the main shortcomings of the web-based services are given as:

- There are no (or limited) options other than offered by the service,
- The lack of different solution strategies as distinct from commercial and scientific software,
- Difficulties in sending large file size and/or receiving results (delays, interruptions, etc.) depending on the Internet connection speed,
- No access to the service during the update of the service or in case of other problems.

More detailed information about online processing services can be found in Alkan, Ilici, and Ozulu (2016) and Lipatnikov and Shevchuk (2019).

In this study, the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) service was used to calculate the PPP-derived coordinates. The CSRS-PPP is an online post-processing service operated by the NRCan. NRCan has processed more than 3 million GNSS (GPS and GLONASS) data sets with CSRS-PPP service since 2003, when it was put into service (Donahue, Hassen, and Banville 2018). The PPP-derived coordinates are calculated from the single or dual-frequency GNSS data in static or kinematic modes. The only thing that needs to be done by the service users is to submit their valid observation file (RINEX, *.zip, *gzip, *.gz, *.z, *.YYo) over the user-friendly web page of the service by selecting some options including processing mode (static or kinematic), the reference frame of the output coordinates (NAD83 or ITRF), and Ocean Tide Loading (OTL) file, if required. The user must also introduce a valid e-mail address for getting the processing results. The service produces one corrected averaged coordinate when the data is processed in static mode while producing a corrected track in kinematic mode. If the kinematic mode is chosen, the data is processed with a forward-backward processing strategy. The NRCan is planning an update to the CSRS-PPP service on 20 October 2020, and the service will be upgraded from version 2 to version 3. This modernization will include the PPP with ambiguity resolution (PPP-AR) for the data collected after 1 January 2018. The CSRS-PPP service uses the best available precise products provided by NRCan and IGS depending on the latency. NRCan 30 s clock and 15 s orbit products for GPS and GLONASS are computed using data from the IGS global tracking network. NRCan has switched to the Bernese 5.0 software for its Ultra-Rapid, Rapid and Final product estimation since 24 May 2011. Comparing the NRCan rapid products against the ESA final products shows that NRCan orbit product accuracy for GPS and GLONASS are 2.0 cm and 4.0 cm, respectively. In addition, the satellite clock products accuracies are 0.07 ns and 0.09 ns for GPS and GLONASS, respectively (Donahue, Ghoddousi-Fard, and Mireault 2014). Summary of the using precise products by CSRS-PPP service is given in Table 1 (Donahue, Hassen, and Banville 2018).

Martin et al. (2011) compared the PPP-derived coordinates using Bernese v5.0 scientific software, and APPS, CSRS-PPP, GAPS, MagicGNSS online services. They concluded that these different softwares produced almost the same results in the order of centimeter for the horizontal component and in centimeter level for the height component except GAPS. Dawidowicz and Krzan (2014) found that the CSRS-PPP service provided 5 cm horizontal accuracy and double for vertical accuracy by processing the 0.5-hour lasting GPS static data. Krzan, Dawidowicz, and Świątek (2014) investigated the position accuracy calculated by using CSRS-PPP service, which provides an equal accuracy to the most precise scientific software, as stated in many academic studies. In this study, the accuracy performance of CSRS-PPP and RTKLIB software was compared in a static test and they concluded that the results obtained by RTKLIB had approximately three times lower accuracy compared to the results obtained from CSRS-PPP. According to Yigit (2016), the service provides a few centimeters horizontal and less than 10 cm vertical accuracy in the kinematic mode by using IGS precise satellite orbit and clock products as well as dual-frequency code and phase data. Mendez Astudillo et al. (2018) analyzed the Zenith Tropospheric Delay (ZTD) values, which were estimated by using three different PPP online services, APPS, CSRS-PPP, MagicGNSS, and three desktop software packages, POINT, RTKLIB, and gLAB. The estimated ZTD values obtained with those services and software were compared with the ZTD values provided by the IGS. They found that the results obtained from the CSRS-PPP service were very close to the value of the IGS Tropospheric product. According to Jamieson and Gillins (2018), the attainable accuracy was given as 1 cm for both latitude and longitude components and 2 cm for height component using dual-frequency static data with the CSRS-PPP service. Detailed information about the CSRS-PPP processing service can be found in Tétreault et al. (2005), Mireault et al. (2008), Donahue,

Table 1. CSRS-PPP product summary.

| Product          | Frequency | Latency* |
|------------------|-----------|----------|
| NRCan Ultra-Rapid GPS | Hourly    | 90 minutes |
| NRCan Ultra-Rapid GNSS | 3 hours   | 90 minutes |
| NRCan Rapid GNSS | Daily     | 14–15 hours |
| IGS Final GNSS | Weekly    | 12–15 days |

*Latency is measured from the end of the time correction period.
Hassen, and Banville (2018) and the website of the service (https://webapp.geod.nrcan.gc.ca).

It should be stated that CSRS-PPP could process the GNSS data with a high sampling rate (i.e. higher than 1 s). After submission, the service immediately starts to process and produce different output files within a short time interval. All those files contain different information;

- The PPP results with textual and graphical information are given in a solution report file (.pdf),
- The used parameters and PPP results are given in a summary file (.sum),
- The coordinates of each epoch processed are given in a position file (.pos),
- The positioning and clock information for each epoch processed is given in a comma-separated (.csv) format text file,
- The solution residuals for each epoch/signal pair are given in a residual file (.res),
- If any errors occurred through the processing or if there are warnings, those are given in an error file (.txt).

All those files are sent to the users via an e-mail initially introduced by the user.

3. Experimental work

3.1. Field test

In order to investigate how the observation rate affects the positioning accuracy, a static GNSS measurement was conducted in Çorum Province, Turkey on 11 September 2019 (GPS Day of Year 254). Within this context, a Geodetic Point (GP) was established with having very high sky visibility and a minimum multipath environment (Figure 1). Then, the static measurement was occupied on the GP lasting about 4 -hour time period by tracking all available GPS and GLONASS satellites in view with a minimum elevation cut-off angle of 10 degrees. The observation recording interval was set to the 10 Hz (0.1 s). It should be noted that only GPS and GLONASS satellite data were collected because the CSRS-PPP service currently processes only GPS and GLONASS satellite constellations.

Through the survey, multi-constellation and multi-frequency supported Trimble R10 geodetic grade GNSS receiver with an internal antenna was used. This 440-channel receiver is capable of tracking GPS, GLONASS, Galileo, BeiDou, QZSS and NavIC (IRNSS) satellites at 1 Hz, 2 Hz, 5 Hz, 10 Hz, and 20 Hz positioning rates. The positioning accuracy is given as $[3 \text{ mm } + 0.1 \text{ ppm RMS (Horizontal)}]$ and $[3.5 \text{ mm } + 0.4 \text{ ppm RMS (Vertical)}]$ for High-Precision Static survey for R10 receiver. The latest and detailed information about the used Trimble R10 receiver could be obtained from (https://geospatial.trimble.com).

The total tracked satellite number (GPS +GLONASS) and PDOP values for the static test measurement were depicted in Figure 2. According to the figure, the minimum, maximum, and average total tracked satellite numbers were 14, 17, and 16, respectively. Additionally, the minimum, maximum, and average PDOP values were 1.2, 1.6, and 1.4, respectively.

In order to get an idea about the collected GNSS data quality, the multipath and Signal-to-Noise (SNR)
ratio graphics using the data above 10-degree elevation angle for the carrier frequencies of both constellations (G:GPS and R:GLONASS) were created using BKG Ntrip Client (BNC) software QC tool, and given as skyplot in Figure 3 left and right, respectively. Plots in Figure 3 clearly show that almost all SNR values exceed the limit of 35 dBHz and multipath values were obtained less than 1 meter for both frequencies in the constellations.

3.2. Data processing

The collected static GNSS data at 0.1 s sampling rate were converted to the standard RINEX file. In order to investigate the effect of different sampling rates on PPP solutions, the original GNSS data set with 0.1 s sampling rate were decimated into the different data sets having 0.2 s, 0.5 s, 1 s, 5 s, 10 s, 30 s, 60 s, and 120 s sampling rates using the software gfzrnx-RINEX GNSS Data Conversion and Manipulation Toolbox. GFZ German Research Center for Geosciences’ gfzrnx software is a powerful toolbox that can mainly be used for RINEX data: i) check and repair; ii) conversion between the versions; iii) data split/splice; iv) data manipulations (data sampling, GNSS constellation, and observation type selection); and v) data comparison, and so on. The software supports GPS, GLONASS, BeiDou, Galileo, IRNSS, QZSS. All

Figure 2. The total number of observed satellites and PDOPs for the field test.

Figure 3. Multipath (left) and signal-to-noise (right) values for field test data.
functions and usability of this software are given in Nischan (2016).

All these RINEX observation files (4 hours and all decimated files) were submitted to the CSRS-PPP online processing service the day after the data collection date by choosing the static and kinematic processing options. When the data processing was completed by the service within a few minutes to several 10 minutes depending on the file size, e-mails were received containing URL links that include the results. All files that contained much information in addition to PPP-derived coordinates were then downloaded using these links. After the post-processing of the GNSS data sets, the PPP-derived kinematic coordinates of each measurement epoch and corrected averaged static coordinates were obtained. Some of the processing options used through the processing stages are given in Table 2.

As it can be seen from Table 2, NRCan’ Rapid precise satellite orbits and clocks data were used during the processing due to the files were sent to the service the day after data collection day (i.e. approximately 1-day latency).

In order to make a precise assessment of the PPP-derived coordinates, it was necessary to calculate the known coordinates of the occupied geodetic point. For this purpose, two of the nearest Turkish National Permanent RTK Network/TUSAGA-Aktif stations CORU (40°.570411 N, 34°.982204 E, 922.097 m) and SUNL (40°.153978 N, 34°.368910 E, 807.302 m) were used as reference stations. The reference station’s GNSS observation data, ITRF coordinates and velocities were retrieved from the related website. The collected data from both reference and rover (GP) stations were processed carrier phase-based differential method with Trimble commercial GNSS processing software, Trimble Business Center (TBC), in the current epoch. The coordinates of the established geodetic point were calculated with ambiguity fixed solution within 3 mm horizontal and 11 mm height standard error. During the process, precise IGS final precise orbits were used. TBC software uses the uncombined multi-frequency mode with ionospheric modeling to process baselines between 2 and 20 km.

Tropospheric delays are computed using the Hopfield model along with Niell mapping function.

The PPP-derived coordinates obtained from each decimated sampling rate were compared to known values of the GP for northing, easting, 2D Position and height components. The whole of the differences obtained from 0.1 s, 0.2 s, 0.5 s, 1 s, 5 s, 10 s, 30 s, 60 s, and 120 s data sampling rates were separately depicted in Figure 4 for static processing option and Figure 5 for kinematic processing option.

When the static solution results given in Figure 4 were investigated, the best results were obtained from the processing of the 0.1 s sampling rate (2.1 cm for the 2D position and ~1.6 cm for height component). In the result of processing data with intervals of 5 s or less, no improvement was observed in the 2D position, and an average of 2 cm difference was obtained in all processing scenarios. However, as a result of the processing of the measuring intervals of 30 s, 60 s, and 120 s, slightly larger differences were obtained than those with shorter measuring intervals.

According to Figure 4, it was clearly seen that the 2D position differences were dominated by easting component. This can be caused by inaccurate TUSAGA-Aktif station velocity values used in relative solution. Because, the CSRS-PPP coordinates come as in current datum and epoch, but the reference coordinates used for comparison come from the current epoch coordinates of the TUSAGA-Aktif station, which was calculated using its velocity vectors. In addition, we can see the same problem in kinematic solutions as well (Figure 5).

The results were also investigated as maximum and minimum values for all kinematic processing scenarios and were given in Table 3.

According to the comparison of differences between kinematic PPP-derived coordinates and their known values (Figure 5 and Table 3), in contrast to the static solution, the highest differences were obtained for the sampling rate at 0.1 s for northing, easting, 2D position, and height components. A positive relationship between the observation recording rate and magnitude of the differences (i.e. higher observation recording rate, higher differences) were found. In general, it is clearly seen that higher sampling rates did not significantly improve the kinematic PPP solutions performance when compared to the processing results obtained from lower data sampling rates. This is due to the high temporal correlation between observations with a higher sampling rate. It was caused by multipath and atmospheric errors (tropospheric and ionospheric), which remained constant with a slow change in satellite positions during high-frequency measurements (Miller, O’Keefe, and Gao 2012; Odolinski 2012). This means that high-rate data have a high temporal correlation. For instance, at higher sampling rates such as 1 s or higher (i.e. 0.5 s, 0.2 s, or so) was concerning, there was only a slight change in satellite geometry and

| Table 2. Processing options summary used by CSRS-PPP. |
|----------------------------------------------------------|
| **Processing mode** | **Static** | **Kinematic** |
| GNSS System | GPS and GLONASS | |
| Observations | Phase and Code | |
| Frequency | L1, L2 | |
| Precise Satellite Orbits | NRCan Rapid (EMR 15 s) | NRCan Rapid (EMR 30 s) |
| Precise Satellite Clocks | | |
| Product Interpolation | Yes | |
| Phase-center Corrections | IGS (ATX) | |
| Tropospheric Model | GPT+GMF | |
| Ionospheric Model | L3 (iono-free) | |
| Elevation Cut-off (degrees) | 10 | |
| Observation Interval(s) | 0.1; 0.2; 0.5; 1; 5; 10; 30; 60; 120 | |
atmospheric conditions between observations. Unless accounted for properly, such temporal correlation would deteriorate the solution. As the sampling rate decreases, the temporal correlation between observations decreases as well, which improves the solution performance (A. El-Rabbany, personal communication, 14 September 2019).

Although high-rate GNSS-PPP did not improve the solutions, detecting and monitoring the dynamic behavior of engineering structures and seismology require high-rate GNSS sampling rate. For instance, many researchers, e.g. Wang et al. (2012) and Xu et al. (2013), suggested that the 10 Hz or higher GNSS sampling rate is necessary for detecting the high-frequency displacement information for both seismology and engineering studies. Tang et al. (2019)

Figure 4. Differences between PPP-derived and known coordinates (for static processing option).

Figure 5. Epoch-by-epoch differences between PPP-derived and known coordinates (for kinematic processing option).

Table 3. Maximum and minimum differences were obtained from kinematic processing scenarios.

| Sampling Rates | Max. Northing (cm) | Min. Northing (cm) | Max. Easting (cm) | Min. Easting (cm) | Max. 2D Pos. (cm) | Min. 2D Pos. (cm) | Max. Height (cm) | Min. Height (cm) |
|----------------|-------------------|-------------------|------------------|------------------|-------------------|------------------|----------------|----------------|
| 0.1 s          | 2.5               | −2.9              | 4.5              | −1.4             | 4.5               | 0.0              | 7.5            | −14.3           |
| 0.2 s          | 2.5               | −2.7              | 4.4              | −1.4             | 4.4               | 0.0              | 7.2            | −13.1           |
| 0.5 s          | 2.4               | −2.8              | 4.3              | −1.2             | 4.4               | 0.0              | 6.1            | −11.8           |
| 1 s            | 2.4               | −2.8              | 4.3              | −1.1             | 4.4               | 0.0              | 5.7            | −10.9           |
| 5 s            | 2.4               | −2.4              | 4.2              | −0.9             | 4.1               | 0.1              | 4.5            | −9.7            |
| 10 s           | 2.5               | −2.4              | 3.8              | −0.8             | 3.9               | 0.2              | 4.3            | −9.2            |
| 30 s           | 1.2               | −2.0              | 3.7              | 0.2              | 3.7               | 0.7              | 4.1            | −8.0            |
| 60 s           | 1.2               | −1.8              | 3.6              | 0.8              | 3.7               | 0.8              | 3.7            | −7.1            |
| 120 s          | 1.3               | −1.4              | 3.4              | 0.7              | 3.4               | 1.0              | 3.3            | −6.5            |
expressed that detection of deflection and vibration with the GNSS technique in structures requires 1 s or higher sampling rate. Thus, high-rate GNSS-PPP is essential for this type of project.

The results were also investigated in terms of precision and accuracy. Within this frame, the precision (i.e. standard deviation-Std.Dev.) and the accuracy (i.e. Root Mean Square Error-RMSE) were calculated (Table 4 and Figure 6).

In order to figure out the internal accuracy (precision) of the CSRS-PPP kinematic solution for all intervals, the kinematic PPP epoch-by-epoch coordinates were compared to their own mean values as 2D positional scatter plot (Figure 7).

When the results were analyzed in terms of the precision (i.e. Standard Deviation) and the accuracy, it was clearly seen that there was an inverse proportion between the measurement interval (sampling rate) and the calculated values. The results in Table 4, Figures 6 and 7 show that higher sampling rates produced low-accurate PPP results in the kinematic process. In this study, the highest-rate PPP solution, i.e. 0.1 s sampling rate, achieved an accuracy of about 2.2 cm RMSE in 2D position and 4.2 cm RMSE for height component. On the contrary, the lowest-rate PPP, i.e. 120 s sampling rate, produced 2.1 cm RMSE in 2D position and 2.7 cm RMSE for height component. Another point of these results shows that the accuracy of the east component was found slightly weaker than that in the north component. The design of satellite orbits and the motion of satellites can cause this situation too (Cai 2009).

According to this study, considering the 2D scatter plot obtained as a result of the sampling interval of 0.1 s, it can be said that a two-dimensional instantaneous movement of a point below 2.2 cm cannot be defined as deformation and that a minimum 3.5 cm movement can be a significant movement with 95% confidence level. On the contrary, as it was seen from Figure 7, with 30 s or lower sampling rate data, smaller movements could be determined as significant since the two-dimensional positioning precision increases. The low-frequency data have increased the position accuracy and hence the small movements could be determined as significant deformations. However, it was difficult or impossible to obtain instant movement with sparse data, which was undesirable in seismogeodesy and monitoring engineering structures.

4. Conclusions

In this study, the accuracy of the PPP method as a function of data sampling rates has been investigated. For this purpose, a field test was conducted, and the coordinates of different scenarios were calculated by CSRS-PPP online post-processing service. The performance of the PPP technique with different sampling rates was analyzed and their results were compared.

According to the overall static and kinematic processing results, the mean differences between PPP and known coordinates were found at a few cm-level of accuracies for position and height components. The kinematic PPP results revealed that the differences between the coordinates derived from PPP and

Table 4. Standard deviation and RMSE of differences obtained for kinematic processing scenarios.

| Sampling rates (s) | Northing (cm) | Easting (cm) | 2D Pos. (cm) | Height (cm) |
|-------------------|--------------|--------------|-------------|------------|
|                   | Std. RMSE    | Std. RMSE    | Std. RMSE   | Std. RMSE  |
| 0.1 s             | 0.7 0.8      | 0.9 2.1      | 0.8 2.2     | 3.8 4.2    |
| 0.2 s             | 0.7 0.7      | 0.8 2.0      | 0.8 2.2     | 3.6 4.1    |
| 0.5 s             | 0.7 0.7      | 0.8 2.0      | 0.7 2.1     | 3.4 3.8    |
| 1 s               | 0.7 0.7      | 0.7 1.9      | 0.7 2.0     | 3.2 3.7    |
| 5 s               | 0.7 0.7      | 0.6 1.8      | 0.6 2.0     | 2.7 3.5    |
| 10 s              | 0.7 0.7      | 0.6 1.9      | 0.6 2.0     | 2.6 3.3    |
| 30 s              | 0.6 0.6      | 0.5 2.0      | 0.5 2.1     | 2.4 3.1    |
| 60 s              | 0.6 0.6      | 0.5 2.0      | 0.5 2.1     | 2.2 3.0    |
| 120 s             | 0.6 0.5      | 0.5 2.1      | 0.5 2.1     | 1.9 2.7    |

Figure 6. Standard deviation and RMSE of differences obtained for kinematic processing scenarios.
known values increased with higher data sampling intervals. In terms of precision and accuracy, it was found that the higher sampling rates produced relatively low-level PPP solutions in kinematic results.

The results of this study show that it was not necessary to collect GNSS data with high-rate intervals for many surveying projects requiring cm-level accuracy. Instead, 30 s or even lower data intervals like 60 s, or 120 s data intervals were found sufficient to obtain satisfactory results in static 4-h GNSS data observation. On the contrary, the high-rate GNSS PPP technique is essential to identify the 3D dynamic displacements of a wide range of engineering structures. This study indicated that high-rate PPP can accurately detect cm-level displacements in an absolute manner both in vertical and horizontal when the data were processed with the online processing service. Additionally, with the availability of the third version of the CSRS-PPP post-processing online service after 20 October 2020, faster convergence, higher accuracy, and ambiguity-fixed positioning will be obtained. With the updated version of the service, much smaller movements are expected to be detected as significant deformation.

These results imply that the PPP technique has become a strong alternative to the relative positioning method. In addition to this, with the advent of the high logging rates, GNSS receivers provide the high-rate PPP positioning. The high-rate real-time/post-processed PPP can be used in earth sciences and civil

Figure 7. 2D scatter plots for CSRS-PPP kinematic solutions for all intervals in 5 cm circle (Easting: horizontal axis, northing: vertical axis; the dashed red circle shows the 95% confidence level for the differences).
engineering to characterize the dynamic behaviors of a wide range of engineering structures and to monitor the earthquakes. The results reveal that high-rate PPP is a powerful tool for the identification of 3D dynamic displacements of a wide range of engineering structures that are under the effect of natural (i.e. wind) or human-sourced (i.e. traffic) loadings.

Acknowledgments

The authors greatly appreciate the NRCan for the CSRS-PPP (Canadian Spatial Reference System-Precise Point Positioning) online service. The authors also thank the editors and the anonymous reviewers for their valuable comments that significantly improved the quality of the manuscript.

Notes on contributors

Serdar Erol is an associate professor in the Geomatics Engineering Department at Istanbul Technical University (ITU), Turkey. His research areas include GNSS, engineering geodesy, spectral analysis, deformation monitoring and analysis, satellite altimetry, and height systems.

Reha Metin Alkan holds the PhD degree from the Istanbul Technical University (ITU), Turkey. He is currently serving as a full professor in Department of Geomatics Engineering at ITU. His area mainly covers satellite-based positioning, and engineering surveying.

I. Murat Ozulu is a PhD student in the Department of Geomatics, Yildiz Technical University, Turkey. His research interests include geodesy, GNSS, engineering surveying and geodetic documentation studies at archaeological sites.

Veli Ilci is working as an Assistant Professor at Ondokuz Mayas University in Turkey. His areas of research include multi sensor-based positioning, engineering surveying and GNSS applications.

ORCID

Serdar Erol https://orcid.org/0000-0002-7100-8267
Reha Metin Alkan https://orcid.org/0000-0002-1981-9783
I. Murat Ozulu https://orcid.org/0000-0002-0963-3600
Veli Ilci https://orcid.org/0000-0002-9485-874X

Data availability statement

The data that support the findings of this study are available from the corresponding author [S.E.,] upon reasonable request.

References

Alkan, R. M., V. Ilci, and I. M. Ozulu. 2016. "Web-based GNSS Data Processing Services as an Alternative to Conventional Processing Technique." Paper presented at the Proceedings of the FIG Working Week 2016, Christchurch, New Zealand, May 2–6.

Cai, C. 2009. "Precise Point Positioning Using Dual-Frequency GPS and GLONASS Measurements." MSc Thesis, Department of Geomatics Engineering, University of Calgary, Alberta, Canada. https://www.ucalgary.ca/engo_webdocs/YG/09.20291_ChangshengCai.pdf

Choy, S., S. Bisnath, and C. Rizos. 2017. "Uncovering Common Misconceptions in GNSS Precise Point Positioning and Its Future Prospect." GPS Solutions 21 (1): 13–22. doi: 10.1007/s10291-016-0545-x.

Choy, S., and K. Harima. 2019. "Satellite Delivery of High-accuracy GNSS Precise Point Positioning Service: An Overview for Australia." Journal of Spatial Science 64 (2): 197–208. doi: 10.1080/14498596.2018.1427155.

Dawidowicz, K., and G. Krzan. 2014. "Coordinate Estimation Accuracy of Static Precise Point Positioning Using On-line PPP Service, A Case Study." Acta Geodaetica et Geographia Hungarica 49 (1): 37–55. doi: 10.1007/s40328-013-0038-0.

Denys, P., A. Liggett, R. Odolinski, C. Pearson, D. Stewart, and R. Winefield. 2017. "Network RTK-New Zealand: A Summary of the Concepts, Methods, Limitations and Services in New Zealand." NZIS Positioning and Measurement. https://www.surveyspatialnz.org/Attachment/Action=Download&Attachment_id=3121

DeSanto, J. B., C. D. Chadwell, and D. T. Sandwell. 2019. "Kinematic Post-processing of Ship Navigation Data Using Precise Point Positioning." Journal of Navigation 72 (3): 795–804. doi: 10.1017/S0373463318000887.

Donahue, B., R. Ghoddousi-Fard, and Y. Mireault. 2014. "Current Status and Future Plans at the Natural Resources Canada (NRCan) Analysis Centre." Paper presented at the IGS Workshop 2014, Pasadena, California, USA, June 23–27.

Donahue, B., E. Hassen, and S. Banville. 2018. "CSRS-PPP-Transitioning to a Modernized Positioning Service in Canada." Canadian Geodetic Survey, Natural Resources Canada. ACLS Webinar, June 13. http://www.acls-aact.ca/wp-content/uploads/2018/06/CSRS-PPP-Transition-Plan-2018-ACLS-webinar.pptx

El-Mowafy, A. 2012. "Precise Real-Time Positioning Using Network RTK." In Global Navigation Satellite Systems: Signal, Theory and Applications, edited by S. Jin, 161–188. InTech Publishing. doi: 10.5772/29502.

Héroux, P., and J. Koubi. 2001. "GPS Precise Point Positioning Using IGS Orbit Products." Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy 26 (6–8): 573–578. doi: 10.1016/S1464-1899(01)00103-X.

Hofmann-Wellenhof, B., K. Legat, and M. Wieser. 2003. Navigation: Principles of Positioning and Guidance. 1st ed. Vienna-New York: Springer.

Jamieson, M., and D. T. Gillins. 2018. "Comparative Analysis of Online Static GNSS Postprocessing Services." Journal of Surveying Engineering 144 (4). doi: 10.1061/(ASCE)SU.1943-5428.0000256.

Kalogeropoulos, M. R., C. O. Yigit, and J. W. Hu. 2018. "Analysis of the Dynamic Behavior of Structures Using the High-rate GNSS-PPP Method Combined with a Wavelet-neural Model: Numerical Simulation and Experimental Tests." Advances in Space Research 61 (6): 1512–1524. doi: 10.1016/j.asr.2018.01.005.

Klisik, D., M. Szolucha, and K. Kroszczyński. 2018. "Accuracy of Precise Point Positioning (PPP) with the Use of Different International GNSS Service (IGS) Products and Stochastic Modelling." Geodesy and Cartography 67 (2): 207–238. doi: 10.24425/gac.2018.125472.

Krzan, G., K. Dawidowicz, and K. Świątek. 2014. "Comparison of Position Determination Accuracy Conducted by PPP Technique Using Web-Based Online
Service and Dedicated Scientific Software.” Paper presented at the 9th International Conference “Environmental Engineering”, Vilnius, Lithuania, May 22–23. doi:10.3846/enviro.2014.226.

Kudlacik, I., J. Kaplan, J. Bosy, and G. Lizurek. 2019. “Seismic Phenomena in the Light of High-rate GPS Precise Point Positioning Results.” Acta Geodynaemica et Geomaterialia 16 (1): 99–112. doi:10.13168/AGG.2019.0008.

Lipatnikov, L. A., and S. O. Shevchuk. 2019. Cost Effective Precise Positioning with GNSS. 82. Denmark: International Federation of Surveyors (FIG). https://www.fig.net/resources/publications/figpub/pub74/ Figpub74.pdf

Martín, A., A. B. Anquela, R. Capilla, and J. L. Berné. 2011. “PPP Technique Analysis Based on Time Convergence, Repeatability, IGS Products, Different Software Processing, and GPS+GLONASS Constellation.” Journal of Surveying Engineering 137 (3): 99–108. doi:10.1061/(ASCE)SU.1943-5428.0000047.

Mendez Astudillo, J., L. Lau, Y.-T. Tang, and T. Moore. 2018. “Analysing the Zenith Tropospheric Delay Estimates in On-line Precise Point Positioning (PPP) Services and PPP Software Packages.” Sensors 18 (2): 580. doi:10.3390/s18020580.

Miller, C., K. O’Keefe, and Y. Gao. 2012. “Time Correlation in GNSS Positioning over Short Baselines.” Journal of Surveying Engineering 138 (1): 17–24. doi:10.1061/(ASCE)SU.1943-5428.0000057.

Mireault, Y., P. Tétreault, F. Lahaye, P. Héroux, and J. Kouba. 2008. “Online Precise Point Positioning: A New, Timely Service from Natural Resources Canada.” GPS World 19 (9): 59–64.

Nischan, T. 2016. GFZRNX-RINEX GNSS Data Conversion and Manipulation Toolbox (Version 1.05). GFZ Data Services. doi:10.5880/GFZ.1.2016.002.

Odolinski, R. 2012. “Temporal Correlation for Network RTK Positioning.” GPS Solutions 16 (2): 147–155. doi:10.1007/s10291-011-0213-0.

Rizos, C., V. Janssen, C. Roberts, and T. Grinter. 2012. “Precise Point Positioning: Is the Era of Differential GNSS Positioning Drawing to an End?” Paper presented at the FIG Working Week 2012, 5909. Rome, Italy, 6–10 May.

Seepersad, G., and S. Bisnath. 2014. “Challenges in Assessing PPP Performance.” Journal of Applied Geodesy 8 (3): 205–222. doi:10.1515/jag-2014-0008.

Tang, X., X. Li, G. W. Roberts, C. M. Hancock, H. deLigt, and F. Guo. 2019. “1 Hz GPS Satellites Clock Correction Estimations to Support High-Rate Dynamic PPP GPS Applied on the Severn Suspension Bridge for Deflection Detection.” GPS Solutions 23 (2): Article:28. doi:10.1007/s10291-018-0813-z.

Tétreault, P., J. Kouba, P. Héroux, and P. Legree. 2005. “CSRS-PPP: An Internet Service for GPS User Access to the Canadian Spatial Reference Frame.” Geomatica 59 (1): 17–28. doi:10.5623/geomat-2005-0004.

Wang, G., F. Blume, C. Meertens, P. Ibanez, and M. Schulze. 2012. “Performance of High-Rate Kinematic GPS during Strong shaking: Observations from Shake Table Tests and the 2010 Chile earthquake.” Journal of Geodetic Science 2 (1): 15–30. doi:10.2478/jgss-2011-0020.

Xu, P., C. Shi, R. Fang, J. Liu, X. Niu, Q. Zhang, and T. Yanagidani. 2013. “High-rate Precise Point Positioning (PPP) to Measure Seismic Wave Motions: An Experimental Comparison of GPS PPP with Inertial Measurement Units.” Journal of Geodesy 87 (4): 361–372. doi:10.1007/s00190-012-0606-z.

Yigit, C. O. 2016. “Experimental Assessment of Post-processed Kinematic Precise Point Positioning Method for Structural Health Monitoring.” Geomatics, Natural Hazards and Risk 7 (1): 360–383. doi:10.1080/19475705.2014.917724.

Yigit, C. O., and G. Eralp. 2017. “Experimental Testing of High-rate GNSS Precise Point Positioning (PPP) Method for Detecting Dynamic Vertical Displacement Response of Engineering Structures.” Geomatics, Natural Hazards and Risk 8 (2): 893–904. doi:10.1080/19475705.2017.1284160.

Zumberge, J. F., M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb. 1997. “Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks.” Journal of Geophysical Research 102 (B3): 5005–5017. doi:10.1029/96JB03860.