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Accuracy comparison of post-processed PPP and real-time absolute positioning techniques

Reha Metin Alkan[a], Serdar Erol[a], I. Murat Ozulu[b] and Veli Ilci[b]

[a]Department of Geomatics Engineering, Istanbul Technical University, Istanbul, Turkey; [b]Technical Vocational School, Hitit University, Çorum, Turkey

ABSTRACT
The main motivation of this study is to assess the accuracy performance of the real-time global GNSS PPP positioning service, i.e. Trimble CenterPoint RTX, and online PPP post-processing service, i.e. CSRS-PPP, in Çorum Province of Turkey. Within this scope, a geodetic point was established and GNSS data were logged in static mode at a measurement interval of 1 Hz. At the same time, the real-time coordinates of each measurement epoch were determined with the Trimble CenterPoint RTX positioning service using L-band geostationary satellite delivery. The collected GNSS data were also sent to the CSRS-PPP service and the coordinates of each measurement epoch were calculated. According to comparison of the coordinates obtained from CenterPoint RTX to the known coordinates, it was concluded that the 3D real-time positioning achieved at centimeter-level of accuracy within convergence time of a few minutes. On the other hand, CSRS-PPP also provided centimeter-level accurate positioning with post-processing mode. The overall results show that, the attainable accuracy with both approaches provided the requirements of the many scientific and practical surveying applications.

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1. Introduction

Until recently, as a common way, carrier-phase-based differential GNSS method should be applied in order to make a positioning within centimeter-level of accuracy. However, this requires at least two GNSS receivers (at least one reference and one rover) and post-processing of the collected data with a proper GNSS data processing software. This procedure generally requires costly field operation besides further office work. It should be noted that, this method cannot be used for the real-time field applications. In 1990s, Real-Time Kinematic (RTK) GPS technique was introduced for accurate real-time positioning requirements. In this method, which is also called as Single-baseline RTK, the distance-dependent biases restrict the distance between rover and its base station to the limit of 10–20 km (El-Mowafy 2012). If long-range

CONTACT Serdar Erol erol@itu.edu.tr

RTK is used, the corrections are transmitted to the user via internet and/or GSM Network up to 50 km baseline length (Janssen 2009). The Network RTK (NRTK) has been developed to overcome the distance-dependent error sources by using a network solution of GNSS reference stations spread over a wide area (Rizos 2002). The requirement of nearby infra-structure (establishment of reference station, a communication link, power supply, security, field logistics and so on) for both Single-baseline and NRTK positioning is the main disadvantage of RTK positioning.

Latest developments on satellite and receiver systems and analyzing methods emerges some new techniques like Precise Point Positioning (PPP) in order to make positioning with high-accuracy in a more convenient way both in real-time and post-processing modes. PPP provides very accurate absolute positioning in static or kinematic modes, utilizing un-differenced pseudorange and carrier-phase observations collecting by only a single GNSS receiver along with precise satellite orbit and clock products with higher flexibility and cost-effectively on a global scale (Zumberge et al. 1997; Kouba and Héroux 2001; Kouba 2003; Anquela et al. 2013; Lou et al. 2016; Yigit 2016; Choy et al. 2017; Kouba et al. 2017; Krasuski et al. 2018a; DeSanto et al. 2019). However, the most important shortcoming of the technique is the requirement of long convergence time (typically needs about 30 minutes for achieving centimeter-level accuracy) to resolve ambiguities. Although such a long convergence time is limited to its applications in some surveying tasks (especially in real-time applications), the use of the PPP technique has increased day by day all over the world due to its several advantages like ease of use, high-accuracy, cost-effectiveness.

There are different methods for obtaining PPP-derived coordinates as follow;

- scientific or commercial GNSS processing software,
- web-based processing services,
- using in-house software coded by researchers.

Among them, web-based PPP services give an opportunity to users for estimating 3D coordinates because they offer free and un-limited access, without requirement of any GNSS processing software and knowledge. When the users with a valid e-mail address and an internet-connected computer send their GNSS data to the system via the web page of the relevant service or via e-mail/FTP, services automatically start to process and PPP-derived coordinates including report and some useful information are sent to the users via e-mail in a fairly short period of time. The online GNSS processing services are became as a strong alternative to traditional approaches.

In this study, one of the most widely used online processing services in the world, The Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) was used. According to the Donahue et al. (2018), the service has processed more than three million GNSS datasets (89% static and 11% kinematic modes) for approximately 6000 individual users in the world-wide since 2003. This free online service has been operated by the Geodetic Survey Division of Natural Resources Canada (NRCan) (Krasuski 2015). The collected single or dual frequency GNSS observations in static or kinematic modes are accepted. The CSRS-PPP provides cm-level solutions with converged float solutions (Grinter and Janssen 2012). Users just need to submit their

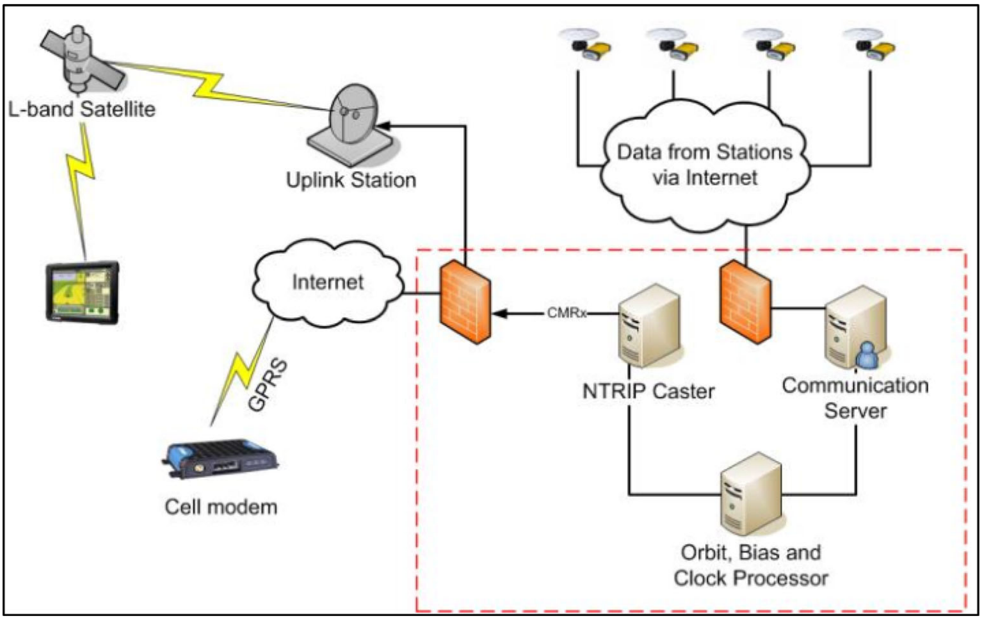

Figure 1. Workflow of the Trimble RTX system (Leandro et al. 2011).

collected GNSS data in Receiver Independent Exchange (RINEX) format and its variation, Compact RINEX, to the service through the service's user-friendly website. After uploading the collected GNSS data to the service, the estimated PPP-derived coordinates along with graphical analysis, comprehensive reports are sent to the valid e-mail address within minutes. It should be noted that, the coordinates are calculated at the current ITRF datum and epoch of the submitted GNSS data. The latest and detailed information about the CSRS-PPP service can be examined in Natural Resources Canada (2019).

The recent progresses in the real-time positioning technologies and applications enable the users to perform precise positioning on centimeter-level accuracy. Nowadays, there are some satellite and/or cellular/internet based GNSS correction services, which provide services commercially. One of them is real-time Trimble RTX (Real Time eXtended) global GNSS correction service that has been released in the US in mid-2011 for achieving 3D real-time absolute positioning within centimeter to metre level of accuracy depending on the correction type both in static or kinematic applications (Chen et al. 2011). There are four different products provided by Trimble RTX correction service as: CenterPoint, FieldPoint, RangePoint and ViewPoint. In this study, Trimble CenterPoint RTX among them was used. Hereafter the Trimble CenterPoint RTX will be referred to as 'Trimble RTX' or only 'RTX' within this study. In this service, the products and necessary corrections, like precise satellite orbits and satellite clocks, ionospheric and tropospheric models, code and phase biases, and other auxiliary information, are computed via the Trimble's worldwide multi-GNSS tracking network. This network has approximately 120 globally distributed reference stations and they broadcast to the user via L-band geostationary satellites or cellular/internet connections (Glocker et al. 2012). Nowadays, the system supports the GPS, GLONASS, Galileo, BeiDou and QZSS constellations. The ionosphere is modelled with the global ionospheric model since 2013 and this reduces the convergence time significantly (Nardo et al. 2015). The CenterPoint RTX convergence time is given as less than 15 minutes for world-wide and less than 1 minute in most of central North America and Europe (Turkey is not included). The Trimble global RTX system also employs a fast-start system that allows semi-instantaneous convergence by using a known starting position. This allows geometric distance in the equation to be known, leaving only the neutral atmosphere delay and the receiver clock as the solely unknowns. The RTX system stores the last position of the antenna and uses it as the known starting position when a new initialization is required. It is claimed that this technique can now achieve better than 2 cm horizontal and 5 cm vertical accuracy (RMS) depending on the atmospheric conditions, solar activity, obstructions, interference and user's location (Trimble 2019a). The schematic workflow of the Trimble RTX system is illustrated in Figure 1.

The basic phase and code measurement equations for the PPP solution are given as follows (El-Mowafy 2011; Leandro et al. 2011; Cai et al. 2015; Krasuski et al. 2018b):

$$\begin{aligned}\Phi_i = {} & \rho + c(dT - dt) + T - I_i + \lambda_i N_i + A_i - a_i + (W_\Phi - w_\Phi)\lambda_i \\ & + B_{\Phi_i} - b_{\Phi_i} + D + R + M_{\Phi_i} + n_{\Phi_i}\end{aligned} \tag{1}$$

and,

$$P_i = \rho + c(dT - dt) + T + I_i + A_i - a_i + B_{P_i} - b_{P_i} + D + R + M_{P_i} + n_{P_i} \tag{2}$$

where:

Φ_i and P_i: GNSS carrier-phase and pseudorange measurements for ith frequency (m), respectively,
ρ: geometric distance between receiver antenna and satellite (m)
c: speed of light in vacuum (m/s),
dT: receiver clock error (s),
dt: satellite clock error (s),
T: tropospheric delay (m),
I_i: ionospheric delay for ith frequency (m),
λ_i: carrier-phase wavelength for ith frequency (m),
N_i: integer carrier-phase ambiguity for ith frequency (cycles),
A_i: receiver antenna offset and directional variation correction for ith frequency (m),
a_i: satellite antenna offset and directional variation correction for ith frequency (m),
W_Φ: receiver antenna phase wind-up effect (cycles),
w_Φ: satellite antenna phase wind-up effect (cycles),
B_{Φ_i}: carrier-phase receiver bias for ith frequency (m),
B_{P_i}: pseudorange receiver bias for ith frequency (m),
b_{Φ_i}: carrier-phase satellite bias for ith frequency (m),
b_{P_i}: pseudorange satellite bias for ith frequency (m),

D: combined site displacement effects due to Earth, ocean tide and atmospheric loading (m),
R: relativistic effects (m),
M_{Φ_i}: carrier-phase multipath for ith frequency (m),
M_{P_i}: pseudorange multipath for ith frequency (m),
n_{Φ_i}: carrier-phase observation noise and other un-modelled effects for ith frequency (m),
n_{P_i}: pseudorange observation noise and other un-modelled effects for ith frequency (m).

The ionosphere-free combination of the different frequencies is constructing in order to mitigate the first-order error due to ionospheric delay in PPP technique. In this case, the PPP solution is computed using the so-called ionosphere-free equations that are expressed as (El-Mowafy 2011; Cai et al. 2015):

$$\Phi_{iono-free} = (f_1^2.\Phi_1 - f_2^2.\Phi_2)/(f_1^2 - f_2^2) \tag{3}$$

$$\mathrm{P}_{iono-free} = (f_1^2.P_1 - f_2^2.P_2)/(f_1^2 - f_2^2) \tag{4}$$

In these equations, $\Phi_{iono-free}$ and $\mathrm{P}_{iono-free}$ are the ionosphere-free carrier-phase and pseudorange measurements (m), respectively, and, f_1 and f_2 are the carrier-phase frequencies (Hz).

A number of GNSS-related effects and corrections like antenna offset and directional variation corrections; satellite and receiver clock errors; tropospheric and ionospheric delays; site displacement effects; phase wind-up effects; relativistic effects; polar motion; code and carrier-phase biases and the others should be accounted in order to obtain global cm-level accurate positioning in Trimble CenterPoint RTX. The technical details and methodology on modelling of all these effects have been described in literatures such as Leandro et al. (2011), Glocker et al. (2012).

The use of this service has been increasing in different application areas with having many advantages provided to users all over the world (Chen et al. 2011; Glocker et al. 2012; Leandro et al. 2012; Nardo et al. 2015; Ochałek et al. 2018; dos Santos et al. 2019; İlçi 2019).

2. Case study

In order to assess the accuracy performance of the Trimble CenterPoint RTX real-time PPP positioning service and the CSRS-PPP online GNSS post-processing service, a test measurement was conducted in Çorum City, Turkey on 2nd August, 2017 (Day of Year 214). Within this test procedure, a geodetic point that has a very high clear sky visibility in all directions and clear of obstacles and potential multipath sources was established (Figure 2).

For the test measurement, the data were collected about 70 minutes at 1 second interval, which gives about 4,200 measurement epochs, by observing all available GPS, GLONASS, BDS and Galileo satellites with 10° elevation mask in static mode.

Figure 2. The study area (*left*) and test measurement (*right*).

In this test, Trimble R10 GNSS receiver with internal antenna was used. This multi-constellation and multi-frequency receiver is capable of receiving Trimble CenterPoint RTX corrections. The main accuracy and convergence specification of the R10 receiver is given in Table 1.

After the CenterPoint RTX solutions converges to cm-level of accuracy within a few minutes by starting the measurement with known points using quick start mode, the static test was then started. While the raw data were being logged into GNSS receiver for later processing, the real-time coordinates of each measurement epoch were simultaneously determined as ambiguity-fixed solution with the Trimble CenterPoint RTX GNSS correction service by observing all available GNSS satellites including GPS (G), GLONASS (R), Galileo (E) and BDS (C). Through the measurement, minimum, average, and maximum total tracked satellite numbers and PDOP values were found as 22, 23, 25 and 1.1, 1.2, 1.3, respectively (Figure 3). The total tracked satellite number and PDOP values for both the CenterPoint RTX and CSRS-PPP service were separately depicted in the Figure 3.

After the test measurement was completed, the collected data in RINEX format were submitted to the CSRS-PPP post-processing service by choosing kinematic mode. Shortly after the file was uploaded to the service, the PPP-derived coordinates in the ITRF datum and some other reports, graphs, and documents were retrieved via e-mail from the services. According to the CSRS-PPP results, it was obtained that the used number of total GPS (G) and GLONASS (R) satellites was found 14, 15, and 17, as minimum, average, and maximum, respectively. On the other hand, the PDOP values were found 1.2, 1.3, and 1.4 as minimum, average, and maximum, respectively (Figure 3).

The options that used through CSRS-PPP processing stage is given in Table 2.

It is important to emphasize that, CSRS-PPP uses the combination of GPS + GLONASS satellites data. However, the service plans to be made in the near future include all GNSS constellations and signals (GeoED 2019). On the contrary, real-time RTX is able to determine real-time coordinates from all observations on all available satellites.

In order to figure out the precision (internal accuracy) of the Trimble CenterPoint RTX and CSRS-PPP services, the measured/calculated coordinates are compared to their own mean values as scatter plot (Figure 4).

In order to inspect the distributions of calculated easting, northing and height differences, histograms are constructed for each solution. For this purpose, the

Table 1. Positioning performance of the used GNSS receiver (Trimble 2019b).

Surveying Mode	Accuracy / Convergence Time	
Static GNSS Surveying	*High Precision Static*	
	Horizontal	3 mm + 0.1 ppm RMS
	Vertical	3.5 mm + 0.4 ppm RMS
	Static and Fast Static	
	Horizontal	3 mm + 0.5 ppm RMS
	Vertical	5 mm + 0.5 ppm RMS
Trimble RTX Technology (Satellite and Cellular/Internet (IP))	*CenterPoint RTX*	
	Horizontal	2 cm RMS
	Vertical	5 cm RMS
	RTX convergence time for specified precisions – World-wide	<15 minutes
	RTX QuickStart convergence time for specified precisions	<1 minute
	RTX convergence time for specified precisions in selected regions (Trimble RTX Fast Regions)	<1 minute

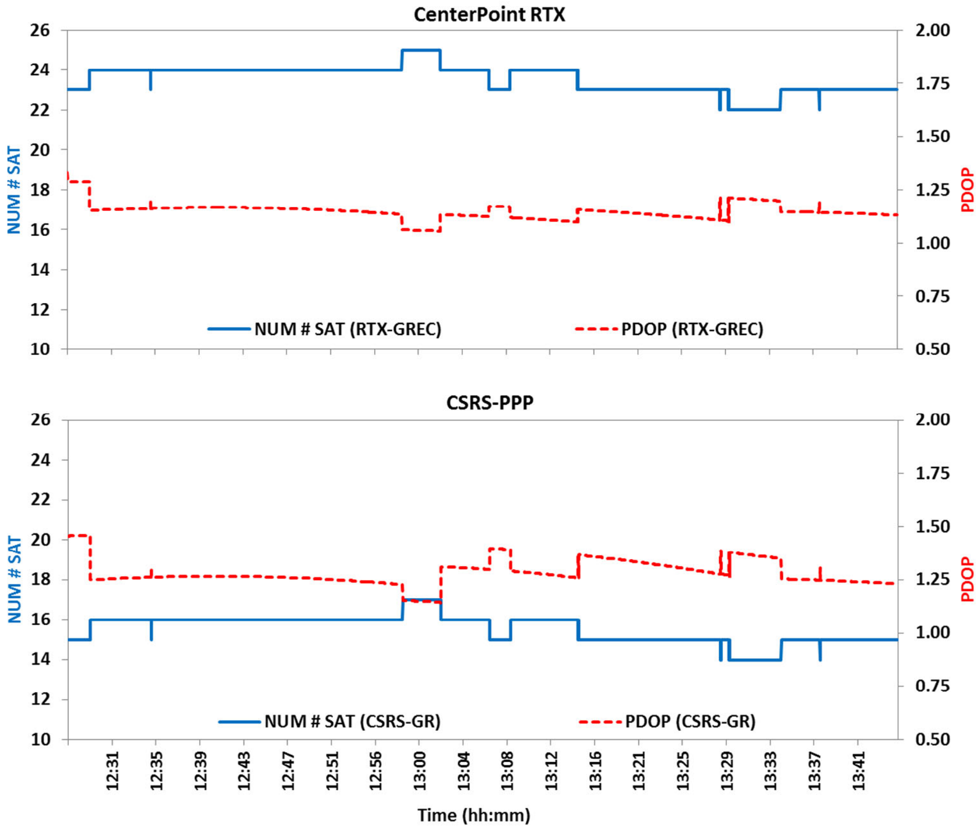

Figure 3. The total number of satellites and PDOPs for solutions.

differences split into 10 bins. The histograms provide visual representations (distributions) of differences between the Trimble CenterPoint RTX and CSRS-PPP solution with their own mean values separately (Figure 5).

As can be seen from the Figure 5, according to this study, the differences were found in the range of approximately −3 cm to 3 cm for easting and northing

Table 2. The used processing options for CSRS-PPP service.

Used Software	CSRS-PPP GPSPACE v1.05 11216
Processing Mode	Kinematic
GNSS System	GPS + GLONASS
Frequency Observed	L3
Observation Processed	Code&Phase
Observation Interval (second)	1
Cut-off Elevation (deg)	10
Satellite Orbits and Clocks	IGS Final Precise
Ionospheric Model	L1&L2 Default
Pseudorange Residuals (m)	0.95 for GPS, 1.46 for GLONASS
Carrier Phase Residuals (cm)	0.83 for GPS, 0.87 for GLONASS
Phase-center Corrections	IGS (ATX)
P1-C1 bias	Applied
P2-C2 bias	Applied
Phase wind-up	Modelled
Solid Earth and Polar Tides	Modelled
Clock Interpolation	Yes
Parameter Smoothing	Yes
Cycle-slip Filtering	Yes
Reference Frame	ITRF
Marker (Station) Coordinates	Estimated
Troposphere Zenith Delay (TZD)	Estimated
Receiver Clock Offset	Estimated
Carrier-phase Ambiguity Term	Estimated

components whereas for height component is almost twice worsened, i.e. within −6 cm to 6 cm.

In order to make accuracy assessment of Trimble CenterPoint RTX real-time kinematic PPP and post-processed CSRS-PPP kinematic solutions, the coordinates of the established geodetic point were calculated with conventional carrier-phase-based relative method by taking nearest TUSAGA-Aktif (or Turkish RTK CORS Network/CORS-TR) points as reference stations. The necessary data were downloaded from the service's website (http://www.tusaga-aktif.gov.tr/). All the data were post-processed and coordinates were calculated with GrafNav commercial post-processing software. This software is capable of processing the multi-GNSS data collected in static and kinematic modes.

The coordinates of the geodetic point that calculated in the ITRF datum were accepted as the true value and the CenterPoint RTX-derived and CSRS-PPP-derived coordinates were compared for horizontal and vertical components. The corresponding differences in easting, northing, 2D-position and height components are shown in Figure 6, and the statistical results are given in Table 3.

According to Figure 6 and Table 3, for CenterPoint RTX real-time correction service, the difference between the known values reaches up to 24 cm at the beginning of the measurement. As mentioned above, requirement for convergence time is one of the most important drawbacks of the PPP technique. It can be clearly seen from Figure 6 that the initial convergence time of PPP solution was about 5 minutes. After this period, notably better results were achieved. Note that, this is not the case for the post-processing CSRS-PPP service because it uses the forward and backward processing strategy when the kinematic option is selected (Alkan et al. 2017). According to this study, the results show that, it is possible to make positioning with the Trimble CenterPoint RTX service with a difference of 5.5 cm or better (with an error of ±