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Multi-GNSS Kinematic Precise Point Positioning: Some Results in South Korea

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ABSTRACT

Precise Point Positioning (PPP) method is based on dual-frequency data of Global Navigation Satellite Systems (GNSS). The recent multi-constellations GNSS (multi-GNSS) enable us to bring great opportunities for enhanced precise positioning, navigation, and timing. In the paper, the multi-GNSS PPP with a combination of four systems (GPS, GLONASS, Galileo, and BeiDou) is analyzed to evaluate the improvement on positioning accuracy and convergence time. GNSS observations obtained from DAEJ reference station in South Korea are processed with both the multi-GNSS PPP and the GPS-only PPP. The performance of multi-GNSS PPP is not dramatically improved when compared to that of GPS only PPP. Its performance could be affected by the orbit errors of BeiDou geostationary satellites. However, multi-GNSS PPP can significantly improve the convergence speed of GPS-only PPP in terms of position accuracy.

Keywords: PPP, multi-GNSS, Positioning accuracy, convergence speed

1. INTRODUCTION

Precise Point Positioning (PPP) using the Global Navigation Satellite System (GNSS) can determine positioning of users from several millimeters to a few centimeters (cm) if dual-frequency observation data are employed (Zumberge et al. 1997). Since the PPP technique can achieve high accuracy of positioning, it has been widely used in precise orbit determination of low-orbit satellites, precise timing, and GNSS meteorology (Kouba & Heroux 2001, Gao & Shen 2002, Zhang & Andersen 2006, Geng et al. 2010).

In recent years, the European Union (EU) and China have launched their own global satellite navigation systems: Galileo and BeiDou, so that the use of PPP through multi-system has been increased (Dach et al. 2009, Melgard et al. 2009, Cai & Gao 2013, Chen et al. 2015). The Global Positioning System (GPS) has been modernized steadily and Russia has also operated the GLObal NAvigation Satellite System (GLONASS) stably since 2012. Furthermore, the EU has launched the 12th Galileo satellite recently indicating the global satellite navigation system is now entering a final stage of full operation rapidly. BeiDou in China has started positioning, navigation and timing (PNT) services in Asia-Pacific region from the late 2012. In particular, it aims to provide full operational capability by 2020 and has invested heavily in launching satellites and improving performance in navigation systems.

The multi-GNSS PPP, which combines all existing global satellite navigation systems, can improve positioning accuracy and convergence speed due to the use of a large number of observation data compared with using a GPS-only PPP. Li et al. (2015) developed a PPP model using four different navigation systems (GPS + GLONASS + Galileo + BeiDou). They reported the results that multi-GNSS static PPP had improved positioning accuracy by about 25% and convergence speed by about 70% compared with those using GPS-only static PPP. Ren et al. (2015)

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presented that PPP performance had improved in multi-GNSS PPP compared with GPS-only PPP. In particular, mean positioning accuracy in the horizontal and vertical directions had improved by 20% and 30%, respectively. Seepersad & Bisnath (2014) reported that GPS static PPP took around 20 minutes (min) to reach 20 cm or less horizontal positioning accuracy within 95% confidence level and GPS kinematic PPP took longer convergence speed than GPS static PPP. Particularly, they presented that at least 60 min convergence speed was required to obtain a 5 cm or less horizontal positioning accuracy statistically.

In order to determine user position accurately through the PPP method, precise orbit and clock products of navigation satellite must be available. Similarly, it is also necessary to have precise information about not only existing GPS and GLONASS orbit and clock products but also precise products about Galileo and BeiDou in order to perform multi-GNSS PPP. International GNSS Service (IGS) has provided precise orbit and clock products of multi-GNSS through the Multi-GNSS Experiment campaign. In particular, IGS Analysis Centers at GeoForschungs Zentrum in Germany, Wuhan University in China, and Center for Orbit Determination in Europe in Switzerland provide orbit and satellite clock products of Galileo and BeiDou satellites, so that data of Multi-GNSS PPP can be processed.

The present study introduces a strategy required for multi-GNSS PPP and analyzes positioning accuracy and convergence speed of multi-GNSS PPP using measurements of different navigation systems received at the GNSS reference station in the Korea Astronomy and Space Science Institute. In addition, the results of multi-GNSS PPP are compared to those of GPS PPP.

2. MULTI-GNSS PPP PROCESSING STRATEGY

In order to perform PPP using measurements of different navigations systems received at GNSS receivers, it is necessary to select dual-frequency for each navigation satellite system. The present study employs L1 (1575.42 MHz) and L2 (1227.60 MHz) of the GPS and frequencies calculated through Eqs. (1) and (2) using frequency division multiple access.

$$L1 = (1602 + k \times 0.5625)\ \text{MHz} \tag{1}$$

$$L2 = (1246 + k \times 0.4375)\ \text{MHz} \tag{2}$$

Here, k (k = 0,1,2,...) refers to a frequency channel number.

The Galileo signal employs E1 (1575.42 MHz) and E5a (1176.45 MHz), and the BeiDou signal employs B1 (1561.098 MHz) and B2 (1207.14 MHz). The reason for using dual-frequency data in PPP data processing is to remove an ionospheric error, which is regarded as the largest error when the navigation signals of GNSS transmit from a satellite to a receiver (Kouba & Heroux 2001, Geng et al. 2010). The measurement equation for removing the ionospheric error is presented in Eq. (3) (Odijk 2003).

$$L_{IF} = \frac{f_1^2}{f_1^2 - f_2^2} L1 - \frac{f_2^2}{f_1^2 - f_2^2} L2 \tag{3}$$

Here, L_{IF} refers to observables derived by the ionosphere-free linear combination, and f_1 and f_2 refer to different frequencies of navigation systems.

A variety of models and methods should be considered to obtain precise positioning solution through PPP data processing. For the tropospheric dry delay, which is one of the important estimate variables, the Saastamoinen model (Saastamoinen 1973) and global mapping function (GMF) developed by Boehm et al. (2006) were applied. For the meteorological information (temperature and pressure) required as input values of the Saastamoinen model, global pressure and temperature 2 (GPT2) model developed by Lagler et al. (2013) was employed. Furthermore, a tropospheric gradient component (G_N, G_E) in the horizontal direction was designed to be estimated to improve accuracy of wet delay. For a phase center offset (PCO) of satellite antenna for each navigation system, a PCO of receiver, and a phase center variation (PCV), information provided by igs08.atx was used and bi-linear interpolation technique was used to interpolate a PCV. Additionally, models and methods applied for PPP are presented in Table 1 in detail. The variable vector calculated through multi-GNSS PPP data processing can be expressed as shown in Eq. (4).

$$X = (x, y, z, dtr, ZWD, G_N, G_E, ISB_R, ISB_E, ISB_C, N) \tag{4}$$

Here, x, y, and z refer to a receiver position; dtr refers to a clock error of the receiver; Zenith Wet Delay (ZWD) is a tropospheric wet delay value; ISB_R, ISB_E, and SB_C refer to the inter-system biases of GLONASS, Galileo, and BeiDou on the basis of the GPS system. N refers to phase ambiguity parameter.

3. RESULTS AND ANALYSIS

In order to analyze positioning accuracy at the receiver estimated by the multi-GNSS PPP, data obtained from Daejeon (DAEJ) GNSS reference station in the Korea

Table 1. Multi-GNSS PPP processing strategy.

Item	Models / Methods
Observations	Un-differenced ionospheric free linear combination
Signal	GPS: L1/L2; GLONASS: L1/L2; Galileo: E1/E5a; BeiDou: B1/B2
Elevation cutoff	7o
Sampling rate	30 sec
Satellite orbit and clock, ERP parameters	GeoForschungs Zentrum products
Satellite PCO	igs08.atx
Receiver PCO/PCV	igs08.atx
Phase wind-up	Considered by Wu et al. (1993)
Solid tide, ocean tide, pole tide	IERS conventions 2010
Receiver clock	Estimated
Ionosphere	Eliminated by LC
ZWD	Estimated with gradients
Mapping function	GMF/GPT2
Integer ambiguity	Float solutions
ISB	Estimated
Estimator	EKF with 3-pass filter

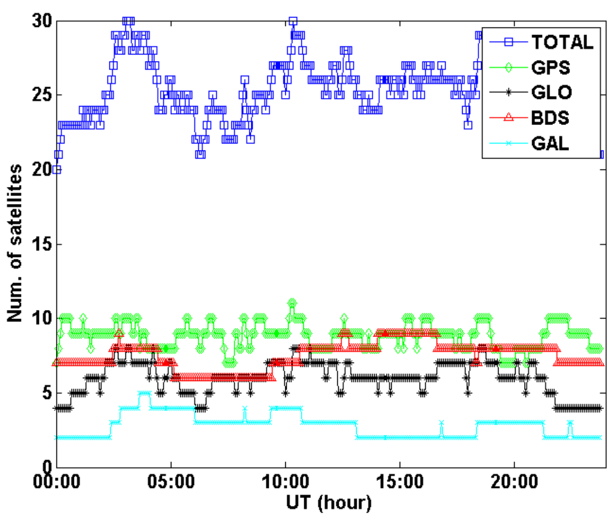

Fig. 1. Diurnal variations of the number of GNSS satellites tracked at 'DAEJ' reference station in South Korea on May 1, 2016.

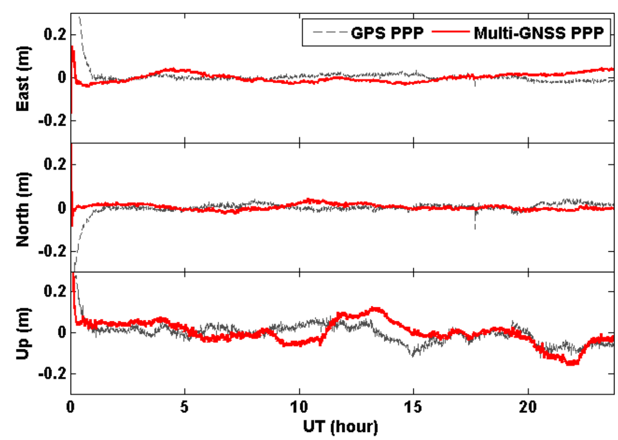

Fig. 2. Comparison of position errors between GPS kinematic PPP and multi-GNSS kinematic PPP. The position errors estimated by the multi-GNSS kinematic PPP are shown by red line, while those of GPS kinematic PPP are represented by gray dashed line.

Astronomy and Space Science Institute were processed. Furthermore, the results were compared with that of GPS-only PPP to compare a convergence speed of the initial position. The processing period of the GNSS observation data was 31 days from May 1 to 31, 2016 and data processing was done every 30 sec.

First, satellite data received at the DAEJ GNSS reference station on May 1, 2016 were analyzed to determine visibility about navigation satellites over the Korean Peninsula. Fig. 1 shows the change in the number of GNSS navigation satellites received for a day. At least 20 up to 30 navigation satellites were observed at the DAEJ GNSS reference station. Except for Galileo satellite in the EU, at least four satellites were observed regardless of temporal change in all of GPS, GLONASS, and BeiDou. It is remarkable that more BeiDou satellites were observed on average than GLONASS satellites over the Korean Peninsula in recent years.

Fig. 2 shows a time series of positioning error at the reference station estimated via multi-GNSS PPP and GPS-only PPP, using data received for a day from DAEJ reference station on May 1, 2016, respectively. In the figure, GPS PPP and multi-GNSS PPP are marked with gray dotted line and red solid line, respectively. The IGS analysis data was used for an accurate coordinate in the DAEJ reference station in order to ensure reliability of positioning error. Fig. 2 can be analyzed from two different points of view. First, positioning accuracy can be compared according to different data processing methods. Although multi-GNSS PPP that combined data of GPS+GLONASS+Galileo+BeiDou navigation satellites was expected to have better positioning accuracy than that of GPS PPP, a root mean square (RMS) value increased from 1.05 cm to 1.81 cm and from 3.81 cm to 4.93 cm in the east and up directions, respectively, indicating positioning accuracy degradation instead. That

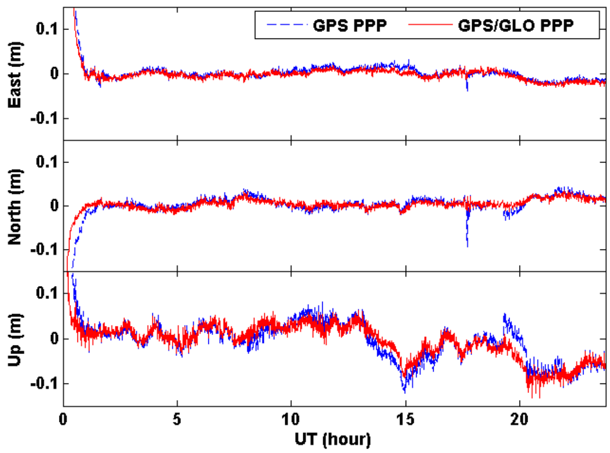

Fig. 3. Comparison of position errors between GPS PPP and combined GPS/GLONASS PPP. The GPS/GLONASS PPP is plotted by red line. The GPS PPP is displayed by blue dashed line.

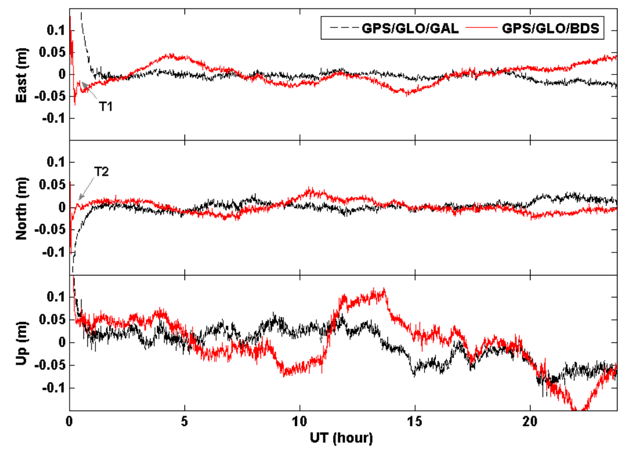

Fig. 5. Comparison of position errors between combined GPS/GLONASS/Galileo PPP and GPS/GLONASS/BeiDou PPP. The GPS/GLONASS/Galileo PPP is plotted by red line. The GPS/GLONASS/Galileo PPP is represented by black dashed line.

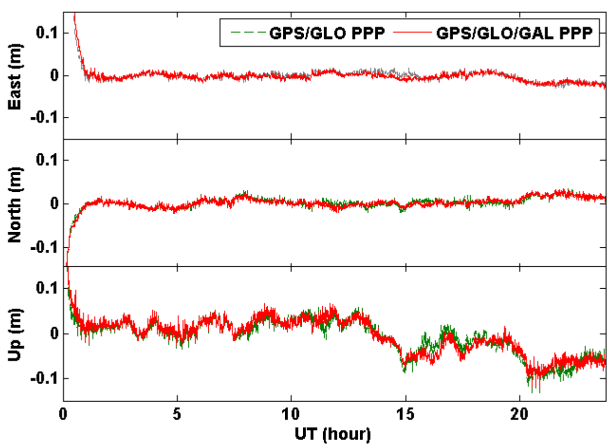

Fig. 4. Comparison of position errors between GPS/GLONASS PPP and GPS/GLONASS/Galileo PPP. The GPS/GLONASS/Galileo PPP is plotted by red line. The GPS/GLONASS is represented by green dashed line.

is, the results in Fig. 2 suggest that multi-GNSS PPP cannot expect improvements on positioning accuracy compared with GPS PPP. Furthermore, in order to analyze the cause, PPP data processing that combined GPS and GLONASS was implemented.

Fig. 3 shows a comparison of positioning error estimated by GPS-only PPP and GPS/GLONASS PPP over time. An RMS value of positioning error in GPS/GLONASS PPP was improved within the 95% confidence level in the components of east-west direction, south-north direction, and up-down direction from 1.05 cm to 0.96 cm, from 1.26 cm to 0.98 cm, and 3.81 cm to 3.48 cm, respectively, compared with those in GPS PPP. The improvement on positioning accuracy due to GPS/GLONASS PPP was also reported by Choi et al. (2014). Thus, the combination of GPS and GLONASS is found not as the cause of the degradation in positioning accuracy. Next, PPP data processing that combined GPS, GLONASS, and Galileo was conducted. Fig. 4 shows a comparison of PPP results between GPS/GLONASS PPP and GPS/GLONASS/Galileo PPP. Even if Galileo-observed information was integrated with GPS and GLONASS combination, no significant effect was revealed in PPP results. This result may be due to not many Galileo satellites observed over the Korean Peninsula. In order to more clearly distinguish the effect of BDS, results of GPS/GLONASS/Galileo PPP and GPS/GLONASS/BeiDou PPP were compared. Fig. 5 shows time series of positioning error according to the above combinations, respectively. The results of GPS/GLONASS/BeiDou combination, which was marked with red solid line, increased RMS values significantly, particularly in the east-west direction and up direction from 0.90 cm to 2.01 cm and from 3.60 cm to 5.36 cm. Based on the above results, BeiDou was found as significantly influential on positioning accuracy. In contrast, BeiDou was found influential on initial convergence speed of user positioning determination as shown in T1 and T2 marked in Fig. 5.

From the results of Figs. 2 and 5, the reason for not improving on positioning accuracy in multi-GNSS PPP was due to the effect of the BDS (BeiDou) navigation system. According to the IGS technical report in 2015, an along-track orbit error of the BeiDou satellite located in the geostationary orbit was more than 2 meter reportedly. Accordingly, such large orbit error in the BeiDou satellite was regarded as influential on the performance of multi-GNSS PPP. In particular, since an orbit error of the BeiDou satellite (Geostationary Earth Orbit, GEO) located in the geostationary orbit was larger than those of Medium Earth Orbit satellite and Inclined Geo-Synchronous Orbit satellite,

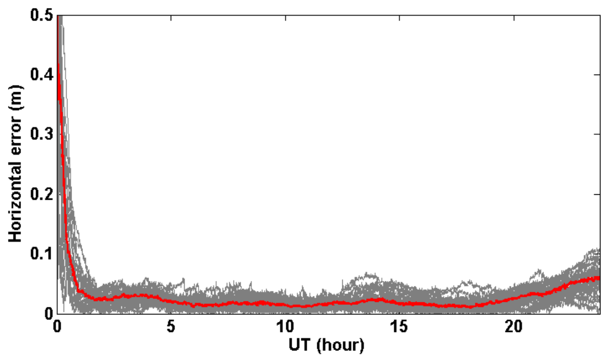

Fig. 6. The horizontal errors estimated by Multi-GNSS PPP for 31 days from May 1 to May 31, 2016. The gray lines indicate the position results. The red line represents the median value of them.

it may be a critically influential factor to the performance of multi-GNSS PPP.

Second, initial convergence speed in multi-GNSS PPP was significantly faster than that of GPS PPP as shown in Fig. 2. In particular, a fast convergence speed in the east and north, which were horizontal direction component, was observed. A convergence speed is one of the important factors since it helps to improve positioning stability in PPP. The following methods: integer ambiguity resolution, use of multi-GNSS, higher order ionospheric effects, and numerical weather model have been adopted to make the convergence speed faster in recent years (Elmas et al. 2011, Li & Zhang 2015, Rabbou 2015, Lu et al. 2016). In the present study, a convergence speed was calculated using multi-GNSS and the results were compared with those of GPS PPP.

Fig. 6 shows a time series of positioning error in the horizontal direction calculated by multi-GNSS PPP from May 1 to 31, 2016. The positioning error in the horizontal direction processed daily for 31 days is marked with a gray dotted line while a red dotted line depicts a converted median value of the positioning error. The positioning error in the horizontal direction was calculated using Eq. (5).

$$\mathrm{H}_{err} = \sqrt{(North_{err})^2 + (East_{err})^2} \qquad (5)$$

Fig. 7 shows the comparison of initial convergence speed between multi-GNSS PPP and GPS-only PPP. The error of GPS PPP in the horizontal direction was also calculated with the method presented in Fig. 6. In Fig. 7, t1 and t2 refer to a time where an error in the horizontal direction is converged within 20 cm, and t3 and t4 refer to a time where an error is converged within 5 cm, respectively. t1 and t2, which are a time where an error is converged within 20 cm calculated by the two methods, were 9.6 min and 21.0 min, respectively. Furthermore, t3 and t4, which are a time where an error is converged within 5 cm, were calculated as 26.4 min and 48.0 min, respectively. Based on the above result, multi-GNSS PPP played an important role in improving a convergence speed more than GPS-only PPP did, which was approximately twice faster.

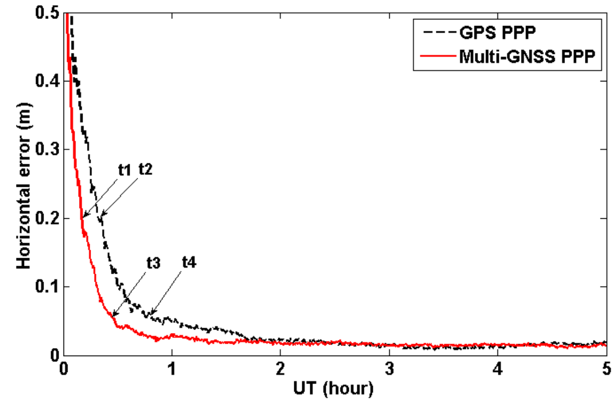

Fig. 7. Comparison of convergence times between GPS PPP and Multi-GNSS PPP. The marked t1 and t2 indicate a convergence time to reach a horizontal accuracy of 20 cm, respectively. The t3 and t4 are a time to converge to 5 cm with different methods.

4. CONCLUSIONS

The present study analyzed user's positioning accuracy utilizing multi-GNSS PPP. Positioning accuracy using multi-GNSS PPP was expected to be improved. However, positioning accuracy in a certain specific direction was rather decreased compared with that of GPS PPP. To analyze the cause of the decrease, each of PPP data processing on the following combinations of GPS+GLONASS, GPS+GLONASS+Galileo, and GPS+GLONASS+BeiDou was conducted. The analysis on different combinations of PPP showed that the reason for the reduction in positioning accuracy was due to the BeiDou navigation satellite. Tan et al. (2016) conducted precision orbit determination of the BeiDou satellite in recent years, in which an orbit error of BeiDou C01–C05 located in the geostationary orbit was large enough still. Ultimately, it was expected that the result of multi-GNSS PPP proposed in the present study was affected by the orbit error of satellite located in the geostationary orbit among the BeiDou satellites.

The user's positioning accuracy did not improve through multi-GNSS PPP but a convergence speed was certainly improved. A time where an error in the horizontal direction was converged within 20 cm and 5 cm was calculated, respectively, thereby comparing the results between multi-GNSS PPP and GPS PPP. A convergence speed in multi-GNSS PPP was twice faster at both sections than that of GPS PPP.

For the future study, not only positioning accuracy but also convergence speed will be improved through multi-GNSS PPP since more signals of navigation satellites will be observed over the Korean Peninsula than the present.

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