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Precise Point Positioning using the BeiDou Navigation Satellite System in South Korea

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ABSTRACT

Global Positioning System (GPS) Precise Point Positioning (PPP) has been extensively used for geodetic applications. Since December 2012, BeiDou navigation satellite system has provided regional positioning, navigation and timing (PNT) services over the Asia-Pacific region. Recently, many studies on BeiDou system have been conducted, particularly in the area of precise orbit determination and precise positioning. In this paper PPP method based on BeiDou observations are presented. GPS and BeiDou data obtained from Mokpo (MKPO) station are processed using the Korea Astronomy and Space Science Institute Global Navigation Satellite System (GNSS) PPP software. The positions are derived from the GPS PPP, BeiDou B_1/B_2 PPP and BeiDou B_1/B_3 PPP, respectively. The position errors on BeiDou PPP show a mean bias < 2 cm in the east and north components and approximately 3 cm in the vertical component. It indicates that BeiDou PPP is ready for the precise positioning applications in the Asia-Pacific region. In addition, BeiDou tropospheric zenith total delay (ZTD) is compared to GPS ZTD at MKPO station. The mean value of their difference is approximately 0.52 cm.

Keywords: BeiDou, GPS, positioning error, root mean square

1. INTRODUCTION

Precise point positioning (PPP) was developed in the mid-1990s by the Jet Propulsion Laboratory in the United States. PPP is a method that independently calculates the position of a receiver at high accuracy without the correction information of a Global Positioning System (GPS) reference station (Zumberge et al. 1997). However, as PPP requires accurate information (e.g., satellite orbit and satellite clock error), its usage has been limited compared to the real-time kinematic.

To obtain 1~2 cm level user position accuracy through PPP, satellite orbit (*.sp3), satellite clock (*.clk), and earth rotation parameter (*.erp) that are provided by the international Global Navigation Satellite System (GNSS) analysis centers are basically required. In particular, due to the steady improvement in the accuracy of final products provided by the GNSS analysis centers, the position of a user can be more precisely calculated using PPP. The performance of GPS PPP for position determination has already been presented in many reports (Zumberge et al. 1997, Kouba & Héroux 2001, Gao & Shen 2002, Geng et al. 2010a).

In the late 2000s, PPP using the GLObal NAvigation Satellite System (GLONASS) (i.e., Russian navigation satellites) was introduced, and the performance of combined PPP with GPS was also presented (Li et al. 2009, Tolman et al. 2010). In addition, after 2012, China independently developed the BeiDou satellite navigation system. It is currently consisted of 14 satellites, and provides positioning and navigation service although it is limited to some regions. In particular, the GeoForschungs Zentrum in Germany and Wuhan University in China provide accurate products for the orbit and clock of BeiDou navigation satellites, and thus PPP experiment is possible.

Recently, Shi et al. (2012) and Montenbruck & Steigenberger (2013) performed precise orbit determination of BeiDou satellites, and directly applied to a kinematic

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PPP experiment with the calculated satellite orbit and clock information. They reported that the horizontal error was about 5 cm and the vertical error of the static PPP was up to 12 cm because the precision of the calculated orbit (10~20 cm level) and clock information of the navigation satellites was low due to limited BeiDou reference stations. Through a static PPP experiment, Zhao et al. (2013) showed that the horizontal error was less than 1 cm and the vertical error was about 3 cm for a reference station located at the southern region of China.

In this study, BeiDou data received at the Mokpo (MKPO) reference station were processed using the GNSS PPP software developed by the Korea Astronomy and Space Science Institute, and the position of the GNSS reference station was determined. Its performance was also analyzed by comparing the BeiDou kinematic PPP result with the GPS kinematic PPP result.

2. BEIDOU MEASUREMENTS AND PROCESSING STRATEGY

BeiDou navigation satellites transmit three frequencies (B_1 ~ 1561.098 MHz, B_2 ~ 1207.14 MHz, and B_3 ~ 1268.52 MHz) to users. To accurately estimate the position of a user based on PPP, dual frequency observation data are used to eliminate ionospheric error which is the largest error in the signals transmitted from GNSS satellites to the receiver (Kouba & Héroux 2001, Geng et al. 2010b). Similar to GPS signals, BeiDou signals consist of code and carrier phase. If they are linearly combined as shown in Eq. (1), more than 99% of ionospheric error can be eliminated.

$$B_{IF} = \frac{f_1^2}{f_1^2 - f_{2,3}^2} B_1 - \frac{f_{2,3}^2}{f_1^2 - f_{2,3}^2} B_{2,3} \quad (1)$$

where B_{IF} represents the observed value after ionosphere-free linear combination, and f_1, f_2, and f_3 represent the B_1, B_2, and B_3 frequencies, respectively. In this study, each position calculation was performed using two dual frequency combinations (i.e., B_1/B_2 and B_1/B_3).

The parameters that are calculated using PPP data processing include reference station coordinates, zenith wet delay (ZWD), receiver clock bias, and carrier phase float ambiguities. In this regard, zenith total delay (ZTD) was calculated as the sum of the zenith hydrostatic delay (ZHD) estimated by the Saastamoinen model and the global mapping function and of the ZWD estimated by the PPP. The input parameters necessary for the calculation of ZHD were also obtained by the global pressure and temperature model (Boehm et al. 2007). For the phase center offset (PCO) of the BeiDou satellite antenna, the values (0.634 m, -0.003 m, and 1.075 m) provided by the satellite manufacturer were applied; and the PCO and phase center variation (PCV) of the receiver were not considered in the PPP data processing since relevant information had not been provided. Table 1 summaries the models for BeiDou PPP.

Table 1. BeiDou PPP processing strategy.

Item	Models
Observations	Ionosphere-free linear combination (code & carrier phase)
Frequency	B_1, B_2, B_3
Elevation (E) cutoff	7°
Measurement weighting	1/sin(E)^2
Satellite orbit and clock, ERP parameters	GeoForschungs zentrum products
Satellite PCO	Default values provided by manufacturer
Receiver PCO & PCV	Not applied
Phase wind-up	Applied
Station displacement	Solid Earth tide, ocean tide loading, pole tide
Receiver clock	Estimated
ZTD/ZWD	Estimated
Mapping function	Global mapping function
Ambiguity	Float solutions
Estimation filter	EKF with 3-pass filter

Lastly, for the ambiguity in the extended Kalman filter, float ambiguities, rather than integer ambiguities, were used to obtain the user position and ZWD. In addition, for the error correction in the initial convergence interval, the 3-pass filter was applied (Salazar et al. 2010, Choi et al. 2012).

3. RESULTS

To analyze the positioning accuracy of BeiDou navigation satellites using PPP, data received during three days (from June 1, 2014 (DOY 152) to June 3, 2014 (DOY 154)) at the MKPO reference station operated by the Korea Astronomy and Space Science Institute were processed. At the MKPO reference station, Trimble NetR9 receiver and TRM59800 type antenna had been established, and the navigation signals of GPS, GLONASS, BeiDou, Galileo, and Quasi-Zenith Satellite System have been recorded at 30 second intervals. In the case of the PPP data processing, the parameters were estimated by 300 second intervals.

To analyze the visibility of BeiDou navigation satellites in the Korean Peninsula, observation data received at the MKPO reference station on June 1, 2014 were analyzed. Fig. 1 shows variations in the number of BeiDou navigation satellites received during a day. For the MKPO reference station, the number of observed BeiDou navigation satellites ranged from between 6 and 10. Currently, a total

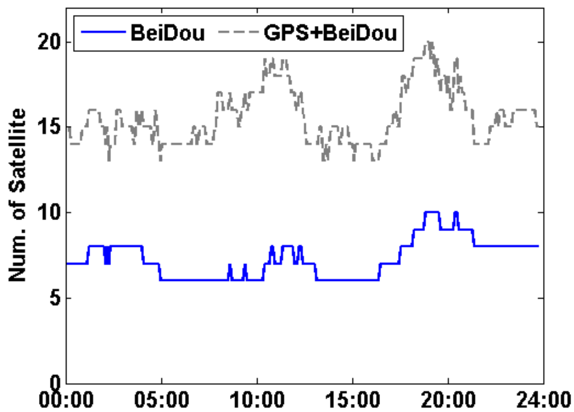

Fig. 1. Diurnal variations of the number of satellite tracked at MKPO station on June 1, 2014. The blue line represents variations of the number of BeiDou satellite.

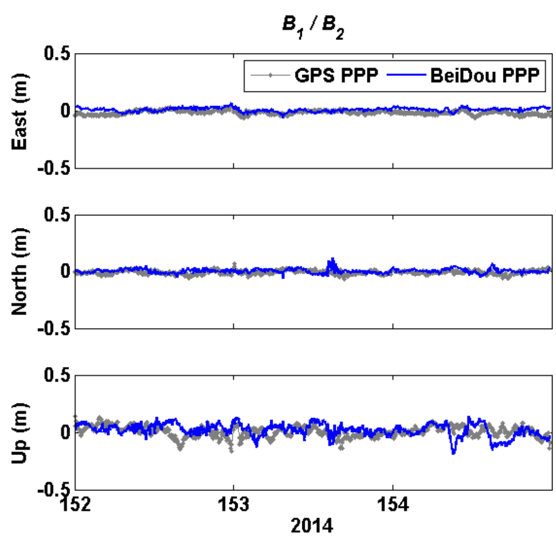

Fig. 2. Position errors between BeiDou kinematic PPP (B_1/B_2) and GPS kinematic PPP.

of 14 BeiDou navigation satellites are operated on the geostationary earth orbit, the medium earth orbit, and the inclined geosynchronous satellite orbit; and the signals of at least more than six satellites can be received in the Korean Peninsula. Thus, there is no problem in obtaining accurate position information. Also, when GPS satellites are added to BeiDou navigation satellites, the number of observed satellites increases between 13 and 20, as shown in Fig. 1.

BeiDou navigation satellites transmit three frequencies, and thus, data processing was first performed by the linear combination of the B_1 and B_2 signals that are commonly used. Fig. 2 shows the kinematic PPP results using the GPS and BeiDou data observed at the MKPO reference station during three days, respectively. In this regard, for the analysis of position errors, the coordinates calculated by the high-precision GNSS PPP analysis software developed by the Korea Astronomy and Space Science Institute were used as true values. For the GPS kinematic PPP, the averaged horizontal error was less than 1 cm and the averaged vertical error was 1.22 cm within the 95% confidence interval, and the root mean square (RMS) values were 1.52 cm, 1.43 cm, and 3.68 cm in the east-west, north-south, and altitude directions, respectively. In Fig. 2, the blue solid line represents the kinematic PPP data processing result using the BeiDou B_1 and B_2 frequencies. As shown in Fig. 2, the position errors of all directional components were similar to those for the GPS PPP results, based on the processing results of the three days. In the case of the averaged horizontal position error, the BeiDou PPP result was more accurate than the GPS PPP result.

Tegedor et al. (2014) reported that navigation satellites on the geostationary earth orbit showed lower orbit accuracy than navigation satellites on other orbits (e.g., the medium earth orbit). In particular, they analyzed the along-track component of geostationary earth orbit satellites through the processing results of the three days, and reported that the estimated RMS value for the orbital error was 20 ~ 40 cm. Despite the report suggesting lower orbit accuracy of specific geostationary earth orbit satellites, the present data processing indicated that BeiDou could obtain results similar to those of GPS even in the Korean Peninsula. If the PCO and PCV for the receiver are applied, it is expected that the position accuracy would be improved.

As for the averaged position errors obtained through the BeiDou B_1/B_2 kinematic PPP, the horizontal error was less than about 0.7 cm and the vertical error was 1.88 cm. The RMS values for the position errors were 1.79 cm and 1.96 cm in the east-west and north-south directions, respectively, and the vertical component was less than 5.84 cm.

Fig. 3 shows the result of the BeiDou B_1/B_3 kinematic PPP. The position accuracy was similar to that of the BeiDou B_1/B_2 result. Similar results were obtained because the same products of satellite orbit and satellite clock error were used although data processing was performed based on the combinations of different signals. As for the averaged position errors obtained through the B_1/B_3 kinematic PPP, the horizontal component was similar to that of the B_1/B_2 combination, but the vertical component had lower position accuracy. The RMS values for the position errors showed slightly lower performance in all directional components compared to those of the B_1/B_2 combination, but the vertical component showed a large difference (several cm level). Table 2 summarizes the detailed results of the position errors. In general, the PPP result using BeiDou in the Korean Peninsula showed slightly lower position accuracy and

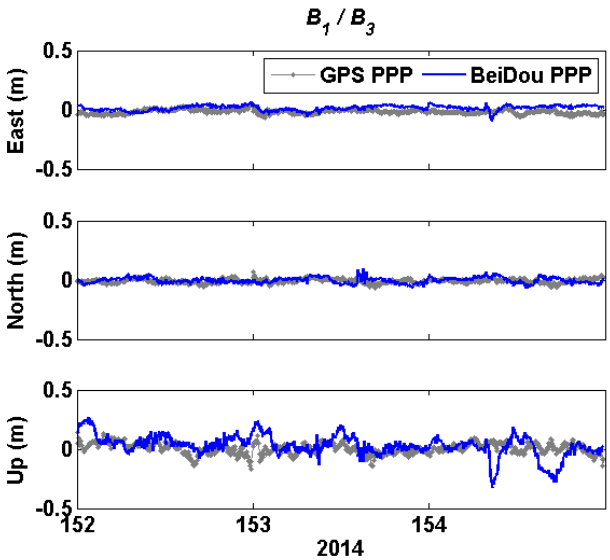

Fig. 3. Position errors between BeiDou kinematic PPP (B_1/B_3) and GPS kinematic PPP.

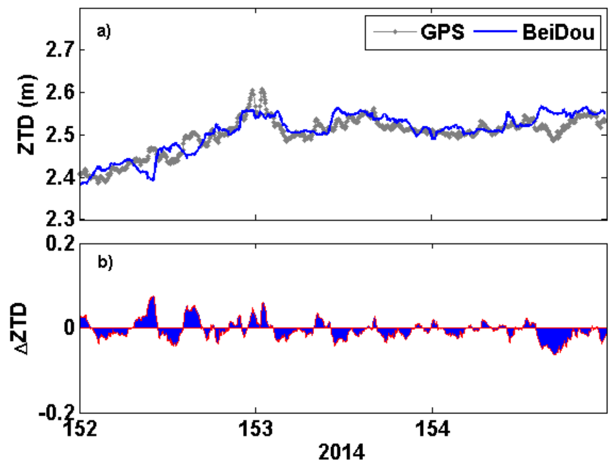

Fig. 4. The tropospheric ZTD values estimated by GPS PPP and BeiDou PPP. a) tropospheric ZTD variations, b) difference between GPS ZTD and BeiDou ZTD.

Table 2. Comparison of position errors.

Kinematic PPP	Position errors within 95% confidence level (unit: cm)					
	Mean			RMS		
	East	North	Up	East	North	Up
GPS	0.84	0.46	1.22	1.52	1.43	3.68
BeiDou B_1/B_2	0.63	0.26	1.88	1.79	1.96	5.84
BeiDou B_1/B_3	1.32	-0.46	2.88	2.55	2.51	9.48

precision compared to GPS. However, horizontal position accuracy could be determined within 2 cm on average, and the maximum RMS value for the position error was less than 10 cm.

Calculation of stable position information is directly related with the tropospheric estimation. Thus, the tropospheric ZTDs estimated by the GPS PPP and the BeiDou PPP were compared. Fig. 4a) shows the time series of the tropospheric ZTDs calculated by GPS and BeiDou, respectively. The blue solid line represents the values estimated by BeiDou, and the gray solid line represents the values estimated by GPS. Fig. 4b) shows the difference between the GPS ZTD and the BeiDou ZTD. The maximum difference of the tropospheric delay both the two systems was about 7 cm, and the mean value and the RMS value for the difference were 0.52 cm and 2.32 cm, respectively.

4. CONCLUSIONS

In this study, position determination of a reference station was performed by developing PPP method using BeiDou navigation satellites, and its performance was analyzed by comparing the BeiDou PPP and GPS PPP results. First, data received during three days at the MKPO reference station operated by the Korea Astronomy and Space Science Institute were processed using kinematic PPP, and parameters were estimated in 300 second intervals. The BeiDou PPP data processing result showed similar position errors compared to the GPS PPP, but the RMS values for the position errors showed relatively lower performance in all directional components compared to those of the GPS PPP.

This study showed that position determination could be performed at an accuracy of less than several cm by using BeiDou kinematic PPP in the Korean Peninsula. Comparison of the tropospheric ZTDs estimated by GPS and BeiDou indicated that they are also coincident well within about 0.52 cm below on average.

In this study, PPP data processing was performed using data of BeiDou navigation satellites received in the Korean Peninsula, and its performance for the position accuracy was presented. In particular, the performance of the BeiDou PPP was slightly lower than that of the GPS PPP, but the improvement of position accuracy is expected when the BeiDou system is stabilized and the number of navigation satellites increases.

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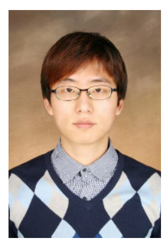

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