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Combined GPS/BeiDou Positioning Performance in South Korea

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ABSTRACT

The BeiDou is a satellite-based positioning and navigation system, which is under construction by the China Satellite Navigation Office. Until the June of 2014, the constellation of BeiDou navigation satellite system consists of 14 satellites including five geostationary earth orbit (GEO), five inclined geosynchronous earth orbit (IGSO) and four medium earth orbit (MEO). In this paper, we present the positioning results using BeiDou B1 code measurements obtained from three GNSS reference stations (BHAO, SKMA, MKPO). Combined Beidou/GPS positioning results are also compared to BeiDou and GPS only. BeiDou-only positioning errors for the east-west and north-south direction had less than 2 meter with root mean square (RMS) value. However, the positioning error for the up-down direction had larger than 10 meter at a 95% confidence level. Our results also suggest that the position precision is improved by combined BeiDou/GPS compared to BeiDou-only.

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

1. INTRODUCTION

The BeiDou Navigation Satellite System has been independently developed by China with the goal of the operation of a total of 35 satellites. The constellation of the BeiDou system consists of five geostationary earth orbit (GEO) satellites (58.75°E, 80°E, 110.5°E, 140°E, 160°E), 27 medium earth orbit (MEO) satellites, and three inclined geosynchronous earth orbit (IGSO) satellites (BeiDou ICD, 2012). 14 satellites are currently in operation, and the full operational capability for positioning, navigation, and timing is expected before 2020.

The BeiDou system is used for the precise determination of satellite orbits or for the research of precise point positioning (PPP) and relative positioning. According to the previous study, the error of the precise orbit of Beidou navigation satellites was about 10 cm (root mean square, RMS), and the position errors of the Global Navigation Satellite System (GNSS) reference station calculated using a static PPP technique were about 2 cm in the horizontal direction and 7 cm in the vertical direction (Shi et al. 2012). In addition, the average errors of standard point positioning based on the broadcasting ephemeris were about 4 m and 10 m in the horizontal and vertical directions, respectively. In the case of a region with a small number of visible satellites, the horizontal and vertical position errors were up to 10 m and 20 m, respectively (http://journal.polar.gov.cn/EN/abstract//abstract10406.shtml).

The BeiDou system is currently in a development stage, and its ephemeris and satellite clock offsets have lower accuracy than those of the Global Positioning System (GPS). Thus, there are not many papers relevant to the position performance of users. Also, in South Korea, there has been no case in which received BeiDou data were used for positioning. Therefore, the present study would be helpful for understanding the positioning accuracy of the BeiDou system in South Korea.

In this study, we developed a method that calculates position using the GPS and BeiDou observation data received at GNSS reference stations in South Korea. The result of combined GPS/BeiDou positioning was also compared with the results of BeiDou-only positioning and GPS-only positioning, and their performances were analyzed.

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Table 1. Physical parameters of GPS and BeiDou system.

Parameter	GPS	BeiDou
$GM_{\oplus}$	$398600.5 \times 10^9\ m^3/s^2$	$398600.4418 \times 10^9\ m^3/s^2$
$\dot{\Omega}_e$	7.2921150 ×10-5 rad/s	7.2921150×10^{-5} rad/s

2. BEIDOU MEASUREMENT MODELS

2.1 BeiDou navigation satellite orbit model

Unlike GPS, the BeiDou system consists of three satellite constellations (GEO, IGSO, and MEO). The broadcasting ephemeris of BeiDou is very similar to that of GPS, and the orbits of the MEO and IGSO satellites can be calculated using the GPS orbit model. However, to calculate the orbits of the GEO satellites, Eqs. (1-3) which reflect the characteristics of the geostationary earth orbits are used (BeiDou ICD, 2012).

$$\Omega_k = \Omega_0 + \dot{\Omega} t_k - \dot{\Omega}_e t_{oe} \tag{1}$$

$$\begin{Bmatrix} X_{GK} = x_k \cos \Omega_k - y_k \cos i_k \sin \Omega_k \\ Y_{GK} = x_k \cos \Omega_k + y_k \cos i_k \sin \Omega_k \\ Z_{GK} = y_k \sin i_k \end{Bmatrix} \tag{2}$$

where Ω_k is the corrected longitude of ascending node in the China Geodetic Coordinate System 2000 (CGCS2000), t_k is the computed time from ephemeris reference time, t_{oe} is the ephemeris reference time, i_k is the corrected inclination, $\dot{\Omega}$ is the rate of right ascension, and $\dot{\Omega}_e$ is the Earth rotation parameter of CGCS2000 (the value presented in Table 1 was used). x_k and y_k represent the position of the satellite calculated on the orbital plane; and X_{GK}, Y_{GK}, and Z_{GK} represent the satellite position in the inertial system. Based on the position of the satellite calculated using Eq. (2), the satellite position in the CGCS2000 coordinates is finally recalculated using Eq. (3).

$$\begin{Vmatrix} X_K \\ Y_K \\ Z_K \end{Vmatrix} = R_Z(\dot{\Omega}_e t_k) R_X(-5^o) \begin{vmatrix} X_{GK} \\ Y_{GK} \\ Z_{GK} \end{vmatrix} \tag{3}$$

where,

$$R_X(\varphi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & +cos\varphi & +sin\varphi \\ 0 & -sin\varphi & +cos\varphi \end{bmatrix},\ R_Z(\varphi) = \begin{bmatrix} +cos\varphi & +sin\varphi & 0 \\ -sin\varphi & +cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The coordinate transformation parameter between the CGCS2000 coordinate system of BeiDou and the World Geodetic System 1984 (WGS84) of GPS has not yet been accurately announced, but the BeiDou Interface Control Document (ICD) describes that the difference between the two coordinate systems is minute. Therefore, in this study, the coordinate system of BeiDou was assumed as the WGS84 of GPS. The difference between the BeiDou reference time and the GPS time should also be taken into account. The time difference between the two systems is 14 seconds (t_{BeiDou}=t_{GPS}-14).

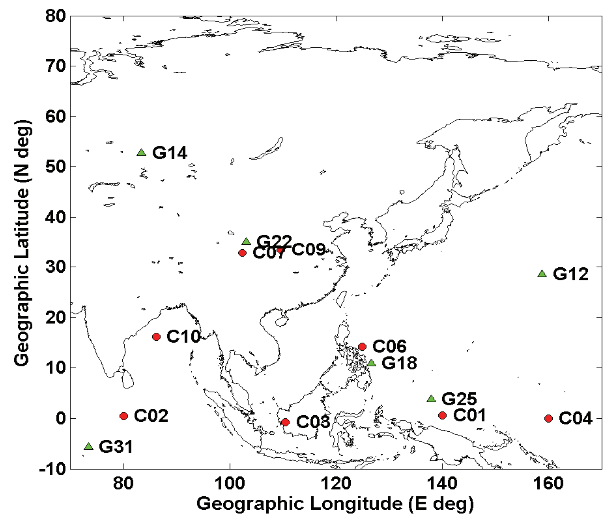

Fig. 1. Calculated GPS and BeiDou satellite positions on June 1, 2014.

Fig. 1 shows the positions of the GPS and BeiDou navigation satellites calculated using the broadcasting ephemeris received at the Bohyeonsan (BHAO) GNSS reference station on June 1, 2014, based on the geographic latitude and longitude. As shown in the Fig. 1, four BeiDou navigation satellites (satellite numbers C1, C2, C3, and C4) were being operated at the geostationary earth orbit.

2.2 Positioning Algorithm

BeiDou navigation satellites transmit three frequencies (B1, B2, and B3) to users. Table 2 summarizes the usable frequencies and wavelengths of the GPS and BeiDou systems. In this study, the L1 C/A (Coarse/Acquisition) code of GPS and the B1 code of BeiDou were used for combined positioning. The measurement equation for the B1 code can be expressed as Eq. (4) (Xu et al. 2013).

$$P_{B1} = \rho + c\delta t^r - c\delta t^s + Trop + Iono_{B1} + \varepsilon \tag{4}$$

Table 2. Signals characteristics of GPS and BeiDou system.

Satellite System	Band (component)	Frequency (MHz)	Wavelength (cm)
GPS	L1	1575.42	19.03
	L2	1227.60	24.42
	L5	1176.45	25.48
BeiDou	B1 (I/Q)	1561.098	19.20
	B2 (I/Q)	1207.140	24.83
	B3 (I/Q)	1268.520	23.63

where ρ is the geometry range between the satellite and the receiver, dt^r and dt^s are the receiver clock and satellite clock errors, respectively, *Trop* is the tropospheric delay error, $Iono_{B1}$ is the ionospheric delay error, ε is the observation noise, and *c* is the speed of light. In the present study, for the calculation of the tropospheric and ionospheric delay errors, a model that is commonly used for GPS (Saastamoinen, Klobuchar) was utilized. For the average temperature, pressure, and relative humidity of the atmosphere that are also needed for the Saastamoinen tropospheric model, 15°, 1013.25 mb, and 0.5 atmospheric parameter values were used, respectively.

To estimate the state vector that includes the position of a user, the weighted least squares method was used (Tarrío et al. 2011).

$$\vec{X} = (H^T W H)^{-1} H^T W \vec{v} \quad (5)$$

where H is the design matrix, W is the weighted matrix depending on the elevation angle of the satellite, and $\vec{v}$ is the pseudorange residual vector. The final calculated state vector is $\vec{X} = [x, y, z, dt_{gps}, dt_{BeiDou}]$, where x, y, z represent the position of a user in the WGS84 reference coordinate system, dt_{gps} is the GPS receiver clock error, and dt_{BeiDou} is the offset of the clock error between GPS and BeiDou.

3. RESULTS

In the present study, an algorithm for data processing of BeiDou navigation satellites was developed; and to analyze the position accuracy of Chinese BeiDou navigation satellites within the Korean Peninsula, data recorded at three GNSS reference stations (Bohyeonsan (BHAO), Seoul (SKMA), and Mokpo (MKPO)) operated by the Korea Astronomy and Space Science Institute were used. In GNSS reference stations, a Trimble NetR9 receiver has been installed and operated, and it receives the signals such as GPS, GLONASS, Galileo, BeiDou, QZSS, SBAS, etc. In addition, the position accuracy of the BeiDou-only and the GPS-only was presented along with the result of the combined GPS/BeiDou positioning, and they were compared and analyzed. Fig. 2 shows the time series of the position errors for each observation time calculated using the GPS and BeiDou data received at the BHAO GNSS reference station on June 1, 2014. The period for data processing was 24 hours, and the position of each reference station was calculated at 30 second intervals based on kinematic positioning. In Fig. 2, the gray solid line represents the position error using only the BeiDou observation data, and the blue dotted line represents the error of the GPS-only positioning. The red solid line represents the result calculated by combining the BeiDou and GPS observation data. In this regard, for the analysis of the position errors, the coordinates calculated using the high-precision GPS PPP analysis software developed by the Korea Astronomy and Space Science Institute were used as the true value. The daily position errors (RMS) of BeiDou in the east-west, north-south, and up-down directions were 1.36 m, 1.80 m, and 11.31 m, respectively, and those of the GPS-only positioning were 0.85 m, 0.78 m, and 3.78 m, respectively. Also, the errors of the combined GPS/BeiDou positioning were 0.73 m, 1.24 m, and 6.21 m, respectively. In the case of the BeiDou-only positioning, the error in the up-down direction was more than 10 m (up to 20 m) at certain points, as shown in Fig. 2. It could be because of the orbit error of the geostationary earth orbit satellites or the satellite clock error. This error of the BeiDou-only positioning is well consistent with the result of Zhu et al. (2013). For the combined GPS/BeiDou positioning, the errors in all the directions (RMS values) decreased compared to those of the BeiDou-only positioning. In particular, the position error in the up-down direction decreased by about half. However, the position error in the up-down direction was larger than that of the GPS-only positioning.

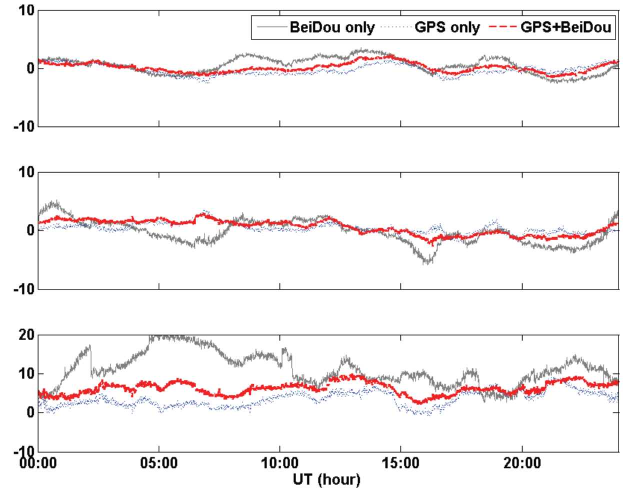

Fig. 2. Position errors between BeiDou only, GPS only, and combined GPS/BeiDou measured at BHAO GNSS reference station on June 1, 2014.

Fig. 3 shows the daily change in the number of visible satellites received at the BHAO reference station. In the case of BeiDou navigation satellites, six to nine satellites were received; and when GPS satellites were included, 13 to 20 satellites were received. In this regard, the elevation angle of the visible satellite was set to more than 10°.

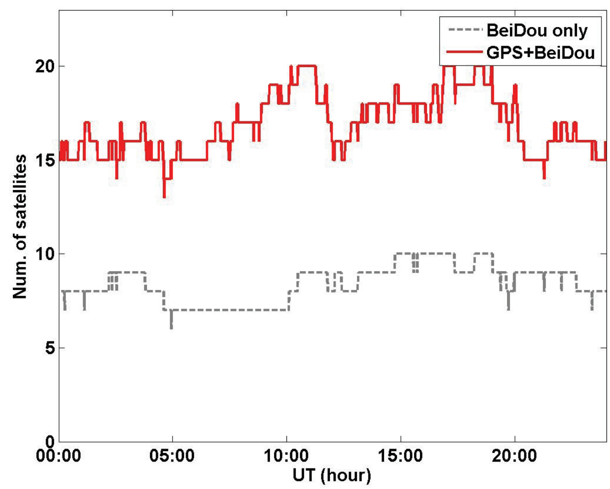

Fig. 3. Satellite visibility between BeiDou only and combined GPS/BeiDou measured at BHAO GNSS reference station on June 1, 2014.

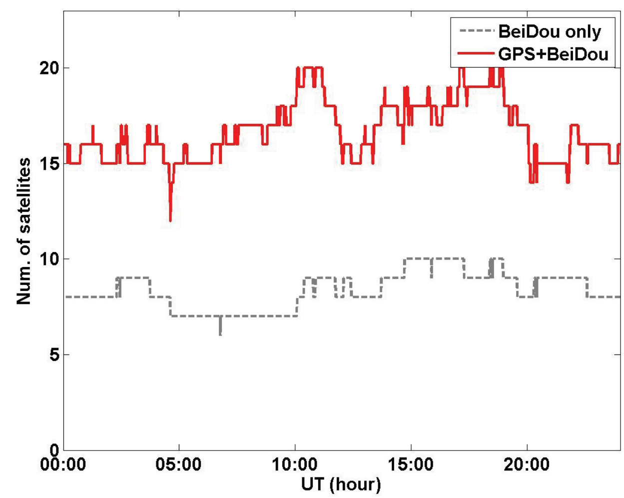

Fig. 5. Satellite visibility between BeiDou only and combined GPS/BeiDou measured at MKPO GNSS reference station on June 1, 2014.

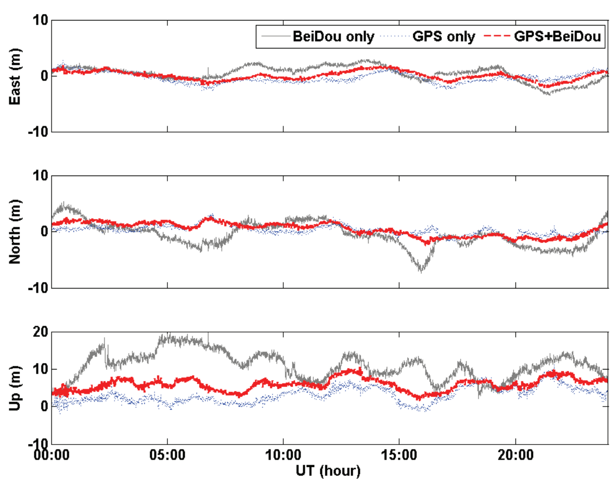

Fig. 4. Position errors between BeiDou only, GPS only, and combined GPS/BeiDou measured at MKPO GNSS stations on June 1, 2014.

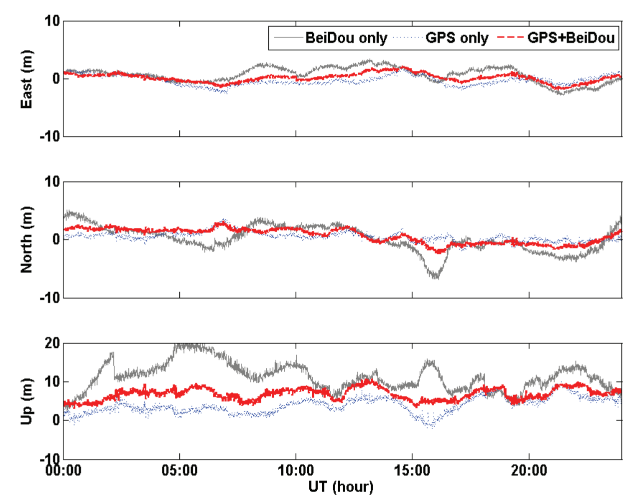

Fig. 6. Position errors between BeiDou only, GPS only, and combined GPS/BeiDou measured at SKMA GNSS stations on June 1, 2014.

Fig. 4 shows the time series of the position errors for the MKPO reference station. The data processing result was similar to that of the BHAO reference station. In the case of the BeiDou-only positioning, the daily position errors (RMS) in the east-west, north-south, and up-down directions were 1.30 m, 1.99 m, and 11.07 m, respectively. For the GPS-only positioning, they were 0.89 m, 0.72 m, and 3.49 m, respectively; and for the combined GPS/BeiDou positioning, they were 0.72 m, 1.20 m, and 5.90 m, respectively. As for the MKPO reference station, the combined GPS/BeiDou positioning also had higher position precision than the BeiDou-only positioning, but the position errors in the north-south and up-down directions were still larger than those of the GPS-only positioning.

Fig. 5 shows the change in the number of visible satellites for the MKPO reference station. In the case of BeiDou navigation satellites, six to nine satellites were received; and when GPS satellites were included, the number of visible satellites was 12 to 20.

Fig. 6 shows the time series of the position errors for the SKMA reference station. The data processing result was similar to those of the BHAO and SKMA reference stations. The errors of the BeiDou-only positioning in the east-west, north-south, and up-down directions were 1.38 m, 1.92 m, and 11.27 m, respectively. For the GPS-only positioning, they were 0.82 m, 0.79 m, and 4.13 m, respectively; and for the combined GPS/BeiDou positioning, they were 0.70 m, 1.30 m, and 6.80 m, respectively. As for the SKMA

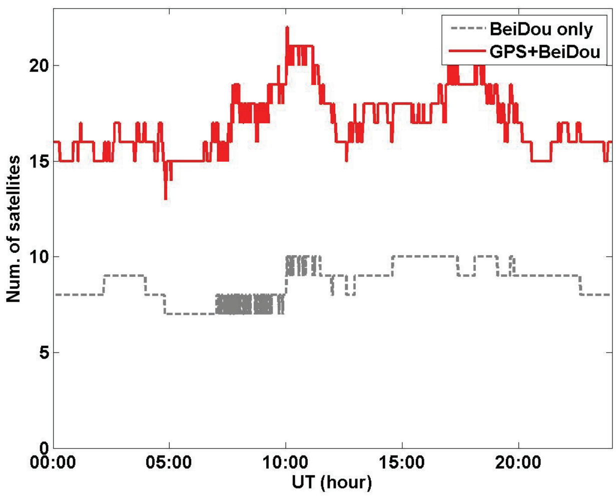

Fig. 7. Satellite visibility between BeiDou only and combined GPS/BeiDou measured at SKMA GNSS reference station on June 1, 2014.

reference station, the combined GPS/BeiDou positioning had higher position accuracy in the up-down direction than the BeiDou-only positioning, similar to the BHAO and MKPO reference stations; but the position error in the up-down direction was again larger than that of the GPS-only positioning.

Fig. 7 shows the change in the number of visible satellites for the SKMA reference station. In the case of BeiDou navigation satellites, 7 to 10 satellites were received; and when GPS satellites were included, 13 to 22 satellites were received.

Table 3 summarizes the average values and RMS values for the daily position errors of the three reference stations. In the case of the BeiDou-only positioning, the average position errors in the east-west and north-south directions were less than 1 m, and the RMS values were less than 2 m, while the average position error and the RMS value in the up-down direction were more than 10 m. This result was identically observed in the three reference stations. It is noteworthy that the combined GPS/BeiDou positioning had smaller average position error and RMS value in the east-west direction than the GPS-only positioning. However, for the average position errors and the RMS values in the north-south and up-down directions, the GPS-only positioning showed superior performance.

In conclusion, this study demonstrated that in South Korea, a user position could be obtained at an error range of 10 m using only BeiDou navigation satellites. It was also found that the combined GPS/BeiDou positioning has an improvement of position accuracy in the east-west direction compared to the GPS only-positioning.

Table 3. Comparison of position errors.

Site name	Method	Position errors within 95% confidence level (Unit: m)					
		Mean			RMS		
		East	North	Up	East	North	Up
BHAO	BeiDou	0.38	-0.21	10.69	1.36	1.80	11.31
	GPS	-0.20	0.27	3.33	0.85	0.78	3.78
	GPS/BeiDou	0.00	0.42	6.04	0.72	1.24	6.21
SKMA	BeiDou	0.59	0.30	10.81	1.38	1.92	11.27
	GPS	-0.23	0.38	3.67	0.82	0.79	4.13
	GPS/BeiDou	0.10	0.56	6.65	0.70	1.32	6.80
MKPO	BeiDou	0.49	-0.43	10.56	1.30	1.99	11.07
	GPS	-0.28	0.15	2.91	0.89	0.72	3.49
	GPS/BeiDou	0.02	0.31	5.70	0.72	1.20	5.90

4. CONCLUSIONS

In this study, we developed an algorithm that calculates a user position using the code observation data of BeiDou navigation satellites received in South Korea. The result of combined GPS/BeiDou positioning was also compared with the results of GPS-only positioning and BeiDou-only positioning. For this purpose, the position for each epoch time was calculated by processing data received during a day at three reference stations (BHAO, SKMA, and MKPO) operated by the Korea Astronomy and Space Science Institute. In the case of the BeiDou-only positioning, the position errors in the east-west and north-south directions were less than 2 m at all the GNSS reference stations, but the error in the up-down direction was more than 10 m. Also, the combined GPS/BeiDou positioning had smaller errors in the east-west, north-south, and up-down directions than the BeiDou-only positioning; and in particular, the error in the up-down direction decreased significantly. However, the combined GPS/BeiDou positioning still had larger position errors than the GPS-only positioning. The number of visible BeiDou satellites received at the GNSS reference stations in South Korea ranged from 5 to 10.

The results of this study suggested that in South Korea, a user position could be determined within an error range of 10 m by processing data of BeiDou navigation satellites. In addition, it was shown that the combined GPS/Beidou positioning has an improvement of position accuracy compared to the BeiDou-only positioning.

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