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Multi-GNSS Standard Point Positioning using GPS, GLONASS, BeiDou and QZSS Measurements Recorded at MKPO Reference Station in South Korea

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ABSTRACT

The Global Navigation Satellite System (GNSS) is undergoing dramatic changes. Nowadays, much more satellites are transmitting navigation data at more frequencies. A multi-GNSS analysis is performed to improve the positioning accuracy by processing combined observations from different GNSS. The multi-GNSS technique can improve significantly the positioning accuracy. In this paper, we present a combined Global Positioning System (GPS), the GLObal NAvigation Satellite System (GLONASS), the China Satellite Navigation System (BeiDou), and the Quasi-Zenith Satellite System (QZSS) standard point positioning (SPP) method to exploit all currently available GNSS observations at Mokpo (MKPO) station in South Korea. We also investigate the multi-GNSS data recorded at MKPO reference station. The positioning accuracy is compared with several combinations of the satellite systems. Because of the different frequencies and signal structure of the different GNSS, inter-system biases (ISB) parameters for code observations have to be estimated together with receiver clocks in multi-GNSS SPP. We also present GPS/GLONASS and GPS/BeiDou ISB values estimated by the daily average.

Keywords: GNSS, multi, position accuracy, ISB

1. INTRODUCTION

The Global Positioning System (GPS) from the United States is a Global Navigation Satellite System. It has been operated more than 30 years and has provided useful position and time information for users. GPS signals can be received anywhere at any time regardless of the weather condition, and thus have been used in various areas. In addition, the demand for GPS has gradually increased in the national defense and civilian areas, and it has become an important public social infrastructure.

As the economic/social/military usefulness of GPS has been emphasized, Russia has established and operated a system called GLObal NAvigation Satellite System (GLONASS), and the European Union and China have established Global Navigation Satellite Systems called Galilleo and China Satellite Navigation System (BeiDou), respectively. In the case of GPS, 31 satellites are currently operated; and in the case of GLONASS, all the 24 navigation satellites have been operated since the end of 2011. Galileo from the European Union is expected to have 30 medium Earth orbit satellites, and six navigation satellites are currently operated. In the case of BeiDou, 14 satellites are currently operated, and a total of 35 satellites are planned to be launched by 2020 (BeiDou ICD 2013). To take the lead in the satellite navigation system area, many countries have competed for prompt system establishment and performance improvement in recent years.

Japan has been developing a local satellite navigation system called Quasi-Zenith Satellite System (QZSS), and one satellite is currently operated (IS-QZSS 2014). QZSS covers the Asia-Oceania region. In particular, it is expected

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to play an important role in securing positioning availability from high elevation angles.

A Global Navigation Satellite System (GNSS) can provide more accurate and precise information, such as geodetic survey, navigation, and time. It is expected that GNSS navigation signals from at least 35 satellites could be received in the Asia-Oceania region after 2020. GNSS would lead to the improvement in positioning accuracy, reliability, and satellite availability, compared to the solution of an individual satellite navigation system such as GPS.

Until recently, studies on combined positioning have been limited to GPS and GLONASS (Cai & Gao 2007, Li et al. 2009, Tolman et al. 2010). However, as the BeiDou and Galileo satellites have recently provided navigation signals, studies on positioning that combine BeiDou or Galileo satellite observations with an existing system have been performed (He et al. 2013, Tegedor et al. 2014, Santerre et al. 2014, Cai et al. 2014, Li et al. 2015). Santerre et al. (2014) reported a position accuracy performance of less than about 5 m by combining GPS, GLONASS, and BeiDou observations received within China, and also separately analyzed the position accuracy performance depending on the elevation cutoff of the satellites.

In the East Asian region, many navigation signals can be received from the GPS stations due to the recent operation of the regional satellite navigation system from China with GPS and GLONASS. One QZSS satellite is in operation, and thus it is needed to analyze positioning accuracy using these signals received in South Korea.

For the performance experiment of the Galileo and BeiDou systems, existing studies investigated position accuracy depending on the combination of the satellite constellation by limiting to Europe and the China regions. In the present study, position accuracy performance was analyzed through various combinations of satellite observations received in South Korea. In particular, position accuracy was analyzed through the combination of QZSS satellite data with GPS, GLONASS, and BeiDou.

In the present study, receiver intersystem biases were also analyzed. The position accuracy performance of the GPS/GLONASS/BeiDou/QZSS combination at the Mokpo (MKPO) reference station in the Korean Peninsula was compared with those of other combinations, and the results were presented.

2. PROCESSING STRTEGY AND METHODS

GPS uses two L bands (L1 ~ 1,575.42 MHz and L2 ~ 1,227.60 MHz), and GLONASS provides information for users using two frequency bands, f_{L1} = (1602 + n × 0.5625) MHz and f_{L2} = (1246 + n × 0.4375) MHz (GLONASS ICD 2008). In this regard, n is the frequency channel number. In addition, BeiDou satellites transmit three frequencies (B1 ~ 1,561.098 MHz, B2 ~ 1,207.140 MHz, and B3 ~ 1,268.520 MHz) (BeiDou ICD 2013), and QZSS uses signals identical to those of GPS.

In this study, GPS L1 C/A (Coarse/Acquisition) code, GLONASS L1 code, BeiDou B1 code, and QZSS L1 code were used to process the GPS, GLONASS, BeiDou, and QZSS observations. Eq. (1) shows the measurement equation using GNSS code phases.

$$P_i^j = \rho^j + cdt + ISB^j - cdT^j + d_{trop}^j + d_{iono/L_i}^j + \varepsilon_{P_i}^j \qquad (1)$$

where the superscript j represents the GNSS satellite. ρ is the geometry range between the satellite and the receiver, and and dT are the clock errors of the receiver and the satellite, respectively. ISB is the intersystem bias; GPS/GLONASS and GPS/BeiDou, and c is the speed of light. d_{trop} is the tropospheric delay error, and $d_{iono/Li}$ is the ionospheric delay error of the GNSS satellite having the i-th frequency. ε_{P_i} includes the receiver noise and the multipath error.

In this study, the Klobuchar model that is used for GPS was utilized to calculate ionospheric delay error, and the ionospheric delay values depending on the frequency of the GNSS satellite was calculated and applied as shown in Eq. (2) based on the fact that ionospheric delay error is inversely proportional to the square of the strength of frequency.

$$d_{iono/L_i} = \left(\frac{f_{GPS\,L1}}{f_{GLSS\,L_i}}\right)^2 \cdot Klob \qquad (2)$$

where $f_{GPS\,L_1}$ includes the GPS L1 frequency, and $f_{GNSS\,L_i}$ includes the GPS L1, GLONASS L1, BeiDou B1, and QZSS L1 frequencies. $Klob$ is the ionospheric delay value calculated by the Klobuchar model. Unlike GPS, BeiDou, and QZSS, the GLONASS system is operated based on frequency division, and thus the frequency for each satellite was determined after recognizing the channel number for each satellite from the navigation file.

To estimate the position, receiver clock error, and the intersystem bias, the weighted least squares method was employed as Eq. (3) (Tarrío et al. 2011).

$$\vec{X} = (H^T W H)^{-1} H^T W \vec{v} \qquad (3)$$

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$$H=\begin{bmatrix}
\frac{x_0-X^{1,G}}{\rho^{1,G}} & \frac{y_0-Y^{1,G}}{\rho^{1,G}} & \frac{z_0-Z^{1,G}}{\rho^{1,G}} & 1 & 0 & 0\\
\vdots & \vdots & \vdots & \vdots & 0 & 0\\
\frac{x_0-X^{n,G}}{\rho^{n,G}} & \frac{y_0-Y^{n,G}}{\rho^{n,G}} & \frac{z_0-Z^{n,G}}{\rho^{n,G}} & 1 & 0 & 0\\
\frac{x_0-X^{1,R}}{\rho^{1,R}} & \frac{y_0-Y^{1,R}}{\rho^{1,R}} & \frac{z_0-Z^{1,R}}{\rho^{1,R}} & 1 & 1 & 0\\
\vdots & \vdots & \vdots & \vdots & \vdots & 0\\
\frac{x_0-X^{n,R}}{\rho^{n,R}} & \frac{y_0-Y^{n,R}}{\rho^{n,R}} & \frac{z_0-Z^{n,R}}{\rho^{n,R}} & 1 & 1 & 0\\
\frac{x_0-X^{1,C}}{\rho^{1,C}} & \frac{y_0-Y^{1,C}}{\rho^{1,C}} & \frac{z_0-Z^{1,C}}{\rho^{1,C}} & 1 & 0 & 1\\
\vdots & \vdots & \vdots & \vdots & 0 & \vdots\\
\frac{x_0-X^{n,C}}{\rho^{n,C}} & \frac{y_0-Y^{n,C}}{\rho^{n,C}} & \frac{z_0-Z^{n,C}}{\rho^{n,C}} & 1 & 0 & 1\\
\frac{x_0-X^{1,Q}}{\rho^{1,Q}} & \frac{y_0-Y^{1,Q}}{\rho^{1,Q}} & \frac{z_0-Z^{1,Q}}{\rho^{1,Q}} & 1 & 0 & 0
\end{bmatrix}_{(3n+1)\times 6} \quad (4)$$

$$W=\begin{bmatrix}
\frac{1}{\sin E^{1,G}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\
0 & 0 & \frac{1}{\sin E^{n,G}} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & \frac{1}{\sin E^{1,R}} & 0 & 0 & 0 & 0 & 0 & 0\\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots\\
0 & 0 & 0 & 0 & 0 & \frac{1}{\sin E^{n,R}} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sin E^{1,C}} & 0 & 0 & 0\\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sin E^{n,C}} & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sin E^{1,Q}}
\end{bmatrix}_{(3n+1)\times(3n+1)} \quad (5)$$

where H is the design matrix, and W is the weighted matrix depending on the satellite elevation angle (E) and it is expressed in Eq. (5). In Eq. (5), additional weighting factor depending on the satellite constellation was not applied. $\check{n}$ is the pseudorange residual vector. G, R, C, and Q represent the GPS, GLONASS, BeiDou, and QZSS, respectively. In Eq. (4), if GPS, GLONASS, BeiDou and one QZSS satellite are received, the size of the design matrix, H, is (3n + 1) × 6, and the residual vector, $\check{n}$, is 3n + 1. The final solution is X = $\{x, y, z, dt, ISB_{G\text{-}R}, ISB_{G\text{-}C}\}$.

A key for data processing is to establish the reference time system and the reference coordinate system. For the reference time system, both GPS and QZSS use the GPS time (GPST), and BeiDou uses the BeiDou Time (BDT), which has a difference of 14 seconds from GPST (BeiDou ICD 2013). GLONASS uses the Coordinated Universal Time (UTC). In the case of the reference coordinate system, the World Geodetic System 84 (WGS 84) for the GPS was applied. BeiDou and QZSS use reference coordinate systems called the China Geodetic Coordinate System 2000 (CGCS2000) and the Japan satellite navigation Geodetic System (JGS), respectively, but CGCS2000 and JGS do not provide parameters for a transformation of the reference coordinate system to WGS84. Therefore, in this study, it was assumed that CGCS2000 and JGS are identical to WGS84. GLONASS uses a reference coordinate system called the Parametry Zemli 1990 (PZ-90); and to convert PZ-90 into WGS84, Eq. (6) was separately applied.

Table 1. Characteristics of GNSS system.

System	GPS	GLONASS	BeiDou	QZSS
Number of satellites	32 (31)	24 (24)	35 (14)	4 (1)
Orbital planes	6	3	3	3
Orbital inclination (deg)	55	65	55	43
Orbital altitude (km)	20,197	19,130	21,540	35,786
Period of revolution	11^h58^m	11^h16^m	12^h53^m	23^h56^m
Time scale	GPST	UTC	BDT	GPST
Coordinate system	WGS84	PZ90	CGCS2000	JGS
Ephemeris update (h)	Every 2	Every 0.5	Every 1	Every 1

$$\begin{pmatrix}x'\\y'\\z'\end{pmatrix}=\begin{pmatrix}x\\y\\z\end{pmatrix}+\begin{pmatrix}D & -R_3 & R_2\\ R_3 & D & -R_1\\ -R_2 & R_1 & D\end{pmatrix}\begin{pmatrix}x\\y\\z\end{pmatrix}+\begin{pmatrix}T_1\\T_2\\T_3\end{pmatrix} \quad (6)$$

where (x', y', z') are the WGS84 reference coordinate values, and (x, y, z) are the PZ-90 reference coordinate values. For a transformation both the two reference coordinate systems, seven parameters $\{T_1, T_2, T_3, D, R_1, R_2, R_3\}$ are required. For the values of $\{T_1, T_2, T_3\}$, {0.07m, 0.00m, 0.77m} were used; for the value of D, -3 parts per billion was used; and for the values of $\{R_1, R_2, R_3\}$, {-19, -4, 353} were used (http://www.navipedia.net/index.php/Reference_Frames_in_GNSS). The units of $\{R_1, R_2, R_3\}$ are mili-arc seconds.

Table 1 summarizes the reference time system and the reference coordinate system used for each satellite navigation system, and it also includes the maximum number of satellites (the number of currently available satellites), orbital plane, orbital inclination, average orbital altitude, and the rotation period of the satellite.

3. RESULTS

To analyze the performance of combined positioning, measurements received at the MKPO GNSS reference station operated by the Korea Astronomy and Space Science Institute were used. For the MKPO GNSS reference station, Trimble NetR9 receiver and TRM59800 antenna have been installed and operated. The Trimble NetR9 receiver used for the experiment can receive GPS, GLONASS, BeiDou, Galileo, and QZSS satellite signals. In addition, the obtained data were converted to a Receiver Independent Exchange format (version, "extended 2.11"). We analyzed observations with the variations in the number of visible satellites over the Korean Peninsula depending on time.

Fig. 1 shows the variations in the number of visible

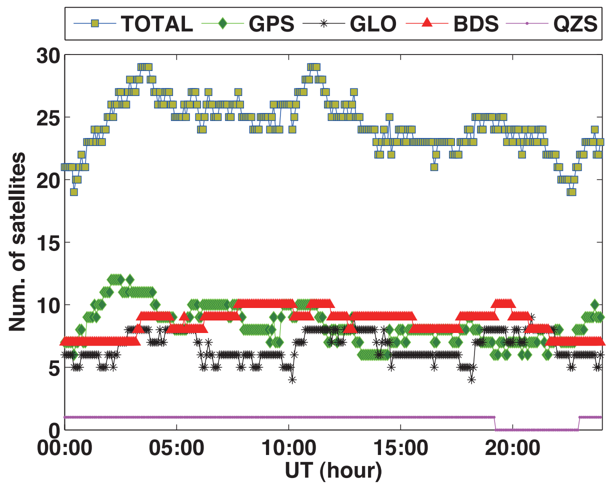

Fig. 1. GNSS visible satellites at MKPO reference station on 1 June 2014.

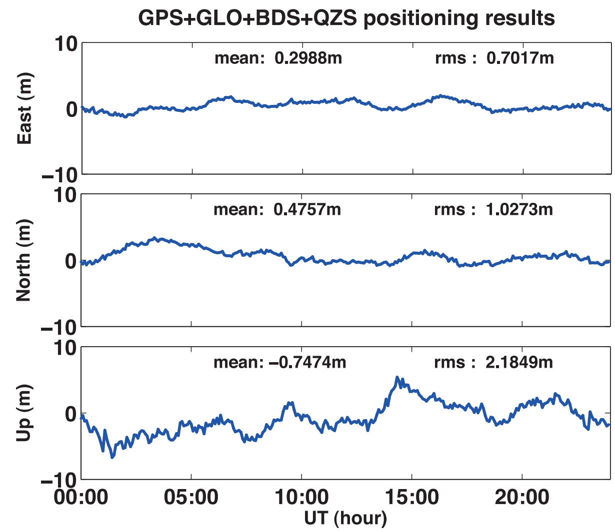

Fig. 2. Combined GPS+GLO+BDS+QZS standard point positioning error.

satellites for GPS, GLONASS (GLO), BeiDou (BDS), and QZSS (QZS), respectively, and the variations in the number of all the satellites depending on time at 15 minute intervals using data received at the MKPO GNSS reference station on June 1, 2014. In Fig. 1, the vertical axis represents the number of visible satellites, and the horizontal axis represents the Universal Time.

The variations in the number of visible satellites for GPS were expressed as green diamonds. For GPS, the maximum number of visible satellites was 12 at 03:00 UT; and during the day, at least six satellites were continuously observed. For GLONASS (GLO), the number of visible satellites was between 4 and 9 on the day. For BeiDou (BDS), the number of visible satellites was between 7 and 10 (expressed as red triangles). BDS had more visible satellites on average compared to GLO in the Korean Peninsula. For QZSS (QZS), the number of visible satellites was one, and a signal was not received from 19:00 to 23:00 UT. This is because the satellite cutoff angle for the receiver was set to 10 degrees. The number of visible satellites for GPS+GLO+BDS+QZS was between 19 and 29 (expressed as gray squares), and the difference in the number of observed satellites depending on time was up to 10. In addition, for the MKPO GNSS reference station, relatively more navigation satellites were observed in the daytime than in the nighttime.

Combined positioning results were obtained by processing the multi-GNSS data received at the MKPO GNSS reference station. Fig. 2 shows the results of the standard point positioning using only single-frequency code phase. The position errors depending on time were presented as the east, north, and up direction components. The absolute position for the position error was obtained based on the static precise point positioning (PPP) method using the GNSS software developed by the Korea Astronomy and Space Science Institute. As shown in Fig. 2, the average values of the daily position errors calculated by the GPS+GLO+BDS+QZS combined positioning were 0.29 m, 0.47 m, and -0.74 m in the east, north, and up directions, respectively. Also, the average position errors in the horizontal directions (east and north) were smaller than that in the vertical direction (up). In the case of the root mean square (RMS) values for the position errors, the position accuracy in the horizontal direction was also outstanding, similar to the average position errors.

To analyze the position accuracy in the horizontal direction, the result of the GPS+GLO+BDS+QZS combined positioning was compared with that of the GPS-only positioning. In Fig. 3, the horizontal position errors shown in Fig. 2 and the horizontal position errors calculated using only GPS are presented, respectively. In Fig. 3, the horizontal axis represents the position error in the east direction, the vertical axis represents the position error in the north direction, and the yellow cross represents the absolute position (0, 0). The horizontal position errors of GPS were expressed as blue circles, and those of GPS+GLO+BDS+QZS were expressed as red stars. As shown in Fig. 3, all the horizontal position errors of the GPS+GLO+BDS+QZS combined positioning were smaller than those of the GPS-only positioning. In particular, the position error in the north direction decreased further compared to the horizontal components. The fact that the position error in the north direction is large can be caused by geometry of the satellites.

To analyze the positioning performance in various combinations of satellites, data processing is performed

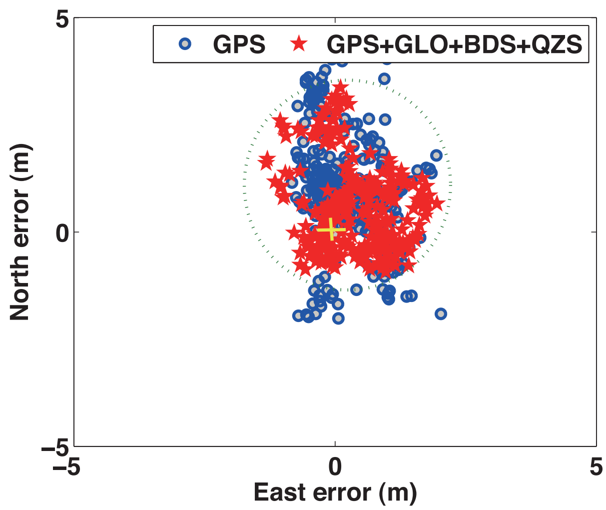

Fig. 3. Comparison of the horizontal position errors between GPS and GPS+GLO+BDS+QZS.

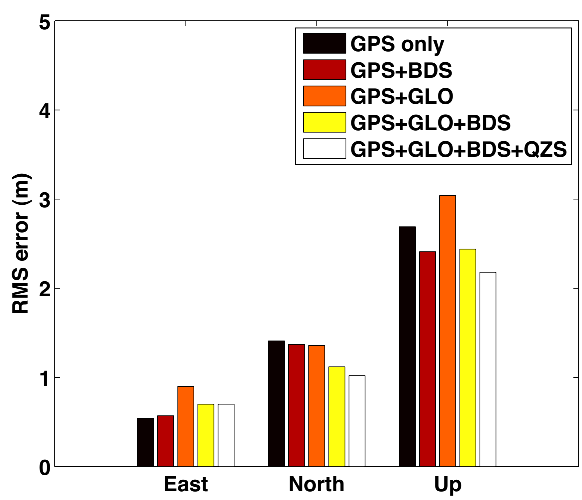

Fig. 4. Position RMS errors calculated by multi-GNSS combinations.

based on a total of five experiment groups. The experiment groups included 'GPS-only', 'GPS+BDS', 'GPS+GLO', 'GPS+GLO+BDS', and 'GPS+GLO+BDS+QZS'.

Fig. 4 shows the RMS values of the position errors calculated based on the experiment groups. In Fig. 4, the horizontal axis represents the RMS value for the position error, and the vertical axis represents the east, north, and up direction components. For the 'GPS+BDS' combination, the RMS value in the east direction increased by 0.03 m compared to that of 'GPS-only', while the RMS values in the north and up directions decreased. Thus, the overall position error decreased compared to that of the 'GPS-only' positioning. On the other hand, for the 'GPS+GLO' combination, the RMS values in the east and up directions showed the largest errors compared to those of the other experiment groups. The RMS values in the north component are smaller than those of 'GPS-only' and 'GPS+BDS'. The results indicated that the 'GPS+GLO' combination had a larger RMS value for the position error than 'GPS-only'. Choi et al. (2013) reported that the GPS and GLONASS combination did not show improved positioning performance within the Korean Peninsula compared to GPS-only positioning. These results of the present study are consistent with the results of the previous study. This could be because GLONASS signals had large noise or the transformation parameters between different reference coordinate systems are not appropriate for the Korean Peninsula in the mid-latitudes. Therefore, transformation parameters for reference coordinate systems need to be directly estimated by the long-term data processing in global.

For the 'GPS+GLO+BDS' combination, the RMS values in all directions decreased compared to those of the 'GPS+GLO' combination. In particular, the difference in the RMS value in the up direction was about 0.6 m, which showed a significant decrease. For the 'GPS+GLO+BDS+QZS' combination, the RMS values in the north and up directions decreased excluding the east direction. When one QZS satellite was added to the 'GPS+GLO+BDS', the RMS value in the up direction decreased further. As a result, the 'GPS+GLO+BDS+QZS' combination affected the position accuracy in the north and up directions.

The analysis of the position precision in the various combinations indicated that the 'GPS+GLO' combination showed relatively lower position precision compared to the other combinations, while the 'GPS+GLO+BDS+QZS' combination showed higher position precision.

Table 2 summarizes the average daily position errors calculated by each combination shown in Fig. 4. For the 'GPS+GLO' combination, the average position errors in the east and up directions relatively increased compared to those of other combinations. An increase of the averaged position errors in specific directions was consistent with an increase in the RMS values. On the other hand, the position error in the north direction was the smallest compared to those of other combinations. In addition, for the 'GPS+GLO+BDS+QZS' combination, the position errors

Table 2. Comparison of position errors within 95% confidence level.

Method	Mean errors (m)			RMS errors (m)		
	East	North	Up	East	North	Up
GPS only	0.12	0.81	-0.94	0.54	1.42	2.69
GPS+BDS	0.10	0.98	-0.90	0.57	1.37	2.41
GPS+GLO	0.39	0.35	-1.39	0.90	1.36	3.04
GPS+GLO+BDS	0.26	0.57	-1.03	0.70	1.12	2.44
GPS+GLO+BDS+QZS	0.29	0.47	-0.74	0.70	1.02	2.18

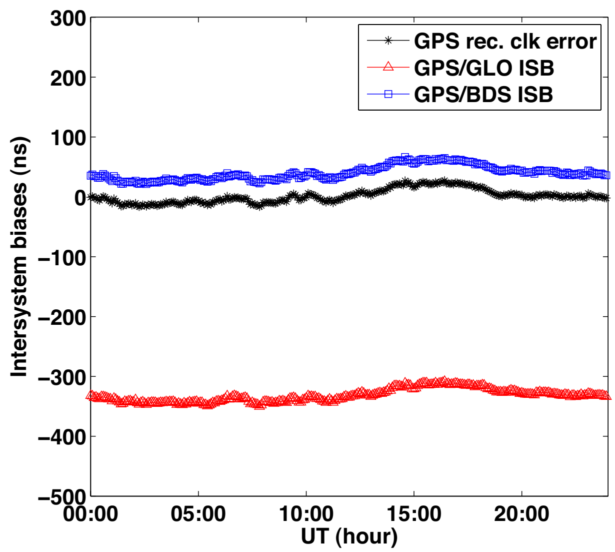

Fig. 5. The temporal variations of GPS/GLONASS ISB and GPS/BeiDou ISB.

in the north and up directions decreased; and in particular, the position accuracy in the up direction was significantly affected.

For the combinations between different systems, an improvement in the position accuracy can be expected due to the increase of visible satellites. However, in the case of the combinations between different navigation systems, the intersystem bias (ISB) should be considered.

Fig. 5 shows the ISB variations of the Trimble NetR9 receiver operated at the MKPO GNSS reference station. The ISB is a relative value between systems. It shows different characteristics for each GNSS receiver, and it also varies depending on data, estimation methods. A large difference could occur due to the data processing method such as standard point positioning and PPP. Wang et al. (2015) reported that the ISB modeling method affected the position error of a user.

In Fig. 5, the horizontal axis represents the time, and the vertical axis represents the ISB value (nano-seconds). In Fig. 5, the black stars represent the variation in the clock error of the GPS receiver, and the red triangles and blue squares represent the variations in the ISB between the GPS and GLONASS (GLO) systems and the ISB between the GPS and BeiDou (BDS) systems, respectively. The receiver clock errors of GLONASS and BeiDou were calculated by the sum of the GPS receiver clock error and the ISB, respectively. The daily averaged ISB between GPS/GLO was -322.21 ns, and that between GPS/BDS was 39.83 ns. Thus, in terms of the absolute value, the daily averaged ISB between GPS/GLO was relatively larger than that between GPS/BDS. Our result was in good agreement with that reported by Schaer (2012).

4. SUMMARY AND CONCLUSIONS

In the present study, the position accuracy performance in the combination of navigation satellites was analyzed using the multi-GNSS data received at MKPO station in South Korea. To compare the position accuracy performance, data processing was performed based on a total of five combinations: 'GPS-only', 'GPS+BDS', 'GPS+GLO', 'GPS+GLO+BDS', and 'GPS+GLO+BDS+QZS'. The analysis of the position errors indicated that the 'GPS+GLO' combination had relatively larger position errors compared to other combinations, while the 'GPS+GLO+BDS+QZS' combination had smaller position errors. Based on this study, it is noted that the combination of many navigation satellites observed at the MKPO station in South Korea affects the position accuracy of users as well as an increase of visible satellites.

In addition, the ISB among different navigation systems was estimated, where the daily averaged ISB values for GPS/GLO and GPS/BDS were -322.21 ns and 39.83 ns, respectively. In addition, the averaged absolute GPS/GLO ISB was larger than GPS/BDS ISB.

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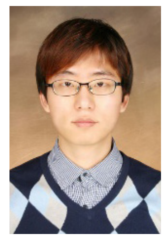

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