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Accuracy Evaluation of IGS-RTS Corrections to Stand-Alone Positioning Based on GPS Code-Pseudorange Measurements

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ABSTRACT

The International GNSS Service (IGS) provides the IGS-Real Time Service (IGS-RTS) corrections that can be used in stand-alone positioning in real time. In this study, the positioning accuracy before and after the application of the corrections to broadcast ephemeris by applying the IGS-RTS corrections at code pseudo-range based stand-alone positioning was compared with positioning result using precise ephemeris. The analysis result on IGS-RTS corrections showed that orbit error and clock error were 0.05 m and 0.5 ns compared to precise ephemeris and accuracy improved by about 8.5% compared to the broadcast ephemeris-applied result when the IGS-RTS was applied to positioning. Furthermore, regionally dispersed five observatories were selected to analyze the effect of external environments on positioning accuracy and positioning errors according to location and time were compared as well as the number of visible satellites and position dilution of precision by observatory were analyzed to verify a correlation with positioning error.

Keywords: IGS-RTS, GPS, code-pseudorange, corrections

1. INTRODUCTION

A positioning method using global positioning system (GPS) satellites can be largely divided into two: a method using carrier phase and a method using code-pseudorange. For the method using carrier phase, positioning algorithms are complex and it is difficult to identify integer ambiguity included in observation value but if integer ambiguity is determined accurately, a level of several cm positioning accuracy can be obtained. On the other hand, for the method using code-pseudorange, positioning algorithms are relatively simple but its accuracy is generally a level of several meter accuracy, which is much lower than that of the method using carrier phase. However, the use of code-pseudorange is better in terms of miniaturization and low price than using carrier phase, which is why most personal mobile terminals used by general users employ chip sets that receive code-pseudorange (Kim 2016).

In order to increase accuracy of code-pseudorange, differential GPS (DGPS) or precise point positioning (PPP) method can be typically used. The DGPS calculates pseudo-range correction (PRC) at the reference station of the known point thereby providing this to the user. It is known to have a level of 1–2 m accuracy. However, since a beacon method using medium-wave broadcast or network transport of radio technical commission for maritime service (RTCM) via Internet protocol (NTRIP) is used in order to deliver the PRC to the user, additional beacon reception equipment is needed or wireless or wired Internet environment shall be maintained and it has a disadvantage of error increase in positioning as a distance is farther away from the reference station (Kim et al. 2012).

On the other hand, since corrections about satellite orbit and clock created from the reference station network instead of a single reference station is supplied in PPP,

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accurate positioning can be possible with a single receiver regardless of a baseline distance between reference station and user. Most of previous studies on PPP in Korea and other nations are based on carrier phase (Heroux & Kouba 1995, Zumberge et al. 1997, Choi et al. 2011). There is a previous study on PPP using code-pseudorange by Park et al. (2014) to apply PPP to mobile terminals. However, since Park et al. (2014) employed precise ephemeris provided by the International GNSS Service (IGS) rather than using corrections of satellite orbit and clock, it can generate a result which is different from that processed by receiving corrections in real time.

In the present study, IGS-Real Time Service (IGS-RTS) corrections-applied stand-alone algorithm based on code-pseudorange was developed. In order to verify the accuracy of IGS-RTS corrections used in correction of satellite orbit and clock, it was compared with precise ephemeris and positioning results were also compared with those using precise ephemeris to evaluate the performance.

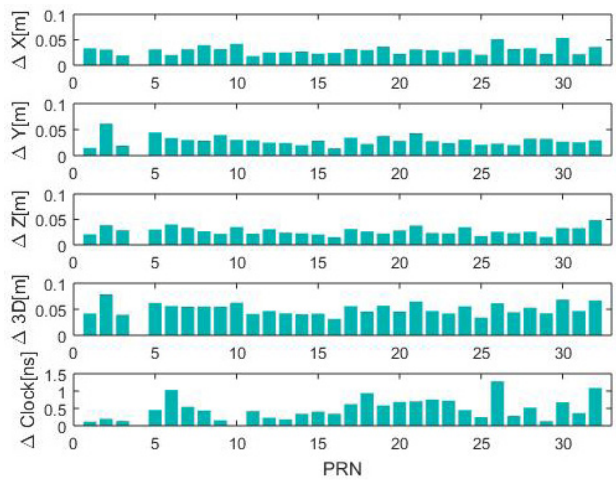

Fig. 1. RMS error (DOY 12) by components of corrected satellite orbit and clock corrections.

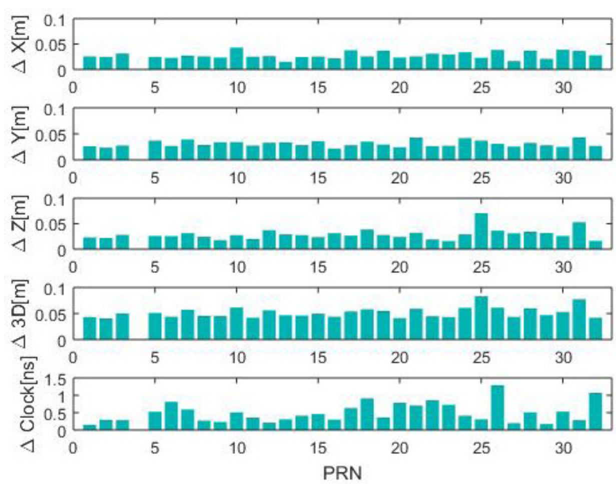

Fig. 2. RMS error (DOY 13) by components of corrected satellite orbit and clock corrections.

2. ANALYSIS ON ACCURACY OF CORRECTIONS

The IGS has operated the IGS-RTS service that provides corrections of satellite orbits and clocks in real time since April 1 in 2013. The data format supplied by the IGS-RTS is a state space representation (SSR) message using RTCM format. The service is provided with three types of streams according to data processing method or types of satellite systems. Each of the streams provides corrections only about satellite orbits and clocks and has a different combination method. The first type IGS01/IGC01 provides corrections made by combining corrections provided by institutions on the basis of epoch. The IGS02 stream provides corrections made by combining corrections using a Kalman filter. The IGS03 stream is a pilot stream in a trial phase, which is different from other streams and provides not only GPS corrections but also GLONASS corrections (ftp://igs.org/pub/resource/pubs/IGS_Real_Time_Service-131031.pdf).

According to Krzan & Przestrzelski (2016), IGS02 stream was more accurate than IGS01 during positioning among two streams that provided corrections for GPS only. Thus, this study used IGS02 stream in order to analyze the accuracy of corrections. In this study, BKG NTRIP Client was used as software to receive data. Assuming that precise ephemeris was a true value, the accuracy of corrections was compared and analyzed. Because precise ephemeris is a center of mass coordinate but corrections provided by the IGS02 stream is provided by antenna phase center coordinate, coordinates were matched by applying the phase center offset prior to the comparison and analysis in this study. The data used in the comparison of accuracy were obtained for two days of January 12 (DOY 12) and 13 (DOY 13) in 2016 and the satellite orbit corrections were received in every 60 sec and the satellite clock corrections were received in every 10 sec.

Figs. 1 and 2 show root mean square (RMS) errors of satellite orbit and clock to which IGS-RTS corrections are applied by date. The satellite orbit correction result showed that the X, Y, and Z axes revealed a consistent level of errors around 3 cm and the corrected 3D RMS error also showed a constant error around 5 cm regardless of date. The satellite clock error showed 0.5 ns on average although it was different from satellite to satellite. Table 1 also show RMS errors of satellite orbit and clock according to corrections

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Table 1. RMS error by component of satellite orbit and clock according to corrections applied.

	DOY12		DOY13	
	Before correction	Before correction	After correction	After correction
X [m]	0.732	0.030	0.703	0.028
Y [m]	0.757	0.029	0.726	0.031
Z [m]	0.750	0.028	0.732	0.029
3D [m]	1.313	0.051	1.267	0.052
Clock [ns]	1.406	0.502	1.494	0.498

Table 2. Latitudes, longitudes, altitudes and reception equipment used in the target observatories.

Observatory	Latitude [°]	Longitude [°]	Height [m]	Receiver name	Antenna type
Suwon (SUWN)	37.74	126.49	47.87	Trimble NetR9	TRM59800.80
Daejeon (DAEJ)	36.40	127.37	117.04	Trimble NetR9	TRM59800.00
Ganghwa (SBSA)	37.28	127.05	83.93	JAVAD Sigma G3T	JAD RingAnt-DM
Naju (SBSE)	35.02	126.71	71.43	JAVAD Sigma G3T	JAD RingAnt-DM
Goseong (SBSP)	38.38	128.46	47.46	JAVAD Sigma G3T	JAD RingAnt-DM

applied by date. Hadas & Bosy (2015) reported that the satellite orbit accuracy of the IGS01 stream was about 5 cm and the satellite clock accuracy was about 0.3 ns and El-Diasty & Elsobeiey (2015) reported that the satellite orbit accuracy was 5 cm and the satellite clock accuracy was 0.5 ns. In previous studies, the result was based on IGS 01. But performance of corrections per stream and performance after applying PPP can be found in the web page of the IGS. The comparison of 3D RMS errors after applying PPP from January 1 to 10 in 2016 using the above information showed that the IGS01 stream had 0.31 m and the IGS02 stream had 0.27 m, indicating a level of cm difference. Thus, it was concluded that performance between IGS01 and IGS02 was similar. Accordingly, it was verified that the present study result showed a similar level in the previous study results.

3. APPLICATION TO POSITIONING AND COMPARISON ON ACCURACY

Positioning was performed using the code-pseudorange based stand-alone positioning algorithm and the positioning performance through the following three methods was analyzed. First, only broadcast ephemeris was used. Second, broadcast ephemeris and IGS-RTS corrections were applied to verify the improvement of accuracy compared to that using only broadcast ephemeris. Third, positioning performance applied corrections was analyzed using precise ephemeris.

3.1 Positioning Target Region

Five regions were selected for the positioning target to evaluate the accuracy. Positioning was conducted using the data provided by Suwon (SUWN), one of the continuously operating reference station in the National Geographic Information Institute, Daejeon (DAEJ) one of the continuously operating reference station in the Korea Astronomy and Space Science Institute, Ganghwa (SBSA), Naju (SBSE), and Goseong (SBSP), three of the continuously operating reference station constructed by Seoul Broadcasting System (SBS) for PPP-RTK in South Korea. For the observation dates, January 12 (DOY12) and 13 (DOY13) in 2016 were used, which were the same as the dates of evaluation on accuracy of corrections. Table 2 summarizes latitudes and longitudes as well as altitudes of the target observatories and types of receivers and antennas used in the observatories.

3.2 Error Model

The code-pseudorange is determined using a difference between satellite time when satellite signal is transmitted and receiver time when the signal is arrived. However, satellite time and receiver time include a clock error. In addition, ionospheric error and tropospheric error due to the influence by the atmosphere, multi-path error caused by the surrounding environment of receivers, and hardware error in receivers and satellites shall also be taken into consideration. The general GPS code-pseudorange equation including the above error model is as follows:

$$p = \rho + c(\delta t_r - \delta t^s) + I + T + M + b_r + b^s + \epsilon \quad (1)$$

where p is a code observation value, ρ is a geometric distance between satellite and receiver, c is the speed of light, δt_r and δt^s are receiver clock error and satellite clock error, I is the ionospheric error, T is the tropospheric error, M is a multi-path error of the code observation value, b_r and b^s are hardware errors of receiver and satellite, and ϵ is a code signal noise. The satellite orbit during general stand-alone positioning rather than precise stand-alone positioning is calculated via broadcast ephemeris and satellite clock error can be modeled using specific polynomial equation with coefficients included in broadcast ephemeris. However, since the accuracy of broadcast ephemeris is 1 m for orbit and 5 ns for satellite clock, these shall be corrected to improve positioning accuracy. In such case, IGS-RTS can be used as a correction value to broadcast ephemeris. Information related to satellite orbit is provided via message type No. 1057 and information related to satellite clock is provided via message type 1058. In the message type 1057, GPS Issue Of Data Ephemeris, radial, along-track, cross-track direction correction value for each PRN, and change rate of correction value over time by each direction are also provided. Using the above information, a method that corrects a satellite coordinate calculated with broadcast ephemeris is as follows:

$$r^s(t) = r^s_{broadcast}(t) - \delta X \tag{2}$$

In Eq. (2), $r^s_{broadcast}$ is a satellite coordinate calculated using broadcast ephemeris, δX is a correction value of satellite orbit calculated using corrections, and $r^s(t)$ is a correction completed satellite orbit coordinate. Here, in order to calculate δX, unit vector and satellite orbit corrections (δO) for each direction are needed and satellite orbit corrections is calculated using a correction value (δO_{radial}, δO_{along}, δO_{cross}) for each direction and change rate ($\delta \dot{O}_{radial}$, $\delta \dot{O}_{along}$, $\delta \dot{O}_{cross}$) over time.

$$\delta X = [e_{radial}\ e_{along}\ e_{cross}]\ \delta O \tag{3}$$

$$\delta O = \begin{bmatrix} \delta O_{radial} \\ \delta O_{along} \\ \delta O_{cross} \end{bmatrix} + \begin{bmatrix} \delta \dot{O}_{radial} \\ \delta \dot{O}_{along} \\ \delta \dot{O}_{cross} \end{bmatrix} (t - t_0) \tag{4}$$

Next, in the message type 1058 that corrects a satellite clock error, coefficients (C_0, C_1, C_2) of polynomial equation are provided to calculate corrections as a format of polynomial equation. A process that calculates corrections of satellite clock error from the SSR message is as follows:

$$dt^s = dt^s_{broadcast} - \frac{\delta C}{speed\ of\ light} \tag{5}$$

$$\delta C = C_0 + C_1(t - t_0) + C_2(t - t_0)^2 \tag{6}$$

In Eq. (5), $dt^s_{broadcast}$ represents a satellite clock error calculated via broadcast ephemeris and δC refers to corrections of satellite clock error calculated using polynomial equation in Eq. (6).

In addition, for the ionospheric error that can be modeled in the code-pseudorange equation, the global ionosphere model provided by the IGS was applied and the tropospheric error was modeled via the global pressure and temperature model using a global mapping function. The detailed equations and definitions about the ionospheric and tropospheric models were discussed in Park et al. (2014) and Won (2015) so they were found in Reference in the present paper.

3.3 Positioning Measurement Result

Data from Ganghwa, Naju, and Goseong provided by the SBS among the observation data were received in every sec. and data from Daejeon and Suwon, which can be received in the IGS, were received in every 30 sec. Due to this difference, all data were sampled with 30 sec. interval to have data processing at the same interval. The CLK file that was provided in every 30 sec. was used rather than using SP3 file provided in every 15 min. for the satellite clock error among precise ephemeris, which was assumed as a true value. For DOY12 day data, which were received normally for 24 hours, data processing was done with 2880 epochs. On the other hand, DOY13 day data were received only up to 17:00. Thus, the other data were matched with 2040 epochs prior to data processing.

Table 3 shows the results via the positioning method by date in the positioning target region. 3D RMS error, to which IGS-RTS corrections was applied on the basis of broadcast ephemeris, was reduced by 0.17 m on average and accuracy was improved by 8.5%. In addition, 3D RMS error, to which IGS-RTS corrections was applied on the basis of precise ephemeris, was reduced by 0.09 m on average and accuracy was improved by 4.8%. The result, to which IGS-RTS corrections was applied on the basis of broadcast ephemeris, was not improved significantly compared to a level of improvement on accuracy of satellite orbit and clock as described in the above. The reason for this was due to the presence of noise that was basically included in the code-pseudorange even if other errors were accurately modeled when the code pseudorange was employed, resulting in possible influence of the noise on the positioning result. Due to this reason, positioning using precise ephemeris was also conducted and the result showed that the IGS-RTS corrections-applied positioning result had a difference less than 10 cm compared to the positioning result using precise ephemeris, resulting in better improvement on accuracy than that using only broadcast ephemeris. Thus, it was concluded that the correction was successfully applied. This can be more clarified if more accurate correction is applied to errors except for satellite orbit and clock errors in the future.

Table 3. Positioning performance by date according to positioning method in the experimental target regions.

Region	Date	Category	RMSE [m]		
			2D	Vertical	3D
Ganghwa (SBSA)	DOY12	BRDC	0.98	1.41	1.72
		RTS	0.80	1.32	1.54
		SP3	0.81	1.21	1.46
	DOY13	BRDC	0.93	2.11	2.30
		RTS	0.89	1.78	1.99
		SP3	0.92	1.75	1.98
Daejeon (DAEJ)	DOY12	BRDC	1.24	1.80	2.18
		RTS	1.14	1.82	2.14
		SP3	1.15	1.63	1.99
	DOY13	BRDC	1.19	2.36	2.64
		RTS	1.10	2.24	2.49
		SP3	1.15	2.15	2.44
Suwon (SUWN)	DOY12	BRDC	0.97	1.39	1.70
		RTS	0.84	1.31	1.56
		SP3	0.81	1.17	1.42
	DOY13	BRDC	0.93	1.90	2.11
		RTS	0.89	1.71	1.93
		SP3	0.93	1.64	1.89
Naju (SBSE)	DOY12	BRDC	0.94	1.50	1.77
		RTS	0.82	1.45	1.67
		SP3	0.80	1.33	1.56
	DOY13	BRDC	0.86	2.03	2.20
		RTS	0.90	1.84	2.05
		SP3	0.90	1.72	1.94
Goseong (SBSP)	DOY12	BRDC	0.97	1.35	1.66
		RTS	0.76	1.29	1.50
		SP3	0.76	1.15	1.38
	DOY13	BRDC	0.92	1.98	2.18
		RTS	0.82	1.67	1.86
		SP3	0.86	1.61	1.82

4. POSITIONING ERROR ACCORDING TO SATELLITE CONFIGURATION AND OBSERVATORY

In this study, the number of visible satellites and Position Dilution Of Precision (PDOP) were analyzed in order to verify the geometric configuration of satellites in the positioning target regions. In addition, two-day positioning results from each observatory were compared in order to verify a pattern of error due to analysis date. Furthermore, five observatories, which were regionally distanced, were selected to verify a difference due to geographical location. Moreover, the target observatories were divided into Suwon and Daejeon Observatories in which NetR9 of Trimble Company was used as a receiver, and Ganghwa, Naju, and Goseong Observatories, in which Sigma G3T of JAVAD Company was used as a receiver, to calculate a correlation coefficient thereby analyzing not only correlation between observatories but also correlation according to a type of receiver.

4.1 PDOP in the Observatories

The dilution of precision that is determined by the geometric configuration of satellites refers to accuracy degradation. It indicates whether a state of the satellite configuration that affects the accuracy of navigation solution is good or bad. Among them, PDOP refers to a degradation rate of precision with regard to 3D positions. If PDOP is less than 5, satellite configuration is said to be good. That is, the lower the value, the better the configuration.

Table 4. Number of visible satellites and PDOP by date in the experimental target regions.

Region	DOY12		DOY13	
	Visible satellite	PDOP	Visible satellite	PDOP
Ganghwa (SBSA)	10.01	1.60	9.89	1.56
Daejeon (DAEJ)	9.24	1.78	9.24	1.77
Suwon (SUWN)	9.21	1.80	9.19	1.81
Naju (SBSE)	9.53	1.73	9.34	1.72
Goseong (SBSP)	9.66	1.65	9.45	1.65

Table 4 shows the number of visible satellites and mean values of PDOP by date in the experimental target regions. The calculated PDOP was not calculated in the data processing process in order to take only the real satellite configuration into consideration but it was calculated using precise ephemeris separately. The result of PDOP was the lowest in Ganghwa followed by Goseong, Naju, Daejeon, and Suwon. Although there was some difference in values, the same order was maintained in DOY12 and DOY13. In addition, a mean value of the number of visible satellites was inversely proportional to the order of the PDOP precisely so that geometric configuration of the satellites became better as the number of visible satellites was increased. However, even if the number of visible satellites at DOY12 was larger than that of DOY13 as shown in Ganghwa observatory, the PDOP in DOY13 was smaller than that in DOY12 in some case. This result indicated that the number of visible satellites was not an absolute determinant of the PDOP value since the satellite configuration was also considered in determining the PDOP value in addition to the number of visible satellites. A difference in PDOP values by observatories and date was not that large, which was less than 2, verifying that the positioning was conducted under the good condition of satellites.

4.2 Correlation Coefficient in the Observatories

Fig. 3 shows a time series of mean 3D RMS error in every hour in order to determine the pattern of positioning errors. The error in each observatory shown in the graph revealed a similar hourly trend. In order to analyze a correlation according to observatory and type of receiver, a correlation coefficient was calculated using 3D RMS error for each observatory and the results are shown in Table 5.

Overall, a correlation coefficient for each observatory

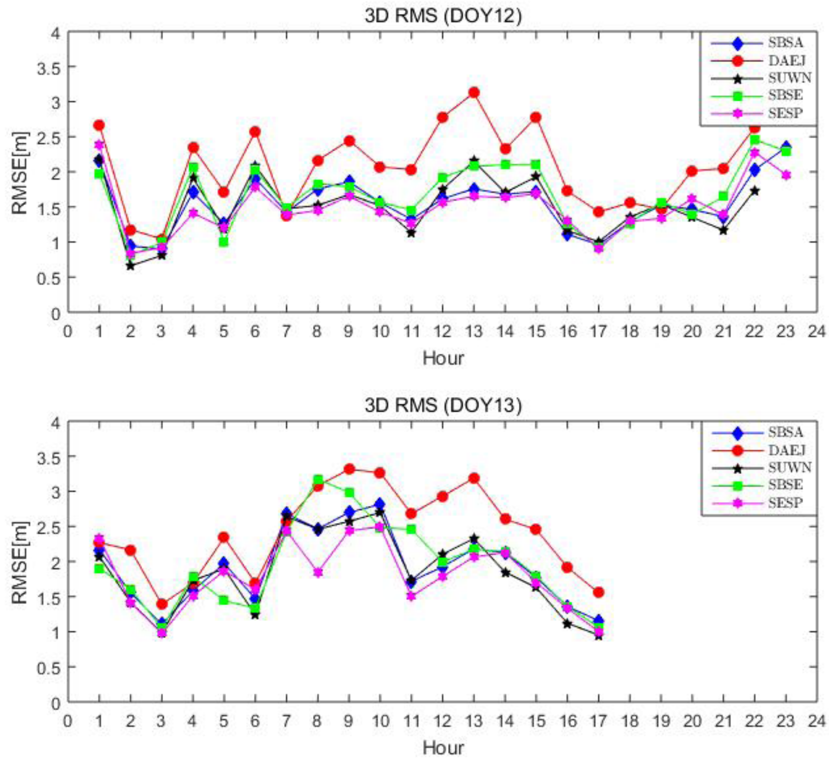

Fig. 3. Mean 3D RMS error by date in the experimental target regions.

Table 5. Correlation coefficient by date in the experimental target regions.

	RMS	Ganghwa	Daejeon	Suwon	Naju	Goseong
	Ganghwa	1				
	Daejeon	0.83	1			
DOY12	Suwon	0.91	0.86	1		
	Naju	0.90	0.87	0.87	1	
	Goseong	0.94	0.78	0.81	0.83	1
	Ganghwa	1				
	Daejeon	0.86	1			
DOY13	Suwon	0.97	0.87	1		
	Naju	0.85	0.86	0.86	1	
	Goseong	0.94	0.76	0.90	0.70	1

was 0.86 on average, which showed a high correlation. In order to verify a correlation according to a type of receiver, a correlation coefficient of Daejeon-Suwon where Trimble NetR9 was used and a correlation coefficient of other observatories were compared. The result showed that a correlation coefficient between the observatories that used the same receiver was 0.86 while a correlation coefficient between observatories that used a different receiver was also 0.86. Thus, no correlation was found according to a type of receiver.

5. CONCLUSION

In this study, the results using corrections-applied broadcast ephemeris were compared to that using precise ephemeris in order to analyze the accuracy of the IGS-RTS corrections. The comparison result showed that the satellite orbit was 5 cm and the satellite clock was 0.5 ns, which were the same as those reported in previous results in other nations. The results of positioning using only broadcast ephemeris and positioning using corrections-applied broadcast ephemeris were compared to analyze positioning accuracy. The comparison result revealed improvements due to corrections. As a result, accuracy was improved by 8.5% due to the reduction in positioning error, which was 0.17 m on average. Furthermore, the results of corrections-applied broadcast ephemeris were compared with those using only precise ephemeris in order to ensure the reliability of the corrections-applied positioning results. The result verified that a difference in the positioning error was less than 10 cm on average, indicating that successful corrections were applied. Moreover, the number of visible satellites and PDOP were calculated to verify the geometric configuration of satellites and correlation coefficients of positioning results at regionally dispersed observatories in Korea were calculated to identify the correlation according to location. The number of visible satellites in the experimental target observatories was more than nine and PDOP value was less than 2, indicating that positioning was conducted at good satellite condition. The analysis results on correlation coefficient of the observatories verified that the positioning error due to the same observation date had a high correlation whereas no significant correlation was found due to a type of receiver. The reasons for the similar hourly pattern of positioning error were due to inaccurate modeling on the errors due to hourly satellite orbit, satellite clock, tropospheric and ionospheric errors resulting in a similar influence.

In this paper, a difference between before and after applying the IGS-RTS corrections to broadcast ephemeris was not so large but positioning error was reduced when corrections was applied. Therefore, if more accurate error modeling can be established through additional research on other error factors such as tropospheric and ionospheric errors or additional corrections such as satellite clock and orbit can be provided in the future, positioning accuracy can be improved in various areas where code pseudorange is utilized such as mobile terminals.

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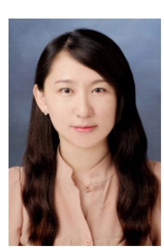

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