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Analysis of the Combined Positioning Accuracy using GPS and GLONASS Navigation Satellites

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ABSTRACT

In this study, positioning results that combined the code observation information of GPS and GLONASS navigation satellites were analyzed. Especially, the distribution of GLONASS satellites observed in Korea and the combined GPS/GLONASS positioning results were presented. The GNSS data received at two reference stations (GRAS in Europe and KOHG in Goheung, Korea) during a day were processed, and the mean value and root mean square (RMS) value of the position error were calculated. The analysis results indicated that the combined GPS/GLONASS positioning did not show significantly improved performance compared to the GPS-only positioning. This could be due to the inter-system hardware bias for GPS/GLONASS receivers, the selection of transformation parameters between reference coordinate systems, the selection of a confidence level for error analysis, or the number of visible satellites at a specific time.

Keywords: GPS, GLONASS, positioning accuracy, GNSS

1. INTRODUCTION

Currently, the global positioning system (GPS) of the United States and the global orbiting navigation satellite system (GLONASS) of Russia are global navigation satellite systems that can perform positioning and provide time information. GPS satellites have been continuously operated as a navigation system since 1980. However, for GLONASS satellites, the service was interrupted for a short period of time due to the financial problem of Russia. Then the satellite launching was resumed after 2007, and total 24 satellites have been arranged on three orbital planes. After November 2012, GLONASS satellites successfully achieved full operation, and resumed precise positioning service, along with the GPS.

In poor observation environment (i.e., downtown area), the GPS occasionally has trouble in determining receiver positions due to the lack of the number of visible satellites (Toshiaki et al. 2000). Also, even though the number of visible satellites is sufficient, the geometric arrangement of GPS satellites affects the positioning accuracy and reliability. To complement this, studies have been conducted, which increase the number of visible satellites and positioning reliability by combining the observation data of GPS satellites and GLONASS satellites (Bruyninx 2007, Dodson et al. 1999, Cai & Gao 2007). The combination of GPS satellites and GLONASS satellites could improve the number of visible satellites and the position dilution of precision (PDOP), compared to when only GPS satellites are used.

GLONASS satellites have large potential for precision navigation and positioning, which has been demonstrated by the International GLONASS Service Pilot Project (Zarraoa et al. 1998).

A combined positioning method, which uses the observation data of GPS and GLONASS satellites, is very similar to a GPS-only positioning method. Both of the two systems are based on the principle of triangulation that considers the distance between satellite and receiver. However, the GPS and GLONASS navigation satellite systems have completely different navigation data structure, reference coordinate system, and reference time system. Therefore, to calculate the final solution by combining the observation data of the two systems, the data interpretation (e.g., satellite orbit determination and statistical error model) needs to be applied differently.

Kim & Park (2009) conducted a study that evaluates the

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orbit accuracy of satellites using the Runge-Kutta method for the orbit prediction of GLONASS satellites. Lee et al. (2010) analyzed the orbit determination and accuracy of GLONASS satellites. Also, Park & Song (2004) derived a GLONASS measurement model, which can simultaneously use the GPS and the GLONASS, and Kang et al. (2001) used the coarse/acquisition (C/A) code and Yuma satellite orbit information to analyze the precision of absolute positioning by combining the observation data of the GPS and the GLONASS.

In this study, an algorithm that calculates positioning results by simultaneously using the observation data of GPS and GLONASS satellites was developed, and the position accuracy was compared with that of GPS-only positioning results.

2. OUTLINE OF THE GPS AND GLONASS SYSTEMS

GPS satellites use two frequencies in the L-band (L1~1575.42MHz and L2~1227.60MHz). Each satellite has its own identification code [i.e., pseudo random noise (PRN) code], and this is an important element of the code division multiple access (CDMA) method.

On the other hand, for the GLONASS system, each satellite uses different frequencies. In other words, frequency division multiple access (FDMA) method is used, and it is somewhat more complicated than the GPS. GLONASS satellites transmit signals in two frequency bands, as shown in Eqs. (1) and (2) (Abbasian & Petovello 2010).

$$f_{L1} = (1602 + n \times 0.5625)\,\mathrm{MHz} \tag{1}$$

$$f_{L2} = (1246 + n \times 0.4375)\,\mathrm{MHz} \tag{2}$$

where n(n=0,1,2,...) represents the frequency channel number.

Table 1 summarizes the comparison of the GPS and GLONASS systems. As shown in the table, the two systems are basically different systems (e.g., number of satellites, reference time system, and reference coordinate system).

The broadcast ephemeris of GPS satellites is sent to users via navigation messages. Navigation messages include orbital elements and other ephemeris information, and GPS satellites perform orbit determination using this ephemeris information. The International GNSS Service (IGS) reported that the error of GPS satellites using broadcast ephemeris is about 1 m level (http://igs.org/components/prods.html). Unlike the GPS, for the broadcast ephemeris of GLONASS satellites, velocity and acceleration components at a specific time are transmitted rather than orbital elements. Therefore, for the orbit determination of GLONASS satellites, six orbital differential equations that were published in the GLONASS interface control document (ICD) are required, as shown in Eqs. (3-8).

Table 1. Comparison of the GPS and GLONASS systems (Reference week number: 1698).

Item	GPS	GLONASS
Number of Satellites	32	24
Satellite orbital plane	6	3
Number of satellites per orbital plane	4 + alternative satellite	8 + alternative satellite
Orbital inclination (degree)	55	64.8
Orbital radius (km)	26,560	25,510
Orbital period	11 hours 58 minutes	11 hours 15 minutes
Reference time system	UTC-based GPS time	UTC-based GLONASS time
Reference coordinate system	WGS84	PZ90
C/A code rate (MHz)	1.023	0.511
C/A code chip length (m)	293	587
P code rate (MHz)	10.23	5.11
P code chip length (m)	29.3	58.7
Signal division	CDMA code division method	FDMA frequency division method
Frequency (MHz)	L1: 1575.42 L2: 1227.60	L1: 1602+n×0.5625 L2: 1646+n×0.4375 n: channel number

$$\frac{dx}{dt} = V_x \tag{3}$$

$$\frac{dy}{dt} = V_y \tag{4}$$

$$\frac{dz}{dt} = V_z \tag{5}$$

$$\frac{dV_x}{dt} = -\frac{\mu}{r^3}x + \frac{3}{2}C_{20}\frac{\mu(a_e^2)}{r^5}x[1-\frac{5z^2}{r^2}] + \omega_3^2 x + 2\omega_3 V_y + \ddot{x} \tag{6}$$

$$\frac{dV_y}{dt} = -\frac{\mu}{r^3}y + \frac{3}{2}C_{20}\frac{\mu(a_e^2)}{r^5}y[1-\frac{5z^2}{r^2}] + \omega_3^2 y - 2\omega_3 V_x + \ddot{y} \tag{7}$$

$$\frac{dV_z}{dt} = -\frac{\mu}{r^3}z + \frac{3}{2}C_{20}\frac{\mu(a_e^2)}{r^5}z[3-\frac{5z^2}{r^2}] + \ddot{z} \tag{8}$$

where, $r = \sqrt{x^2+y^2+z^2}$ gravitational constant, μ= 398600.44km^3/s^2, a_e = 6378136.0m equatorial radius of Earth, C_{20} = -1082.63 x 10^{-6} coefficient of Earth's gravitational field of spherical harmonic expansion, $\omega_3 = 7.292115 \times 10^{-5}$ Earth's rotation rate.

The broadcast ephemeris of GLONASS satellites is transmitted every 30 minutes (15 and 45 minutes on every

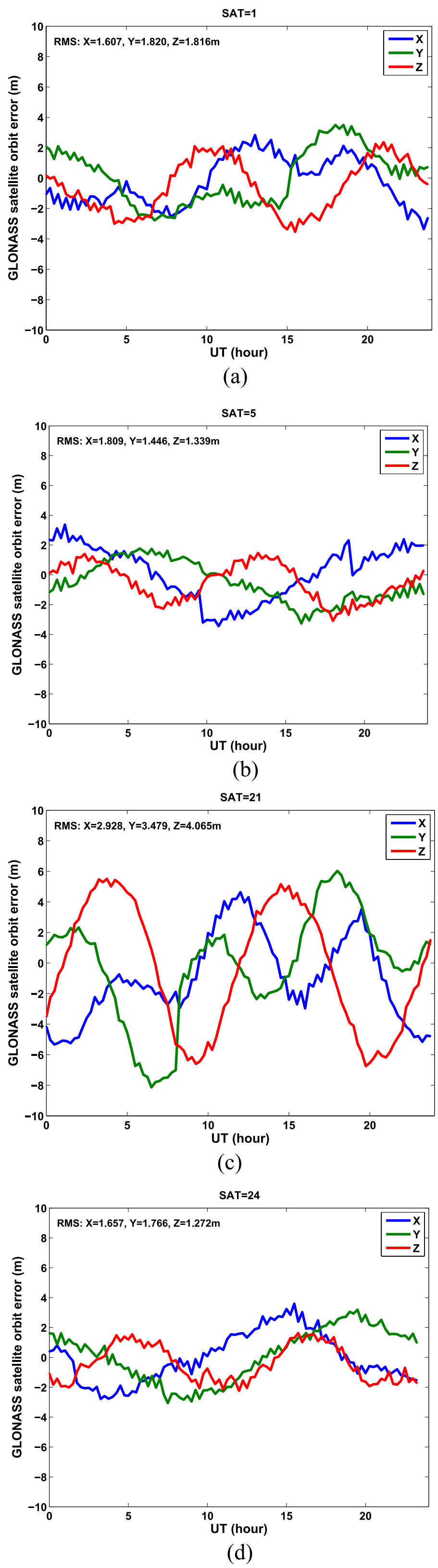

Fig. 1. Orbit error between the GLONASS satellite orbits calculated using broadcast ephemeris and the precise ephemeris: (a) GLONASS satellite 1, (b) GLONASS satellite 5, (c) GLONASS satellite 21, and (d) GLONASS satellite 24.

hour). Thus, to determine satellite orbits at a specific time, a method for propagating orbits is needed. Therefore, in this study, the quartic Runge-Kutta equation that is recommended by the GLONASS ICD (2008) was used. The Runge-Kutta method determines satellite orbits by the numerical integration of the orbital differential equations explained earlier, as shown in Eq. (9) (Rice 1983).

$$y_{n+1} = y_n + \frac{1}{6}(\kappa_1 + 2\kappa_2 + 2\kappa_3 + \kappa_4) \tag{9}$$

where,
$$\kappa_1 = hf(t_n, y_n)$$
$$\kappa_2 = hf(t_n + \frac{h}{2}, y_n + \frac{\kappa_1}{2})$$
$$\kappa_3 = hf(t_n + \frac{h}{2}, y_n + \frac{\kappa_2}{2})$$
$$\kappa_4 = hf(t_n + \frac{h}{2}, y_n + \kappa_3)$$

In Eq. (9), $\frac{1}{6}(\kappa_1 + 2\kappa_2 + 2\kappa_3 + \kappa_4)$ represents the average gradient of the function, and h represents the 'step size'. In this study, h was set to 60, considering the integration time and the satellite orbit propagation precision.

To verify the orbits of GLONASS satellites calculated using broadcast ephemeris, they were compared with the precise ephemeris provided by the IGS. Figs. 1a-d show the orbit error between the GLONASS satellite orbits calculated using broadcast ephemeris and the precise ephemeris (iglxxxxx.sp3). The results of this study were compared with the precise ephemeris, assuming that the precise ephemeris is the true value. For the GLONASS satellite orbits calculated using broadcast ephemeris, the average RMS value for each component was generally 2~3 m level, although there was slight difference among satellites.

3. COMBINED GPS/GLONASS POSITIONING METHOD AND RESULT VERIFICATION

To determine user positions using only the L1 code observation values of the GPS satellites and the GLONASS satellites, the weighted least squares method was applied (Tarrio et al. 2011).

$$\overline{x} = (H^T W H)^{-1} H^T W \overline{v} \tag{10}$$

where H is the design matrix, W is the weight matrix for the GPS satellites and the GLONASS satellites, and is the pseudorange residual vector. The state vector of the final solution is $\overline{x} = [\Delta x, \Delta y, \Delta z, \Delta t_{gps}, \Delta t_{glo}]$, and it consists of the position error in the World Geodetic System (WGS84) reference coordinate, the receiver clock error related with the GPS time, and the receiver clock error related with the GLONASS time.

$$H = \begin{bmatrix} \alpha_x^{gps1} & \alpha_y^{gps1} & \alpha_z^{gps1} & 1 & 0 \\ \alpha_x^{gps2} & \alpha_y^{gps2} & \alpha_z^{gps2} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_x^{gpsN} & \alpha_y^{gpsN} & \alpha_z^{gpsN} & 1 & 0 \\ \alpha_x^{glo1} & \alpha_y^{glo1} & \alpha_z^{glo1} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_x^{gloM} & \alpha_y^{gloM} & \alpha_z^{gloM} & 0 & 1 \end{bmatrix} \tag{11}$$

The data processing time was based on the Universal Time Coordinated (UTC), and the design matrix H was constructed as shown in Eq. (11).

For the reference coordinate system, the GLONASS system uses PZ90, and the GPS system uses WGS84. Therefore, to obtain consistent positioning results, transformation between the different coordinate systems is needed. For the transformation between the reference coordinate systems (i.e., Helmert transformation), total seven parameters are required such as three translation parameters (T_X, T_Y, T_Z), three rotation parameters (R_X, R_Y, R_Z), and a scale factor (S). The transformation equation is shown in Eq. (12) (Boucher & Altamimi 2001).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS84} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{PZ90} + \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} + \begin{bmatrix} S & -R_Z & R_Y \\ R_Z & S & -R_X \\ -R_Y & R_X & S \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{PZ90} \tag{12}$$

To compare and verify the GPS-only positioning results and the combined GPS/GLONASS positioning results, the data from two GNSS reference stations (GRAS in Europe and KOHG in Goheung, Korea) were processed. For data processing, the data received at the reference stations during a day on July 22, 2012 was used.

Fig. 2 shows the number of GPS satellites and the number of combined GPS/GLONASS satellites, observed at the GRAS reference station in Europe. The blue solid line represents the daily variation of the number of GPS satellites, and the red dotted line represents the daily variation of the number of combined GPS/GLONASS satellites. The number of visible GPS satellites was between 6 and 12, and the number of visible combined GPS/GLONASS satellites was between 10 and 21.

Fig. 3 shows the comparison of the positioning results using the observation data of the GRAS reference station. The observation data was processed every 30 seconds. For the position error of the reference station at each time interval, the mean values of east (E), north (N), and Up (U), the root mean square (RMS) value, and the three-dimensional RMS value were calculated. As shown in Fig. 3, it was found that for the GRAS reference station, the GPS-only positioning results and the combined GPS/GLONASS positioning results were not significantly different. In Fig. 3, the combined GPS/GLONASS positioning results had lower mean position error than the GPS-only positioning results, which indicates improved positioning accuracy. However, the combined GPS/GLONASS positioning results had slightly higher three-dimensional RMS value than the GPS-only positioning results, which indicates deteriorated positioning precision.

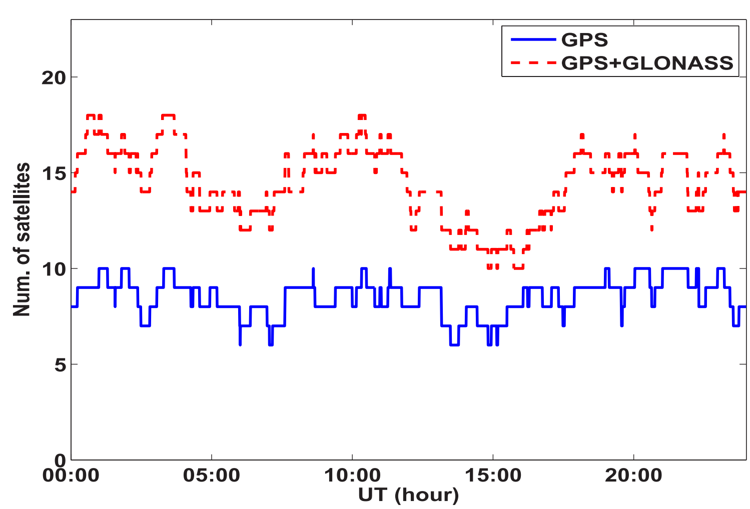

Fig. 2. Comparison of the number of GPS satellites and the number of combined GPS/GLONASS satellites, observed at the GRAS reference station.

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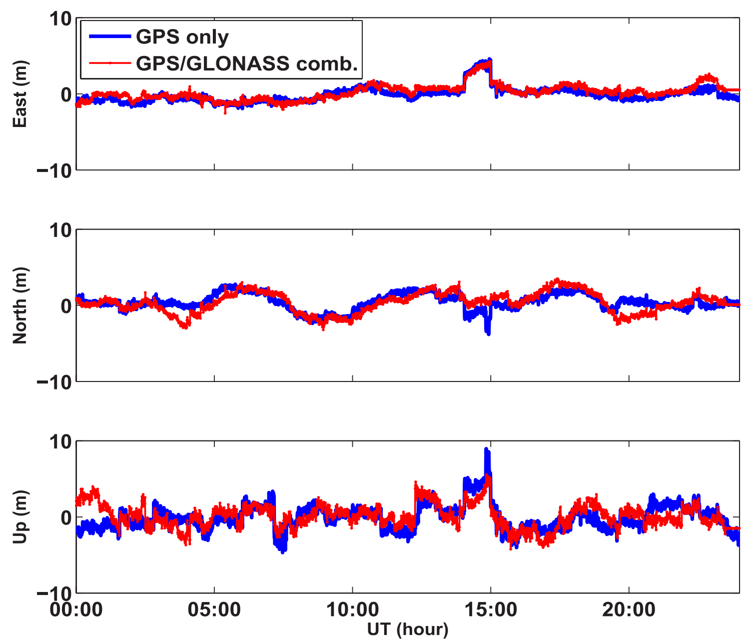

Fig. 3. Comparison of the positioning results at the GRAS reference station.

It was found that for the GRAS reference station, the positioning precision as well as the positioning accuracy was not significantly different between the results obtained from the different positioning methods. This could be due to the differences in the analysis of the data processing results such as the selection of the parameter values necessary for the transformation between the reference coordinate systems and the selection of a confidence level. Also, the increase of observation noise due to the instability of the GLONASS satellite clock could deteriorate the performance of the combined GPS/GLONASS data processing.

Figs. 4 and 5 compare the number of satellites and the positioning results, respectively, observed at the KOHG reference station in Korea. The number of visible GLONASS satellites as well as the number of visible GPS satellites was generally smaller than those at the GRAS reference station. Fig. 5 shows the positioning results using the observation data of the KOHG reference station. The combined GPS/GLONASS data processing results did not show superior performance compared to the GPS-only data results. This could be due to the instability of the estimated GLONASS receiving time, which was caused by the lack of the number of GLONASS satellites received at the KOHG reference station. Also, the complex causes (e.g., increase of observation noise, selection of a confidence level, selection of the transformation parameters between the reference coordinate systems, and inter-system hardware bias) explained earlier in the GRAS data processing results could deteriorate the performance of the combined data processing.

Table 2 shows the calculated statistical values of the GPS-only positioning error and the combined GPS/GLONASS positioning error at a 95% confidence level. It was expected that the position accuracy could be largely improved by combining the observation data of the GPS satellites and the GLONASS satellites. However, as shown in the calculated errors of the different positioning methods, the data processing results of the above two reference stations did not show improved performance. For the KOHG reference station, the combined positioning results showed rather lower positioning accuracy and precision than the GPS-only positioning results; and for the GRAS reference station, the GPS-only positioning results and the combined positioning results showed similar performance. In summary, the increase in the number of visible satellites does not guarantee drastic improvement of positioning accuracy.

Table 2. Comparison of the GPS-only positioning results and the combined GPS/GLONASS positioning results (95% confidence level).

Reference station	Statistical value	GPS-only positioning error (cm)			Combined GPS/GLONASS positioning error (cm)		
		E	N	U	E	N	U
GRAS	Mean RMS 3D RMS	-23.97 69.12	35.69 104.76 108.15	-25.58 135.09	5.63 79.66	26.03 127.62 117.47	1.59 133.75
KOHG	Mean RMS 3D RMS	-5.47 53.67	85.17 125.50 132.26	28.11 173.77	-20.76 105.19	86.49 147.07 151.46	58.80 185.75

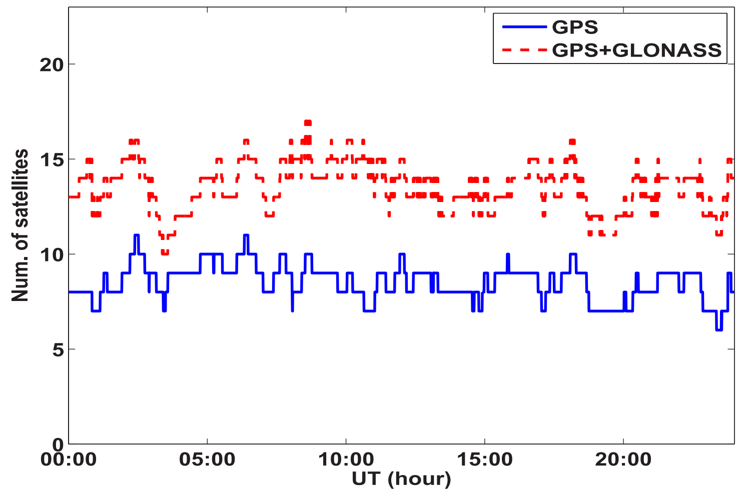

Fig. 4. Comparison of the number of GPS satellites and the number of combined GPS/GLONASS satellites, observed at the KOHG reference station.

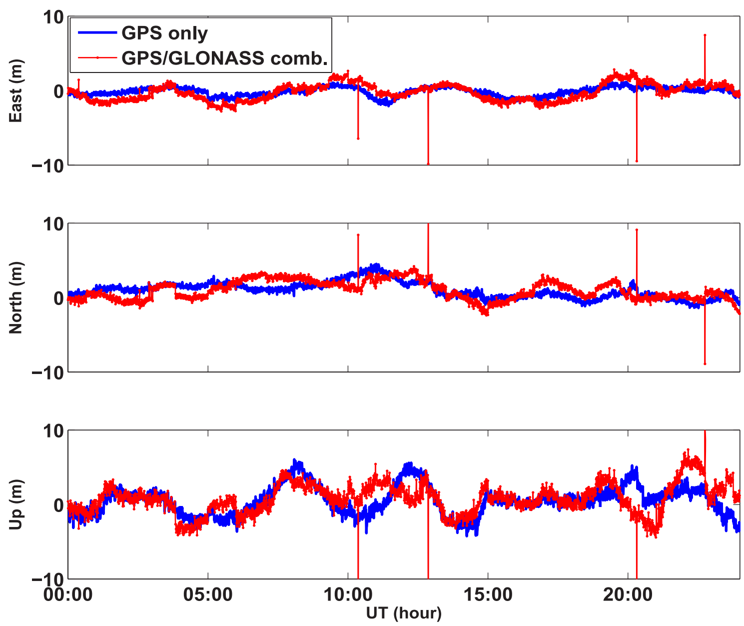

Fig. 5. Comparison of the positioning results at the KOHG reference station.

4. CONCLUSIONS

In this study, positioning was performed based on the combined data processing of the observation data from GPS and GLONASS satellites, and the position accuracy was analyzed by comparing the results with the GPS-only positioning results. The analysis results indicated that the position accuracy of the combined GPS/GLONASS positioning results was similar to or rather lower than that of the GPS-only positioning results. This could be due to the increase of GLONASS observation noise received at the GNSS reference stations, the inter-system hardware bias, the transformation between the reference coordinate systems, the selection of a confidence level for the error analysis, or the number of visible satellites at a specific time. It is thought that these various causes affected the positioning performance. Also, besides the geographical difference between the GRAS and KOHG reference stations, the performance of the GNSS receivers and dissimilar surrounding environments could affect the positioning performance.

Many researchers expect that position accuracy would be improved by the combined data processing of GPS and GLONASS satellites. However, in this study, the improvement of position accuracy was not observed, and this is thought to be due to the various causes explained earlier. If the stable reception of GLONASS satellites as well as GPS satellites can be secured, the positioning accuracy would certainly be improved. Also, it is necessary to re-verify the combined data processing results of the GPS and the GLONASS using precise point positioning (PPP).

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