JPNT 4(2), 43-55 (2015)
http://dx.doi.org/10.11003/JPNT.2015.4.2.043

JPNT Journal of Positioning, Navigation, and Timing

Study on GNSS Constellation Combination to Improve the Current and Future Multi-GNSS Navigation Performance

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ABSTRACT

In the case of satellite navigation positioning, the shielding of satellite signals is determined by the environment of the region at which a user is located, and the navigation performance is determined accordingly. The accuracy of user position determination varies depending on the dilution of precision (DOP) which is a measuring index for the geometric characteristics of visible satellites; and if the minimum visible satellites are not secured, position determination is impossible. Currently, the GLObal NAvigation Satellite system (GLONASS) of Russia is used to supplement the navigation performance of the Global Positioning System (GPS) in regions where GPS cannot be used. In addition, the European Satellite Navigation System (Galileo) of the European Union, the Chinese Satellite Navigation System (BeiDou) of China, the Quasi-Zenith Satellite System (QZSS) of Japan, and the Indian Regional Navigation Satellite System (IRNSS) of India are aimed to achieve the full operational capability (FOC) operation of the navigation system. Thus, the number of satellites available for navigation would rapidly increase, particularly in the Asian region; and when integrated navigation is performed, the improvement of navigation performance is expected to be much larger than that in other regions. To secure a stable and prompt position solution, GPS-GLONASS integrated navigation is generally performed at present. However, as available satellite navigation systems have been diversified, finding the minimum satellite constellation combination to obtain the best navigation performance has recently become an issue. For this purpose, it is necessary to examine and predict the navigation performance that could be obtained by the addition of the third satellite navigation system in addition to GPS-GLONASS. In this study, the current status of the integrated navigation performance for various satellite constellation combinations was analyzed based on 2014, and the navigation performance in 2020 was predicted based on the FOC plan of the satellite navigation system for each country. For this prediction, the orbital elements and nominal almanac data of satellite navigation systems that can be observed in the Korean Peninsula were organized, and the minimum elevation angle expecting signal shielding was established based on Matlab and the performance was predicted in terms of DOP. In the case of integrated navigation, a time offset determination algorithm needs to be considered in order to estimate the clock error between navigation systems, and it was analyzed using two kinds of methods: a satellite navigation message based estimation method and a receiver based method where a user directly performs estimation. This simulation is expected to be used as an index for the establishment of the minimum satellite constellation for obtaining the best navigation performance.

Keywords: multi-constellation, cut-off angle, DOP simulation

1. INTRODUCTION

For the determination of user position based on a satellite navigation system, the possibility of positioning is determined by the number of received signals, and the accuracy is affected by the geometric arrangement of satellites. Accordingly, the number and arrangement of visible satellites is a very important element. In the presence of signal blocking by geographic features as in downtown area, the time in which visible satellites are secured during a day is significantly limited when only GPS is used; while the visibility and accuracy could be improved when multi-constellation is organized by combining various satellite

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Received Jan 19, 2015 **Revised** Mar 02, 2015 **Accepted** Mar 16, 2015

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http://www.gnss.or.kr Print ISSN: 2288-8187 Online ISSN: 2289-0866

constellations. In particular, this prospect is gradually being implemented, as shown by the fact that the number of navigation satellites is expected to increase up to 150 by 2020. The GLONASS of Russia, which currently operates 24 satellites, is planning to operate 30 satellites in 2020, and the Galileo of Europe is also aimed to achieve the FOC of 30 satellites in 2020. In addition, the BeiDou of China, which is currently a regional navigation system, is aimed to establish a global navigation system that operates 35 satellites, in 2017; and the IRNSS and QZSS are planning to operate seven and four satellites in 2016 and 2017, respectively. Therefore, the number of navigation satellites is expected to rapidly increase in the Asian region, so that it would be called 'A Satellite Hotspot', and it is drawing attention as a region where the effect of a multi-GNSS based positioning technique is the largest. For the improvement of navigation performance, and the stable and prompt determination of a position solution, GPS-GLONASS integrated navigation is generally performed at present. However, as available satellite navigation systems have been diversified in Korea, the necessity of finding the minimum satellite constellation combination for obtaining high navigation performance has been suggested.

In this study, visibility analysis simulation was performed based on 2014 for GPS-only positioning, GPS-GLONASS integrated navigation, and integrated navigation using three satellite constellations through the addition of BeiDou, Galileo, QZSS, and IRNSS, respectively; and an optimal combination in the current situation was selected. Also, the same simulation was performed for 2020 when all the systems are expected to achieve FOC, and the navigation performances of each combination were compared and analyzed.

2. TREND AND ESTABLISHMENT PLAN FOR INTERNATIONAL SATELLITE NAVIGATION SYSTEMS

2.1 GPS

GPS is the most representative satellite navigation system, and it was developed with the purpose of the FOC operation of 24 medium earth orbit satellites on six orbital planes by arranging four satellites on each orbital plane at appropriate intervals. The FOC of 24 satellites was announced about 20 years ago; and through the continuous replacement of deteriorated satellites and the addition of new frequency, 32 stabilized satellites are in operation. In 2014, the satellite signals of 31 satellites could be normally received (Ha & Chun 2010). Table 1 summarizes the nominal almanac data of the 24 GPS satellites, which are the initial design values, and the latest almanac data of the 31 satellites, which are currently in service, can be obtained from the United States Coast Guard Navigation Center. Future modernization is expected to be focused on performance improvement rather than the increase in the number of satellites, and thus the almanac data of GPS used for the prediction were organized using the almanac information provided by the United States Coast Guard Navigation Center (The United States Coast Guard Navigation Center 2014).

Table 1. Nominal GPS orbit parameters.

Year	Orbit plan	Semi major axis(km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg.of perigee (deg)	Mean anomaly (deg)	Orbit
2014	A	26659.8	0	55	272.85	0	11.68 / 161.79 41.81 / 268.13	MEO
	B				332.85		80.96 / 204.38 173.34 / 309.98	
	C				32.85		111.88 / 339.67 241.57 / 11.80	
	D				92.85		135.27 / 265.45 167.36 / 35.16	
	E				152.85		197.05 / 333.68 302.60 / 66.07	
	F				212.85		238.89 / 105.21 345.23 / 135.35	

2.2 GLONASS

GLONASS is the satellite navigation system of the former Soviet Union and Russia, and it has been developed with the purpose of the operation of 30 medium earth orbit satellites (24 Operation and 6 Additional). Along with the modernization of GPS, a modernization plan for the performance improvement of GLONASS satellites has been continuously implemented since 2003. The representative contents of the modernization plan include changing the signal transmission method from FDMA to CDMA, adding various civilian signals, increasing the accuracy of position determination, and extending the life of satellites (Heo 2014). Russia is currently not suggesting a detailed launch plan, but they aim to launch six additional satellites for the second FOC. It is most likely that two satellites are launched to three planes where existing satellites are in operation, respectively (JSC M. F. RESHETNEV 2013). Table 2 summarizes the expected almanac data organized by predicting the launch schedule based on the fact that Russia aims to operate 30 satellites by 2020.

Table 2. GLONASS orbit parameters.

Year	Orbit plan	Semi-major axis(km)	Eccentricity	Inclination (deg)	RAAN (deg)	Mean anomaly (deg)		Orbit
2014	Plan #1	25440	0	64.8	120E	145.4436	325.4436	MEO
						190.4436	10.4436	
						235.4436	55.4436	
						280.4436	100.4436	
	Plan #2				240E	130.4436	310.4436	
						170.4436	355.4436	
						220.4436	40.4436	
						265.4436	85.4436	
	Plan #3				360E	115.4436	295.4436	
						160.4436	340.4436	
						205.4436	25.4436	
						250.4436	70.4436	
2016	Plan #1				120E	167.9436	347.9436	
2018	Plan #2				240E	62.9436	242.9436	
2020	Plan #3				360E	182.9436	2.9436	

2.3 BeiDou

BeiDou is the satellite navigation system of China, and it has been developed with the purpose of the FOC of 35 satellites. The satellite configuration is composed of five geostationary orbit satellites, three inclined geosynchronous orbit satellites, and 27 medium earth orbit satellites. In the early stage, it was developed as a regional navigation system, but it will be converted to a navigation system that is aimed at global service. The development of BeiDou is divided into three phases (Phase 1, Phase 2, and Phase 3), and up to Phase 2 has been completed as of 2014. Originally, China planned to complete the establishment of a global satellite navigation system by 2020 (Heo 2014). However, in the 'China Satellite Navigation Conference (CSNS 2014)', they advanced the existing plan and announced that the FOC is expected in 2017 ~ 2018 (INSIDE GNSS 2014). Table 3 summarizes the nominal almanac data and expected launch schedule for BeiDou. In the case of BeiDou, a total of 16 satellites (six GEO satellites, five IGSO satellites, and five MEO satellites) including two spare satellites have been launched until Phase 2; and among them, 14 satellites are in service (INSIDE GNSS 2013). Therefore, additional launch of 23 MEO satellites is expected in Phase 3 where the conversion from a regional navigation system to a global satellite navigation system is implemented. The expected almanac data were organized using the expected FOC year of 2018 based on China's announcement of advancing the FOC from 2020 to 2017 ~ 2018 and based on the orbital elements of the 35 satellites provided by China (China Satellite Navigation Office 2010).

2.4 QZSS

QZSS, which has been developed and operated by the Japan Aerospace Exploration Agency (JAXA), is a Regional Navigation Satellite System (RNSS) that provides service to Japan. Four satellites are expected to first provide official service from 2018 with the purpose of the establishment of an independent navigation system by the FOC operation of seven satellites (Murai 2014, Heo 2014). The configuration of the four satellites, whose detailed plan has been provided so far, includes three IGSO (HEO) satellites and one GEO satellite. The plan and information for the remaining three satellites have not been specified, and thus the operation of only the four satellites was considered in this study. This system has been developed in cooperation with the United States with the purpose of securing visible satellites in downtown area. It has a high availability (99%) within

Table 3. BeiDou orbit parameters.

Year	SV #	Semi-major axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of perigee (deg)	Mean anomaly (deg)	Orbit
2014	1	42164	0	0	158.75E	0	0	GEO
	2				180E			
	3				210.5E			
	4				240E			
	5				260E			
	6			55	218E		0	IGSO
	7				98E		120	
	8				338E		240	
	12	27878			218E		0	MEO
	16						40	
	22				98E		0	
	26						40	
2015	9				218E		80	
	10						120	
	21				98E		80	
	23						120	
	32				338E		0	
	33						40	
2016	11				218E		160	
	13						200	
	24				98E		160	
	25						200	
	34				338E		80	
	35						120	
2017	14				218E		240	
	15						280	
	17						320	
	27				338E		160	
	28						200	
	29						240	
2018	18				98E		240	
	19						280	
	20						320	
2018	30						280	
	31						320	

Table 4. QZSS orbit parameters.

Year	SV #	Semi-major axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of perigee (deg)	Central longitude of ground track(deg)	Orbit
2014	1	42164	0.099	45	80.09E	270E	135	IGSO (HEO)
2016	2				208.03E			
	3				328.09E			
2017	4		0	0	245E	91.753E	127	GEO

Japan, and the position accuracy is also outstanding when combined with GPS (Yoo et al. 2008). Table 4 summarizes the nominal almanac data and expected launch schedule of the four QZSS satellites that are expected to provide service first. A detailed plan has not been provided regarding which orbital satellites will be launched in the corresponding year, and thus the launch schedule was predicted based on 2017 which is the expected FOC year of QZSS. Also, for the orbital elements of the GEO satellite where detailed information has not been provided, the expected almanac data were organized based on the orbital elements of a general GEO satellite and the orbital elements of the navigation systems that launch GEO satellites (BeiDou and IRNSS).

2.5 Galileo

Galileo is aimed to achieve the FOC of 30 medium earth orbit satellites in 2020 by the European Space Agency (ESA), and to provide 4 ~ 8 m level position accuracy around the globe through open service (Ha & Chun 2010). Table 5 summarizes the nominal almanac data and expected launch schedule for Galileo. The final objective of Galileo is the FOC operation of 30 satellites. ESA is expected to select the detailed orbital elements of three additional (spare) satellites after the completion of the launch of 27 satellites and the examination of the operation status, and they have provided the nominal almanac data of the 27 satellites. The Galileo satellite launch schedule provided earlier has low reliability due to the frequent change of the development plan and the delay of the launch schedule. Also, as ESA is currently not providing a detailed satellite launch schedule, the detailed launch schedule of Galileo cannot be drawn yet. Therefore, the launch schedule was predicted based on 2020 which is the expected FOC year. Also, for the three spare satellites where ESA has not provided detailed nominal almanac data, it is expected that the satellites will be additionally launched to three planes where satellites are currently in operation, without adding a new orbital plane. Thus, the expected nominal almanac data were organized based on this (European GNSS Service Centre; http://www.gsc-europa.eu).

Table 5. Galileo orbit parameters.

Year	SV #	Semi-major axis (km)	Eccentricity	Inclination (deg)	98RAAN (deg)	Arg. of perigee (deg)	Mean anomaly (deg)	Orbit
2014	11	29600.318	0	56	120	0	53.33	MEO
	12						93.33	
	19				240		26.66	
	20						66.66	
2015	1				0		0	
	2						40	
	28						20	
	15				120		216.33	
	16						253.33	
2016	3				0		80	
	4						120	
	17				120		293.33	
	18						333.33	
	29						33.33	
2017	5				0		160	
	6						200	
	21				240		106.66	
	22						146.66	
2018	7				0		240	
	8						280	
	23				240		186.66	
	24						226.66	
2019	9				0		320	
	10				120		13.33	
	25				240		266.66	
	26						306.66	
2020	13				120		133.33	
	14						173.33	
	27				240		346.66	
	30				240		46.66	

2.6 IRNSS

IRNSS is the regional navigation system of India, and it has been developed for the operation of a total of seven satellites (four inclined geosynchronous orbit satellites and three geostationary orbit satellites) with the purpose of achieving FOC in early 2016. The range of the service region of IRNSS is 30°*S* ~ 50°*N* latitude and 30°*E* ~ 130°*E* longitude, and the Korean Peninsula, which is 33°*N* ~ 43°*N* latitude and 124°*E* ~ 132°*E* longitude, is completely included in the service region of IRNSS. In the case of IRNSS, a total of three satellites (two inclined geosynchronous orbit satellites and one geostationary orbit satellite) have been launched as of 2014. The Indian Space Research Organisation (ISRO; http://isro.gov.in/), which is the IRNSS operation institution, has not provided the satellite launch order and detailed launch schedule, but the exp.ected almanac data were organized based on 2016 which is the expected FOC year, as summarized in Table 6 (ISRO).

2.7 Synthesis of the Plans for the Establishment of International Satellite Navigation Systems

According to the trend in the navigation satellite launch for each country until 2014, two to three satellites that are operated on the same orbital plane have been launched together to reduce the launch cost. Table 7 summarizes the synthesized plans for the establishment of the satellite navigation systems for each country predicted in each year by collecting the navigation satellite launch schedule for each country and by reflecting the expected launch schedule and launch trend based on the 'Satellite on the Net' and 'Space Calendar' which present the launch schedules of navigation satellites and space launch vehicles (Satellite on the Net 2014, NASA Spaceflight.com 2014, Spaceflight Now 2015).

Table 6. IRNSS orbit parameters.

Year	SV#	Semi-majoraxis (km)	Eccentricity	Inclination (deg)	Central longitude of ground track (deg)	Orbit
2014	1	42164	0	29	55E	IGSO
	2					
2015	3				111E	IGSO
	4			0	34E	GEO
	5					
2014	6				83E	
2016	7				132E	

Table 7. Assumption of GNSS launch plan.

		GPS	GLONASS	BeiDou	Galileo	QZS	IRNSS	Total
2014	Current	31	24	14(16)	4	1	2	79
2015	Current			18	10		5	89
	New launch			6	6		3	
2016	Current		26	24	14	2	7	104
	New launch		2	6	4	1	2	
2017	Current			30	18	4		116
	New launch			6	4	2		
2018	Current		28	35	22			127
	New launch		2	5	4			
2019	Current				26			131
	New launch				4			
2020	Current		30		30			137
	New launch		2		4			

3. VISIBILITY ANALYSIS ALGORITHM

The position information of satellites for the current status analysis of navigation performance and the simulation for the prediction of navigation performance in 2020 was drawn using the almanac information of each satellite constellation. For satellites that are planned to be launched and have not been launched yet, the establishment plan of navigation satellites for each country was reflected using the nominal almanac information that had been suggested as the design values by the official operation institution for each country. Then, the expected almanac data were organized and reflected in the prediction of performance in 2020. By applying the minimum elevation angle expecting satellite signal shielding and the elevation angle for each satellite obtained using the satellite almanac to Eq. (1), the visibility of the corresponding satellite is determined.

$$El_{cutoff} > El^{s} \tag{1}$$

where El_{cutoff} is the minimum elevation angle reflecting the shielding of satellite signals, and El^{s} is the elevation angle of the satellite. When the elevation angle of the satellite is lower than the minimum elevation angle, it is judged as a non-visible satellite from which a user cannot receive satellite signals; and otherwise, it is judged as a visible satellite.

After the extraction of visible satellites, user position and clock error are calculated by navigation equations. In the case of multi-constellation, the reference times for each system are different, and thus their measurements include different clock errors. To resolve this, a method that reflects the difference using the information provided by the satellite navigation message and a method in which the clock error for each satellite navigation system is directly estimated in a receiver are generally used (Joo et al. 2012).

In the first method, each measurement can be synchronized with the GPS time using the offset information from GPSTime included in the navigation message (e.g., Galileo and BeiDou).

The measurement of the GPS satellite i in the GPSTime frame can be simply expressed as Eq. (2).

$$\rho^{i}{}_{GPS,GPST} = d^{i} + B_{GPS} \tag{2}$$

where

d : Measurement excluding the receiver clock error

B_{GPS} : GPS clock error

$GPST$: GPSTime frame

Similar to Eq. (2), the measurement in the XTime frame for the satellite j of the GNSS system X other than GPS can be expressed as Eq. (3).

$$\rho^{j}{}_{X,XT} = d^{j} + B_{X} \tag{3}$$

where

B_X : Clock error of the system X

TX : GNSS XTime frame

In this regard, B_{GXTO}, which is the receiver clock error difference between GPS and GNSS X by the GPS-X Time Offset (GXTO), can be expressed as Eq. (4).

$$B_{GXTO} = B_{X} - B_{GPS} \tag{4}$$

$\rho_{X,GPST}$, which is the measurement of the GNSS system X in the GPSTime frame, can be expressed as Eq. (5), and this indicates the time synchronization between GPS and the system X.

$$\rho_{X,GPST} = \rho_{X,XT} - B_{GXTO} \tag{5}$$

The application of the GPS-Galileo Time Offset estimated using navigation message at an accuracy of about 2.5 ns showed that the Horizontal Precision Error (HEPg) was about 42.7 m and the Vertical Precision Error

(VEPg) was 143.1 m, indicating that the performance deteriorated. Also, when the accuracy was about 16 ns, the HEPg was 51.4 m and the VEPg was 179 m, indicating that the performance deteriorated significantly. Thus, it was found that the performance of the time offset estimation between the systems had a significant effect on the multi-constellation positioning performance However, when the measurement X is synchronized with the GPSTime frame as mentioned above, the observation matrix is identical to that of single satellite navigation, and thus positioning is enabled with only more than four visible satellites regardless of the type of satellite navigation systems (INSIDE GNSS 2007). Therefore, it would be mostly used for positioning in downtown area where the possibility of positioning with a small number of satellites is important rather than positioning performance (e.g., accuracy); and in this study, this was classified as a method that is applied to ‘coarse positioning’.

The above process can be organized using equations, as shown in Eq. (6).

$$z_{cp} = H_{cp} x_{cp} + \upsilon_{cp} \tag{6}$$

where

$$z_{cp} = \begin{bmatrix} \rho^{1}{}_{GPS,GPST} \\ \vdots \\ \rho^{n}{}_{GPS,GPST} \\ \rho^{1}{}_{X,GPST} \\ \vdots \\ \rho^{m}{}_{X,GPST} \end{bmatrix} \quad x_{cp} = \begin{bmatrix} x_{user} \\ y_{user} \\ z_{user} \\ B_{GPS} \end{bmatrix} \quad H_{cp} = \begin{bmatrix} e^{1}{}_{x,GPS} & e^{1}{}_{y,GPS} & e^{1}{}_{z,GPS} & -1 \\ \vdots & & \vdots & \vdots \\ e^{n}{}_{x,GPS} & e^{n}{}_{y,GPS} & e^{n}{}_{z.GPS} & -1 \\ e^{1}{}_{x,X} & e^{1}{}_{y,X} & e^{1}{}_{z,X} & -1 \\ \vdots & & \vdots & \vdots \\ e^{m}{}_{x,X} & e^{m}{}_{y,X} & e^{m}{}_{z,X} & -1 \end{bmatrix}$$

where υ is the noise of the measurement, x_{user}, y_{user}, z_{user} represent the user position on the ECEF axes, and e is the direction vector. Also, the subscripts x, y, z represent the three axes on ECEF, n is the number of GPS satellites, and m is the number of satellites for the GNSS system X.

In the second method where the clock error for each system is directly estimated in a receiver, measurements that have been directly received in each time frame of GPS and GNSS X are used. In this case, accuracy reduction due to the synchronization between the two systems could be avoided, and thus the performance identical to that of a single satellite navigation system could be maintained. Therefore, in this study, this was specified as ‘precise positioning’, and the final observation matrix of precise positioning can be expressed as Eq. (7).

$$z_{pp} = H_{pp} x_{pp} + \upsilon_{pp} \tag{7}$$

where

$$z_{pp} = \begin{bmatrix} \rho^{1}{}_{GPS,GPST} \\ \vdots \\ \rho^{n}{}_{GPS,GPST} \\ \rho^{1}{}_{X,XT} \\ \vdots \\ \rho^{m}{}_{X,XT} \end{bmatrix} \quad x_{pp} = \begin{bmatrix} x_{user} \\ y_{user} \\ z_{user} \\ B_{GPS} \\ B_{X} \end{bmatrix} \quad H_{pp} = \begin{bmatrix} e^{1}{}_{x,GPS} & e^{1}{}_{y,GPS} & e^{1}{}_{z,GPS} & -1 & 0 \\ \vdots & & \vdots & & \vdots \\ e^{n}{}_{x,GPS} & e^{n}{}_{y,GPS} & e^{n}{}_{z,GPS} & -1 & 0 \\ e^{1}{}_{x,X} & e^{1}{}_{y,X} & e^{1}{}_{z,X} & 0 & -1 \\ \vdots & & \vdots & & \vdots \\ e^{m}{}_{x,X} & e^{m}{}_{y,X} & e^{m}{}_{z,X} & 0 & -1 \end{bmatrix}$$

where the subscript *pp* represents the precise positioning.

According to the observation equation, to directly obtain receiver clock error, one more satellite is needed for each system. For example, when GPS and GLONASS are combined, the required minimum number of satellites is 5; and in the case of GPS-GLONASS-Galileo integrated navigation, at least more than six satellites should be secured. Therefore, the effect of the increase in the number of visible satellites by multi-constellation is smaller than that of coarse positioning, but the positioning performance improvement effect including accuracy is outstanding.

4. SIMULATION

4.1 Simulation Environment

The orbital information of satellites for the visibility and DOP analysis of each multi-constellation combination was obtained regarding July 20, 2014 and 2020; and the current status analysis and performance prediction were performed over 24 hours. The current status analysis and performance prediction were conducted by dividing it into coarse positioning and precise positioning.

In the case of coarse positioning, the possibility of position determination by securing the minimum visible satellites is important rather than accuracy. Thus, simulation was performed based on downtown area which is an important target region for location based service, smartphone, and automobile navigation. For this purpose, the average elevation angle for the buildings around the Posco intersection, Teheran street (37.5069°*N* latitude, 127.0566°*E* longitude) was analyzed based on the building data obtained from VWorld (2014), which is a spatial information open platform provided by the Ministry of Land, Infrastructure and Transport; and the result indicated that the value was 55.667°. Considering that this region has the poorest visibility environment in the country, the minimum elevation angle for the satellite signals of coarse positioning was set to 50°. In this case, it was assumed that the clock error between different satellite navigation systems is calculated using the information provided by satellite navigation message as explained earlier.

Precise positioning is a method used for geodetic survey and surveying fields that require precise accuracy. Thus, the minimum elevation angle was set to 15o based on Article 7, Paragraph 7, Section 5, na of the Cadastral Resurvey Regulation, 'For the minimum elevation angle of a satellite, 15^{o} is used' (Ministry of Land, Infrastructure, and Transport 2013). In this case, a method where the clock error for each satellite navigation system is directly estimated in a receiver was applied.

4.2 Simulation Results

The results of the simulation were expressed in the mean, maximum, and minimum values of HDOP, VDOP, PDOP, and the number of visible satellites. The proportion of the time in which positioning is possible among the entire day was specified as visibility over 24hr (VIS24h), which expresses the proportion of the time in which the minimum number of visible satellites required for navigation is satisfied among 24 hours.

In this study, simulation was performed by dividing a day (24 hours) into 15 minute intervals. In this regard, the number of epochs was 289, and $\#SV$ represents the number of visible satellites. In the case of coarse positioning, positioning is possible with only a total of four visible satellites regardless of the type of systems. Thus, for $VIS24h_{cp}$, cases in which the number of visible satellites was more than 4 (the minimum number of satellites necessary for navigation) among the numbers of visible satellites calculated for the entire 289 epochs were expressed as a ratio.

$$VIS24h_{cp} = \left(\frac{Epochs\ in\ which\ \#sv \geq 4}{Total\ Number\ of\ epochs}\right) \times 100 \tag{8}$$

According to the observation equation (Eq. (4)), to directly obtain receiver clock error, one more satellite is needed for each system as explained earlier. Thus, for $VIS24h_{pp}$, cases in which the number of visible satellites was more than (the number of navigation systems constituting multi-constellation + 3) among the numbers of visible satellites calculated for the entire epochs were expressed as a ratio.

$$VIS24h_{pp} = \left(\frac{Epochs\ in\ which\ \#sv \geq \min\ \#SV}{Total\ Number\ of\ epochs}\right) \times 100, \tag{9}$$

where

$\min \#SV = number\ of\ systems\ constituting\ multi-constellation + 3$

In this study, GPS-only positioning, GPS-GLONASS integrated navigation, and multi-constellation using three systems by adding one more navigation system were examined. Therefore, $VIS24h_{cp}$ was calculated for cases in which more than four satellites were secured in every case, while $VIS24h_{pp}$ was calculated for cases in which more than four, five, and six visible satellites were secured, respectively.

4.2.1 Current Status Analysis

4.2.1.1 Coarse Positioning (the minimum elevation angle: 50^{o}, clock error based on navigation message)

The total number of satellites in operation for each navigation system that were reflected in the simulation for July 20, 2014 was 76 (31 satellites for GPS, 24 satellites for GLONASS, 14 satellites for BeiDou, 1 satellite for QZSS, 4 satellites for Galileo, and 2 satellites for IRNSS).

Table 8 summarizes the current status analysis of coarse positioning navigation performance for each multi-constellation combination. For the GPS-only positioning, the average number of visible satellites was 2.65, the maximum number of visible satellites was 5, and the proportion of the time in which positioning is possible was 19.03%; and for the GPS-GLONASS integrated navigation, the average number of visible satellites was 4.62, the maximum number of visible satellites was 8, and the proportion of the time in which positioning is possible was 78.20%. The minimum numbers of visible satellites were identical (1); but as more than four visible satellites were secured on average, the proportion of the time in which positioning is possible increased by 59.17%. For the GPS-GLONASS-BeiDou integrated navigation, the total number of satellites used for navigation was 69; and the average number of visible satellites was 5.01, the mean HDOP value was 8.20, and the proportion of the time in which positioning is possible was 83.05%. For the GPS-GLONASS-Galileo integrated navigation, the total number of satellites was 59, the average number of visible satellites was 5.21, the mean HDOP value was 14.91, and the proportion of the time in which positioning is possible was 85.47%. For the GPS-GLONASS-QZSS integrated navigation, the total number of satellites used for navigation was 56, the average number of visible satellites was 4.98, the mean HDOP value was 8.23, and the proportion of the time in which positioning is possible was 82.35%. For the GPS-GLONASS-IRNSS integrated navigation, the number of satellites used for navigation was 57, the average number of visible satellites was 4.62, the mean HDOP value was 9.26, and the proportion of the time in which positioning is possible was 78.20%. Lastly, when the multi-constellation was organized by integrating all the six satellite constellations (GPS-GLONASS-BeiDou-Galileo-QZSS-IRNSS), the average

Table 8. Current state analysis of multi-constellation coarse positioning performance.

GPS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	76.22	459.9	466.7	2.65	19.03
Max	3797.4	22705	23020	5	
Min	1.76	6.02	6.38	0	

GPS+GLONASS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	9.26	65.07	66.05	4.62	78.20
Max	345.14	5838.1	5848.3	8	
Min	1.37	4.48	4.83	0	

GPS+GLONASS+BeiDou

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	8.20	57.34	58.21	5.01	83.05
Max	345.14	5838.1	5848.3	9	
Min	1.31	4.45	4.73	0	

GPS+GLONASS+Galileo

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	14.91	77.39	**79.27**	**5.21**	**85.47**
Max	1483.7	5838.1	**5848.3**	**9**	
Min	1.37	4.48	**4.83**	**0**	

GPS+GLONASS+QZSS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	8.23	57.71	58.58	4.98	82.35
Max	345.14	5838.1	5848.3	9	
Min	1.37	4.48	4.71	0	

GPS+GLONASS+IRNSS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	9.26	65.07	**66.05**	**4.62**	**78.20**
Max	345.14	5838.1	**5848.3**	**8**	
Min	1.37	4.48	**4.83**	**0**	

GPS+GLONASS+BeiDou+Galileo+QZSS+IRNSS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	13.51	70.66	72.34	5.96	90.31
Max	1483.6	5838	5848.2	10	
Min	1.30	4.45	4.65	0	

number of visible satellites was 5.96, the mean HDOP value was 13.51, and the proportion of the time in which positioning is possible among the entire day was 90.31%.

Table 9 compares the variations in the coarse positioning navigation performance indices for 2014. When compared with the GPS-only positioning, the reduction in the mean HDOP value for the GPS-GLONASS-BeiDou combination was the largest (68.02), but the increase in the proportion of the time in which positioning is possible was 64.02, which was the second largest among the multi-constellation combinations. The effect was insignificant compared to the total number of satellites used for navigation (69). This is thought to be because BeiDou is operated as a regional navigation system as of 2014 and most satellites are located toward China and the west side of Korea and thus the elevation angles of the satellites are low. The increase in the average number of visible satellites was the largest for the GPS-GLONASS-Galileo combination (2.56), and the increase in the proportion of the time in which positioning is possible was also the largest (66.44). For the GPS-GLONASS-QZSS combination, the reduction in the mean HDOP value and the increase in the proportion of the time in which positioning is possible were similar to those of the GPS-GLONASS-BeiDou combination although only one QZSS satellite was added contrary to the case of BeiDou. This is because the QZSS satellite has a high elevation angle (70°~90°). For the GPS-GLONASS-IRNSS combination, the variations in the navigation performance indices were identical to those of the GPS-GLONASS combination. This is because IRNSS is operated as a regional navigation system similar to BeiDou and satellites are located toward India and the west side of Korea and thus the elevation angles of the satellites are low and their effect on the navigation is very small. As a result, it is expected that performing coarse positioning using the GPS-GLONASS-Galileo combination would be the most effective as of 2014.

Table 9. Comparison of coarse positioning navigation performance indexes variations, 2014.

	Mean HDOP		#SV		VIS24h (%)	
	2014	Improvement	2014	Increment	2014	Improvement
GPS	76.22		2.65		19.03	
GPS+GLONASS	9.26	-66.96	4.62	+1.97	78.20	+59.17
GPS+GLONASS+BeiDou	8.20	-68.02	5.01	+2.36	83.05	+64.02
GPS+GLONASS+Galileo	14.91	-61.31	5.21	+2.56	85.47	+66.44
GPS+GLONASS+QZSS	8.23	-67.99	4.98	+2.33	82.35	+63.32
GPS+GLONASS+IRNSS	9.26	-66.96	4.62	+1.97	78.20	+59.17

4.2.1.2 Precise Positioning (the minimum elevation angle: 15°, direct estimation of the clock error between systems in a receiver)

Table 10 summarizes the current status analysis of precise positioning navigation performance for each multi-constellation combination. For the GPS-only positioning, the average number of visible satellites was 7.81, the maximum number of visible satellites was 12, and the mean HDOP value was 1.19; and for the GPS-GLONASS integrated navigation, the average number of

Table 10. Current state analysis of multi-constellation precise positioning performance.

GPS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	1.19	2.00	2.33	7.81	100
Max	1.97	6.40	6.61	12	
Min	0.83	1.25	1.56	5	

GPS+GLONASS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	0.81	1.43	1.64	13.87	100
Max	1.07	2.75	2.90	19	
Min	0.61	1.00	1.23	11	

GPS+GLONASS+BeiDou

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	0.81	1.41	1.63	14.86	100
Max	1.07	2.40	2.54	20	
Min	0.61	1.00	1.23	11	

GPS+GLONASS+Galileo

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	0.80	1.37	1.59	15.21	100
Max	1.03	2.75	2.90	19	
Min	0.60	0.93	1.17	11	

GPS+GLONASS+QZSS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	0.79	1.39	1.60	14.56	100
Max	1.06	2.39	2.55	20	
Min	0.61	0.98	1.17	11	

GPS+GLONASS+IRNSS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	0.81	1.43	1.64	14.27	100
Max	1.07	2.75	2.90	20	
Min	0.61	1.00	1.23	11	

GPS+GLONASS+BeiDou+Galileo+QZSS+IRNSS

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
Mean	0.78	1.33	1.54	17.29	100
Max	1.03	2.17	2.40	22	
Min	0.60	0.91	1.15	12	

visible satellites was 13.87, the maximum number of visible satellites was 19, and the mean HDOP value was 0.81. For the GPS-GLONASS-BeiDou integrated navigation, the average number of visible satellites was 14.86, the maximum number of visible satellites was 20, and the mean HDOP value was 0.81; and for the GPS-GLONASS-Galileo integrated navigation, the average number of visible satellites was 15.21, the maximum number of visible satellites was 19, and the mean HDOP value was 0.80. For the GPS-GLONASS-QZSS integrated navigation, the average number of visible satellites was 14.56, the maximum number of visible satellites was 20, and the mean HDOP value was 0.79; and for the GPS-GLONASS-IRNSS integrated navigation, the average number of visible satellites was 14.27, the maximum number of visible satellites was 20, and the mean HDOP value was 0.81. Lastly, when the multi-constellation was organized by integrating all the six satellite constellations (GPS-GLONASS-BeiDou-Galileo-QZSS-IRNSS), the average number of visible satellites was 17.29, the maximum number of visible satellites was 22, and the mean HDOP value was 0.78.

Table 11 compares the variations in the precise positioning navigation performance indices for 2014. When compared with the GPS-only positioning, the reduction in the mean HDOP value for the GPS-GLONASS-QZSS combination was the largest (0.4), and the increase in the average number of visible satellites for this combination was 6.75, which was the third largest among the combinations. The number of QZSS satellites reflected in this study for 2014 was 1, which was much smaller than the total number of satellites for the other navigation systems. However, it is thought that QZSS had a large effect on the navigation because it had been synchronized with the GPS satellite clock. The reductions in the mean HDOP values of the GPS-GLONASS, GPS-GLONASS-BeiDou, and GPS-GLONASS-IRNSS combinations were 0.38, and the reduction in the mean HDOP value of the GPS-GLONASS-Galileo combination was 0.39. Thus, all the combinations generally showed similar performances. The increase in the average number of visible satellites for the GPS-GLONASS-Galileo combination was 7.4, which was the largest. In this regard, precise positioning can be performed during the entire day for all the combinations. Therefore, based on the reduction in the mean HDOP value which is an index for expressing accuracy, it is thought that performing precise positioning using the GPS-GLONASS-QZSS combination would be the most effective as of 2014.

Table 11. Comparison of precise positioning navigation performance indexes variations, 2014.

	Mean HDOP		#SV		VIS24h (%)
	2014	Improvement	2014	Increment	2014
GPS	1.19		7.81		100
GPS+GLONASS	0.81	-0.38	13.87	+6.06	100
GPS+GLONASS+BeiDou	0.81	-0.38	14.86	+7.05	100
GPS+GLONASS+Galileo	0.80	-0.39	15.21	+7.4	100
GPS+GLONASS+QZSS	0.79	-0.4	14.56	+6.75	100
GPS+GLONASS+IRNSS	0.81	-0.38	14.27	+6.46	100

4.2.2 Performance Prediction

4.2.2.1 Coarse Positioning (the minimum elevation angle: 50°)

The total number of satellites in operation for each navigation system that were reflected in the simulation for July 20, 2020 when all the systems are expected to achieve FOC was 137 (31 satellites for GPS, 30 satellites for GLONASS, 35 satellites for BeiDou, 4 satellites for QZSS, 30 satellites for Galileo, and 7 satellites for IRNSS).

Table 12 summarizes the prediction of the coarse positioning navigation performance for each multi-constellation combination. For the GPS-GLONASS integrated navigation, the total number of satellites used for navigation would be 61; and the average number of visible satellites would be 5.07, the maximum number of visible satellites would be 10, and the mean HDOP value would be 5.09. For the GPS-GLONASS-BeiDou integrated navigation, 96 satellites would be used for navigation; and the average number of visible satellites would be 7.46, the maximum number of visible satellites would be 12, the mean HDOP value would be 2.87, and the proportion of the time in which positioning is possible would be 99.31%. For the GPS-GLONASS-Galileo integrated navigation, the expected number of satellites used for navigation would be 91; and the average number of visible satellites would be 7.83, the maximum number of visible satellites would be 14, the mean HDOP value would be 3.91, and the proportion of the time in which positioning is possible would be 98.27%. For the GPS-GLONASS-QZSS integrated navigation, a total of 65 satellites would be used for positioning; and the average number of visible satellites would be 6.13, the maximum number of visible satellites would be 11, the mean HDOP value would be 5.51, and the proportion of the time in which positioning is possible would be 89.97%. For the GPS-GLONASS-IRNSS integrated navigation, 68 satellites would be used for navigation; and the average number of visible satellites would be 5.17, the maximum number of visible satellites would be 10, the mean HDOP value would be 4.97, and the proportion of the time in which positioning is possible would be 79.59%. Lastly, for the GPS-GLONASS-BeiDou-Galileo-QZSS-IRNSS integrated navigation, the average number of visible satellites would be 11.44, the maximum number of visible satellites would be 18, the mean HDOP value would be 1.69, and positioning would be possible during the entire day.

Table 13 compares the variations in the coarse positioning navigation performance index predictions for 2020. When compared with the GPS-only positioning for 2014, the reduction in the mean HDOP value of the GPS-GLONASS-BeiDou combination was the largest (73.35), and the increase in the proportion of the time in which positioning is possible was 80.28, which was the largest among the multi-constellation combinations. This is because BeiDou changes from a regional navigation system to a global navigation system as it enters Phase 3 after 2014. Thus, unlike the insignificant effect of BeiDou on

Table 12. Prediction of multi-constellation coarse positioning performance.

GPS+GLONASS (2014)						GPS+GLONASS (2020)					
	DOP			#SV	VIS24h (%)		DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP				HDOP	VDOP	PDOP		
Mean	9.26	65.07	66.05	4.62	78.20	Mean	5.09	16.73	17.69	5.07	79.59
Max	345.14	5838.1	5848.3	8		Max	228.43	332.4	403.32	10	
Min	1.37	4.48	4.83	0		Min	1.42	4.71	5.23	0	
GPS+GLONASS+BeiDou						GPS+GLONASS+Galileo					
	DOP			#SV	VIS24h (%)		DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP				HDOP	VDOP	PDOP		
Mean	2.87	10.17	10.62	7.46	99.31	Mean	3.91	14.86	15.41	7.83	98.27
Max	30.83	96.24	99.42	12		Max	96.05	372.07	384.26	14	
Min	1.28	4.29	4.51	0		Min	1.29	4.15	4.37	0	
GPS+GLONASS+QZSS						GPS+GLONASS+IRNSS					
	DOP			#SV	VIS24h (%)		DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP				HDOP	VDOP	PDOP		
Mean	5.51	22.54	23.30	6.13	89.97	Mean	4.97	16.31	17.25	5.17	79.59
Max	481.99	2328.6	2378	11		Max	228.43	332.4	403.32	10	
Min	1.35	4.49	4.82	0		Min	1.42	4.48	4.79	0	
GPS+GLONASS+BeiDou+Galileo+QZSS+IRNSS											
	DOP			#SV	VIS24h (%)						
	HDOP	VDOP	PDOP								
Mean	1.69	6.16	6.40	11.44	100						
Max	6.41	33.84	33.99	18							
Min	1.05	3.34	3.56	6							

Table 13. Comparison of Coarse Positioning Navigation Performance indexes variations, 2020.

	Mean HDOP		#SV		VIS24h (%)	
	2020	Improvement	2020	Increment	2020	Improvement
GPS (2014)	76.22		2.65		19.03	
GPS+GLONASS	5.09	-71.13	5.07	+2.42	79.59	+60.56
GPS+GLONASS+BeiDou	2.87	-73.35	7.46	+4.81	99.31	+80.28
GPS+GLONASS+Galileo	3.97	-72.25	7.83	+5.18	98.27	+79.24
GPS+GLONASS+QZSS	5.51	-70.71	6.13	+3.48	89.97	+70.97
GPS+GLONASS+IRNSS	4.97	-71.25	5.17	+2.52	79.59	+60.56

the proportion of the time in which positioning is possible for 2014, the effect of BeiDou on the proportion of the time in which positioning is possible increased after the achievement of FOC. The increase in the average number of visible satellites for the GPS-GLONASS-Galileo combination was 5.18, which was the largest among the combinations. As a result, for 2020 when all the satellite navigation systems are expected to achieve FOC, it is expected that performing coarse positioning using the GPS-GLONASS-BeiDou combination would be the most effective.

4.2.2.2 Precise Positioning (the minimum elevation angle: 50°)

Table 14 summarizes the prediction of the precise positioning navigation performance for each multi-constellation combination. For the GPS-GLONASS integrated navigation, the average number of visible satellites would be 15.16, the maximum number of visible satellites would be 20, and the mean HDOP value would be 0.78. For the GPS-GLONASS-BeiDou integrated navigation, the average number of visible satellites would be 22.01, the maximum number of visible satellites would be 29, and the mean HDOP value would be 0.62. For the GPS-GLONASS-Galileo integrated navigation, the expected average number of visible satellites would be 23.11, the maximum number of visible satellites would be 30, and the mean HDOP value would be 0.61. For the GPS-GLONASS-QZSS integrated navigation, the average number of visible satellites would be 17.24, the maximum number of visible satellites would be 22, and the mean HDOP value would be 0.72. Also, for the GPS-GLONASS-IRNSS integrated navigation, the average number of visible satellites would be 18.19, the maximum number of visible satellites would be 23, and the mean HDOP value would be 0.74. Lastly, when the multi-constellation is organized by integrating all the six satellite constellations (GPS-GLONASS-BeiDou-Galileo-QZSS-IRNSS), the average number of visible satellites would be 35.05, the maximum number of visible satellites would be 45, and the mean HDOP value would be 0.51.

Table 15 compares the variations in the precise positioning navigation performance indices for 2020. When compared with the GPS-only positioning for 2014, the reduction in the mean HDOP value of the GPS-GLONASS-Galileo combination was the largest (0.58), and the increase in the average number of visible satellites was 15.3, which was also the largest. The reduction in the mean HDOP value for the GPS-GLONASS-BeiDou combination was 0.57, which was

Table 14. Prediction of multi-constellation precise positioning performance.

	DOP			#SV	VIS24h (%)
	HDOP	VDOP	PDOP		
GPS+GLONASS (2014)					
Mean	0.81	1.43	1.64	13.87	100
Max	1.07	2.75	2.90	19	
Min	0.61	1.00	1.23	11	
GPS+GLONASS (2020)					
Mean	0.78	1.43	1.63	15.16	100
Max	1.10	2.42	2.58	20	
Min	0.60	0.98	1.18	10	
GPS+GLONASS+BeiDou (2020)					
Mean	0.62	1.12	1.28	22.01	100
Max	0.79	1.56	1.69	29	
Min	0.51	0.85	0.99	16	
GPS+GLONASS+Galileo (2020)					
Mean	0.61	1.10	1.26	23.11	100
Max	0.82	1.54	1.72	30	
Min	0.50	0.79	0.95	17	
GPS+GLONASS+QZSS (2020)					
Mean	0.72	1.29	1.49	17.24	100
Max	0.97	1.93	2.09	22	
Min	0.58	0.94	1.11	12	
GPS+GLONASS+IRNSS (2020)					
Mean	0.74	1.29	1.49	18.19	100
Max	1.08	1.92	2.09	23	
Min	0.57	0.92	1.12	12	
GPS+GLONASS+BeiDou+Galileo+QZSS+IRNSS (2020)					
Mean	0.51	0.87	1.01	35.05	100
Max	0.62	1.14	1.26	45	
Min	0.42	0.69	0.83	27	

Table 15. Comparison of Precise Positioning Navigation Performance indexes variations, 2020.

	Mean HDOP		#SV		VIS24h (%)
	2020	Improvement	2020	Increment	2020
GPS(2014)	1.19		7.81		100
GPS+GLONASS	0.78	-0.41	15.16	+7.35	100
GPS+GLONASS+BeiDou	0.62	-0.57	22.01	+14.2	100
GPS+GLONASS+Galileo	0.61	-0.58	23.11	+15.3	100
GPS+GLONASS+QZSS	0.72	-0.47	17.24	+9.43	100
GPS+GLONASS+IRNSS	0.74	-0.45	18.19	+10.38	100

similar to that for the GPS-GLONASS-Galileo combination. In the case of the proportion of the time in which positioning is possible, precise positioning would be possible during the entire day (100%) for all the combinations, similar to 2014. As a result, for 2020, it is expected that performing precise positioning using the GPS-GLONASS-Galileo combination would be the most effective.

5. CONCLUSIONS

In this study, for the coarse positioning with the minimum elevation angle of 50° and the precise positioning with the minimum elevation angle of 15°, the visibility of satellites was judged; the proportion of the time in which positioning is possible and the number of visible satellites were examined; and the performance was analyzed in terms of DOP. As the number of satellite constellations constituting the multi-constellation increased, the proportion of the time in which positioning is possible, the number of visible satellites, and the DOP performance also increased. However, when integrated navigations were performed using three satellite constellations by adding BeiDou, Galileo, QZSS, and IRNSS, respectively, to the GPS-GLONASS combination, in order to perform simulation for examining the minimum satellite constellation combination for obtaining the best navigation performance based on the recent issue; as of 2014, the use of the GPS-GLONASS-Galileo combination was the most effective for coarse positioning and the use of the GPS-GLONASS-QZSS combination was the most effective for precise positioning; and for 2020, the use of the GPS-GLONASS-BeiDou combination would be the most effective for coarse positioning and the use of the GPS-GLONASS-Galileo combination would be the most effective for precise positioning. This simulation could be used as an index that can examine the satellite constellation combination for obtaining the best navigation performance using the minimum satellite constellation combination and can examine the navigation performance and the proportion of the time in which positioning is possible for each combination. In the future, a study on simulation accuracy improvement will be performed by reflecting detailed launch plans for each year and month.

ACKNOWLEDGMENTS

This work was supported by the National GNSS Research Center program of Defense Acquisition Program Administration and Agency for Defense Development.

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