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Analysis on the Multi-Constellation SBAS Performance of SDCM in Korea

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ABSTRACT

A Satellite Based Augmentation System (SBAS) provides differential correction and integrity information through geostationary satellite to users in order to reduce Global Navigation Satellite System (GNSS)-related errors such as ionospheric delay and tropospheric delay, and satellite orbit and clock errors and calculate a protection level of the calculated location. A SBAS is a system, which has been set as an international standard by the International Civilian Aviation Organization (ICAO) to be utilized for safe operation of aircrafts. Currently, the Wide Area Augmentation System (WAAS) in the USA, the European Geostationary Navigation Overlay Service (EGNOS) in Europe, MTSAT Satellite Augmentation System (MSAS) in Japan, and GPS-Aided Geo Augmented Navigation (GAGAN) are operated. The System for Differential Correction and Monitoring (SDCM) in Russia is now under construction and testing. All SBASs that are currently under operation including the WAAS in the USA provide correction and integrity information about the Global Positioning System (GPS) whereas the SDCM in Russia that started SBAS-related test services in Russia in recent years provides correction and integrity information about not only the GPS but also the GLONASS. Currently, LUCH-5A(PRN 140), LUCH-5B(PRN 125), and LUCH-5V(PRN 141) are assigned and used as geostationary satellites for the SDCM. Among them, PRN 140 satellite is now broadcasting SBAS test messages for SDCM test services. In particular, since messages broadcast by PRN 140 satellite are received in Korea as well, performance analysis on GPS/GLONASS Multi-Constellation SBAS using the SDCM can be possible. The present paper generated correction and integrity information about GPS and GLONASS using SDCM messages broadcast by the PRN 140 satellite, and performed analysis on GPS/GLONASS Multi-Constellation SBAS performance and APV-I availability by applying GPS and GLONASS observation data received from multiple reference stations, which were operated in the National Geographic Information Institute (NGII) for performance analysis on GPS/GLONASS Multi-Constellation SBAS according to user locations inside South Korea utilizing the above-calculated information.

Keywords: SBAS, SDCM, multi-constellation SBAS, accuracy, protection level, availability

1. INTRODUCTION

A Satellite Based Augmentation System (SBAS) is a system, which has been set as an international standard by the International Civilian Aviation Organization (ICAO). It is utilized for safe operation of aircrafts by providing an augmentation information in order to reduce Global Navigation Satellite System (GNSS)-related errors such as ionospheric delay and tropospheric delay, and satellite orbit and clock errors and calculate a protection level of the calculated location (ICAO 2006). The ICAO recommended the adoption of the SBAS, satellite-based next-generational navigation safety system, at the 10th General Meeting in 1991

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and urged ICAO members to introduce the performance-based navigation in the 36th General Meeting in 2007 (Han et al. 2011). According to the recommendation, a number of nations including the USA, Europe, Japan, India, and Russia have been strive to construct, operate, and develop SBASs based on the L1 SBAS Minimum Operational Performance Standards (MOPS), which are SBAS-related international standards. Currently, the Wide Area Augmentation System (WAAS) in the USA (Bunce 2011), the European Geostationary Navigation Overlay Service (EGNOS) in Europe (Maufroid & Flament 2011), MTSAT Satellite Augmentation System (MSAS) in Japan (Manabe 2008), and GPS-Aided Geo Augmented Navigation (GAGAN) (Sin et al. 2014) are operated. The System for Differential Correction and Monitoring (SDCM) in Russia is currently under construction (Sin et al. 2014). The WAAS, EGNOS, and GAGAN provide services of Approach Procedures with Vertical Guidance (APV-I)-grade performance in all air spaces while the MSAS provides only services of Non Precision Approach of Required Navigation Performance (RNP) 0.3 grade because it lacks the number of reference stations and effects of the ionosphere are significant (Sin et al. 2014). Nations that own a SBAS have made an effort to improve SBAS-related performance and service level. As a part of the efforts, studies on Multi-Constellation SBAS that provides additional correction information about GNSS such as not only the GPS but also the GLObal NAvigation Satellite System (GLONASS) (Sakai et al. 2012). The L1 SBAS MOPS was designed to support Multi-Constellation such as GPS, GLONASS, and etc. originally (RTCA 2006) but all SBAS including the WAAS in the USA that are currently operated provide correction and integrity information about the GPS only (Lawrence 2011). In contrast, the SDCM in Russia, which has started SBAS test services in Russia, provides correction and integrity information about not only the GPS but also the GLONASS (Russian Space System 2012). Currently, LUCH-5A(PRN 140), LUCH-5B(PRN 125), and LUCH-5V(PRN 141) are assigned and used as geostationary satellites for the SDCM. Among them, PRN 140 satellite is now broadcasting SBAS test messages for SDCM test services. In particular, since the Korean Peninsula is covered by the service area of the PRN 140 satellite and messages broadcast by PRN 140 satellite are received in Korea as well, performance analysis on GPS/GLONASS Multi-Constellation SBAS using the SDCM can be possible. Thus, the present paper generated correction and integrity information about GPS and GLONASS using SDCM messages broadcast by the PRN 140 satellite, and performed analysis on GPS/GLONASS Multi-Constellation SBAS performance and APV-I availability by applying GPS and GLONASS observation data received from multiple reference stations, which were operated in the National Geographic Information Institute (NGII).

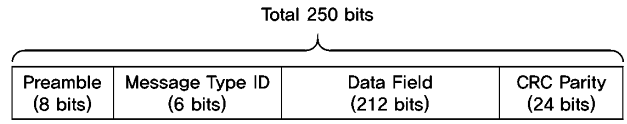

Fig. 1. A drawback of the HDD-based navigation system.

2. SBAS USER ALGORITHM FOR GLONASS

2.1 SBAS Message

SBAS geostationary satellites provide correction and integrity information generated in master stations using GPS-like L1 (1575.42 Mhz) ranging signal and broadcast the signal to a wide area of regions at a transmission rate of 250 bps. The SBAS message structure consists of 8 bits Preamble, 6 bits Message Type ID, 212 bits Data Field, and 24 bits CRC Parity as shown in Fig. 1. In particular, parameters required to generate correction and integrity information is included in the 212 data field (RTCA 2006).

A total of 64 message types (MTs) are assigned as presented in Table 1 to provide parameters required to generate SBAS correction and integrity information (RTCA 2006). Although the number of messages used in the current operating SBAS systems including the WAAS in the USA,

Table 1. SBAS message types and information.

Type	Contents	Type	Contents
0	SBAS test mode	17	GEO Satellite almanacs
1	PRN mask assignments	18	Ionospheric grid point mask
2 to 5	Fast correction & UDRE	19 to 23	Reserved
6	Integrity information (UDRE)	24	Mixed fast & long-term correction
7	Fast correction degradation factor	25	Long-term correction
8	Reserved	26	Ionospheric correction & GIVE
9	GEO navigation message	27	SBAS service message
10	Degradation parameters	28	Clk-Eph Cov. matrix message
11	Reserved	29 to 61	Reserved
12	SBAS network time / UTC offset	62	Internal test message
13 to 16	Reserved	63	Null message

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the EGNOS in Europe, and the MSAS in Japan is different system by system, around 19 messages are employed in general (Seok 2016). MT 1 among currently broadcast messages includes PRN Mask information to identify satellites supported by SBAS systems, which are utilized to calculate fast correction and long-term correction, which are satellite-related correction information in relation to MT 2~7, MT 10, MT 12, MT 24~25, and MT 28, and σ^2_{flt} that is the variance of estimate errors with regard to fast correction and long-term correction. MT 18 includes IGP mask information to identify ionospheric grid point (IGPs) for which ionospheric vertical delay and integrity information inside each of the SBAS system coverage, which is utilized to calculate ionospheric correction, which is ionospheric correction information in relation to MT 10 and MT 26, and σ^2_{UIRE}, which is the variance of estimate error with regard to ionospheric correction.

2.2 GLONASS Time and GLONASS Coordinate System

GLONASS is operated based on the reference clock generated in the GLONASS control segment, in which GLONASS time is adjusted to be synchronized with coordinated universal time (UTC) through the leap second correction in contrast with the GPS.

When user positioning is calculated by combining measurements via GPS and GLONASS, a difference in reference clock between GPS and GLONASS systems must be taken into consideration (ICAO 2006). There are a variety of methods that take a difference in reference clock into consideration. In an SBAS, a method that provides a time offset between two systems to users directly is used. The advantage of this method improves interoperability by fixing the number of unknown variables in the navigation solution equation to four even if user positioning is determined by combining measurements of GPS and GLONASS since GLONASS satellite clock errors calculated in consideration of time offset can be regarded as a measurement from the same constellation rather than different constellations (Sakai et al. 2012) Since the current operating SBAS systems including the WAAS in the USA, the EGNOS in Europe, and the MSAS in Japan support the GPS only, a difference in reference clock between two systems is not considered. Nonetheless, the SDCM in Russia that supports not only the GPS but also GLONASS considers a difference in reference clock between two systems and a time offset between two systems is included in MT 12 (Russian Space System 2012).

In contrast with the GPS that uses the WGS-84 coordinate, GLONASS employs the PZ-90 coordinate made in Russia. According to the GLONASS modernization plan, the PZ-90.02 coordinate, which is nearly equivalent to the ITRF2000 coordinate, has been used since September 2007. Similar to the case of using the reference clock, positions of the GPS and GLONASS satellites in the same coordinate system should be considered when user positioning is calculated using measurements obtained via two systems. The most general method for this is to convert the PZ-90.02 coordinate into the WGS-84 coordinate, and an equation of conversion between two coordinate systems is presented in Eq. (1).

Table 2. PRN mask assignment for SBAS.

PRN	Assignment
1 to 37	GPS
38 to 61	GLONASS
62 to 119	Future GNSS
120 to 138	GEO/SBAS PRN
139 to 210	Future GNSS/GEO/SBAS

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{WGS-84} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PZ-90.02} + \begin{bmatrix} -0.36 \\ 0.08 \\ 0.18 \end{bmatrix} \quad (1)$$

2.3 Limitation of PRN Mask

The PRN mask with regard to GNSS and GEO is assigned in the L1 SBAS MOPS, which is the international SBAS standard as presented in Table 2. The PRN mask included in MT 1 consists of a total of 210 slots whose value is 0 or 1. If a slot value is 0, it means that correction information of a corresponding satellite is not provided. If a slot value is 1, it means that correction information of a corresponding satellite is provided (RTCA 2006).

The most significant shortcoming of the L1 SBAS MOPS is that only up to 51 satellites can be corrected. Since PRN masks with regard to 32 GPS satellites and one to three GEO satellites are assigned and used in existing SBASs, the above limitation is not valid. On the other hand, the SDCM that supports even the GLONASS should assign PRN masks with regard to 24 GLONASS satellites additionally, it is affected by the above limitation.

Fig. 2 shows MT 1 PRN masks of SDCM message received at the Navigation System Laboratory in Sejong University from 00:00 to 24:00 in September 24, 2016, which verified that the current SDCM assigned and employed PRN masks with regard to a total of 51 satellites (26 GPS satellites, 24 GLONASS satellites, and 1 SDCM GEO satellite) except for GPS PRN 1, 5, 6, 24, 26, and 32.

2.4 IOD (Issue of Data)

In MT 25 that is broadcast by the SBAS, the issue of data (IOD) is included along with satellite orbit and clock error

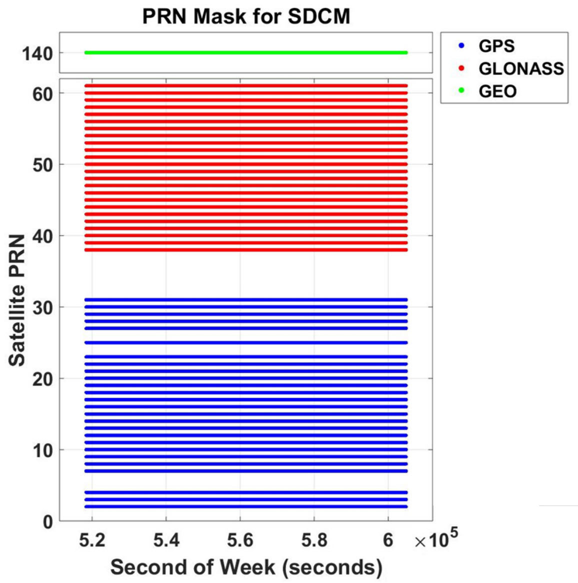

Fig. 2. PRN mask for MT 1 transmitted by SDCM.

Table 3. PRN mask assignment for SBAS.

Data	Bits	Range [s]	Resolution [s]
Operation time	5	30 to 960	30
Delay time	3	0 to 120	30

corrections, which are required to calculate a long-term correction. Users must take the IOD into consideration in the calculation of long-term correction. For the GPS, the IOD is used to check whether GPS broadcast ephemeris used to generate long-term correction in the master stations and GPS broadcast ephemeris used to determine satellite positioning by users are matched. Satellite position and clock errors using a corresponding broadcast ephemeris can be corrected by long-term correction only when IOD ephemeris (IODE), IOD clock (IODC) that are included in GPS broadcast ephemeris of users and IOD are matched. For GLONASS, the IOD refers to a valid time that can apply long-term correction to a satellite position calculated using GLONASS broadcast ephemeris. It consists of operation time (V) and delay time (L) as presented in Table 3. Users can apply long-term correction only to satellite position and clock errors calculated using GLONASS broadcast ephemeris that satisfies Eq. (2). (Russian Space System 2012).

$$t_{LT} - L - V \leq t_r \leq t_{LT} - L \tag{2}$$

In Eq. (2), t_{LT} refers to a time that long-term correction is broadcast at the geostationary satellite and t_r refers to a time that a user receives the GLONASS broadcast ephemeris.

2.5 Long-term Correction for GLONASS Satellite

As mentioned in the above, a process of calculation of long-term correction can vary slightly since the reference clock and coordination system used by each of the GPS and GLONASS systems are different.

For correction information of satellite clock errors, satellite clock error correction ($\delta\Delta t_{SV}$) for GPS satellites can be calculated using Eq. (3) while satellite clock error correction for GLONASS satellites can be calculated via Eq. (4) by considering a time offset (δa_{fG0}) that is a difference in reference clock between GPS time and GLONASS time, which is included in MT 12 (RTCA 2006, Russian Space System 2012).

$$\delta\Delta t_{SV} = \delta a_{f0} + \delta a_{f1} (t - t_0) \tag{3}$$

$$\delta\Delta t_{SV} = \delta a_{f0} + \delta a_{f1} (t - t_0) + \delta a_{fG0} \tag{4}$$

In Eqs. (3) and (4), δa_{f0} and δa_{f1} refer to clock offset error correction and clock drift error correction, and t and t_0 refer to a current time and applicable time of long-term correction.

For correction information of satellite orbit errors, satellite orbit error correction (δx_k, δy_k, δz_k) for both of GPS and GLONASS satellites can be calculated using Eq. (5). However, since correction information of GPS satellites is based on the WGS-84 coordinate system and correction information of GNONASS satellite is based on the PZ-90.02 coordinate system, correction information of GLONASS satellite orbit error shall be converted to the WGS-84 coordinate system using Eq. (1).

$$\begin{bmatrix} \delta x_k \\ \delta y_k \\ \delta z_k \end{bmatrix} = \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} + \begin{bmatrix} \delta \dot{x} \\ \delta \dot{y} \\ \delta \dot{z} \end{bmatrix} (t - t_0) \tag{5}$$

In Eq. (5), δx, δy, and δz refer to correction information of satellite orbit errors, and $\delta\dot{x}$, $\delta\dot{y}$, and $\delta\dot{z}$ refer to correction information of satellite velocity errors. t and t_0 are the same as in Eqs. (3) and (4).

2.6 SBAS Positioning Algorithm

Fig. 3 shows the SBAS positioning algorithm using the augmentation information which is provided by the SDCM. For input data of the algorithm, RINEX Observation Data, Navigation Data, and SBAS Broadcast Message are used. A process of the user positioning calculation is as follows: First, GLONASS L1 code measurement, satellite signal reception time, and GLONASS broadcast ephemeris are

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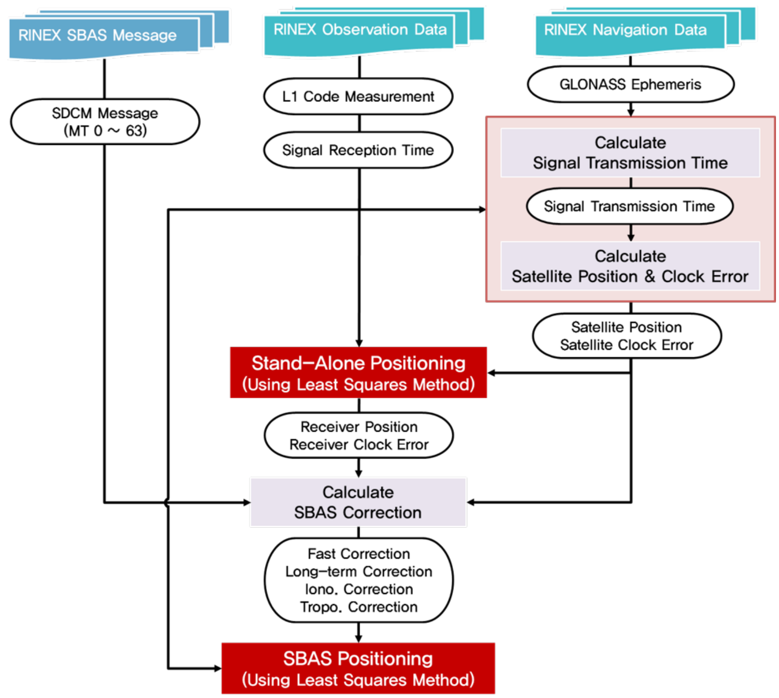


Fig. 3. SBAS positioning algorithm using SDCM corrections.

received as input data and GLONASS satellite position and clock errors are calculated as of the time of the satellite signal transmission. Second, GLONASS L1 code measurement, satellite signal receive time, and GLONASS broadcast ephemeris are received as input data and user position and clock errors are calculated in the stand-alone mode. Third, decoded SDCM message, GLONASS satellite position, and clock errors are received as input data and fast correction and long-term correction, which are GLONASS satellite-related correction information, and ionospheric correction and tropospheric correction, which are atmosphere-related errors, are calculated. Finally, SDCM correction is applied to GLONASS L1 code measurements to calculate user position and clock errors at the SBAS mode.

3. EXPERIMENTAL RESULTS

3.1 GPS/GLONASS Observations Data and SBAS Message

In order to consider various user positions from low to high latitudes in South Korea, the following 17 GNSS reference stations that are operated by the National Geographic Information Institute are selected as shown in Fig. 4: Cheorwon Reference Station (CHUL), Inje Reference Station (INJE), Ganghwa Reference Station (GANH), Hongcheon Reference Station (HONC), Seoul Reference

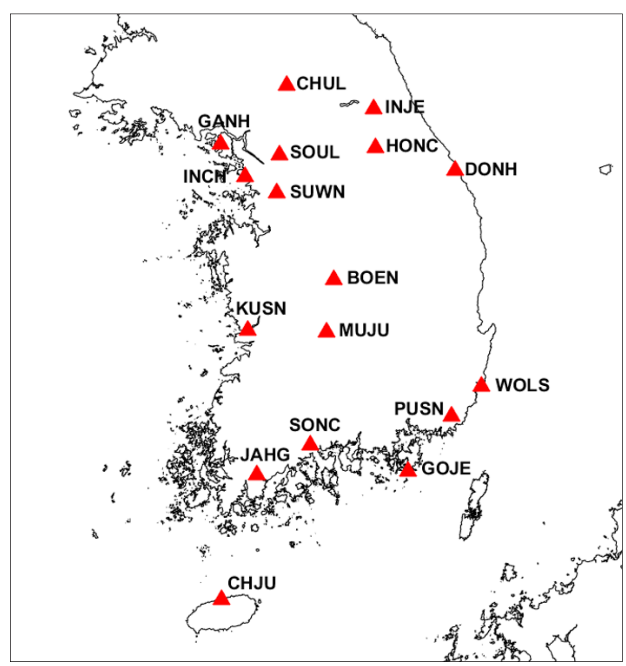
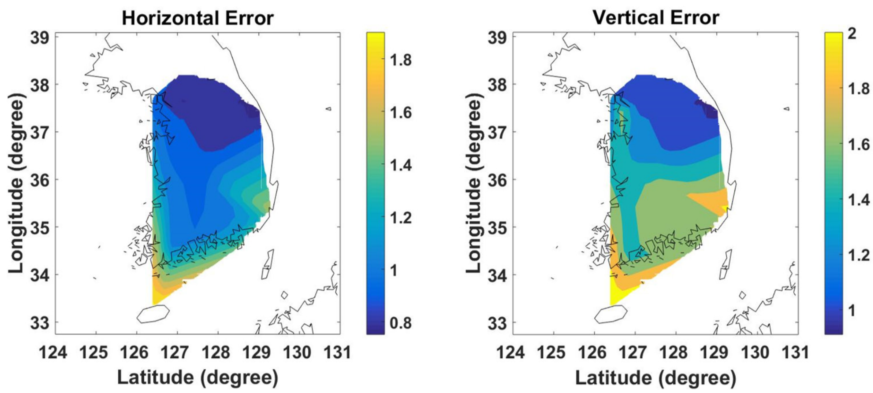


Fig. 4. Location of NGII GNSS reference stations used for the analysis.

Station (SOUL), Donghae Reference Station (DONH), Incheon Reference Station (INCH), Suwon Reference Station (SUWN), Boeun Reference Station (BOEN), Gunsan Reference Station (KUSN), Muju Reference Station (MUJU), Ulsan Reference Station (WOLS), Busan Reference Station (PUSN), Suncheon Reference Station (SONC), Geoje



(a) Horizontal (b) Vertical

Fig. 5. SDCM position accuracy map.

Table 4. Information of 17 GNSS reference stations.

Site name	GNSS receiver	Lat. [N]	Lon. [E]	Hgt. [m]
CHUL	Trimble NetR9	38.273	127.145	289.032
INJE	Trimble NetR5	38.070	128.171	257.483
GANH	Trimble NetR9	37.719	126.390	43.501
HONC	Trimble NetR5	37.709	128.194	372.184
SOUL	Trimble NetR9	37.630	127.080	59.113
DONH	Trimble NetR9	37.507	129.124	69.941
INCH	Trimble NetR5	37.420	126.686	88.464
SUWN	Trimble NetR9	37.276	127.054	83.819
BOEN	Trimble NetR5	36.488	127.730	212.238
KUSN	Leica GR10	36.005	126.762	49.082
MUJU	Trimble NetR8	36.003	127.661	230.189
WOLS	Trimble NetR5	35.504	129.416	99.935
PUSN	Trimble NetR5	35.234	129.075	158.645
SONC	Trimble NetR5	34.958	127.486	43.617
GOJE	Leica GR10	34.722	128.591	61.720
JAHG	Trimble NetR5	34.675	126.899	116.773
CHJU	Trimble NetR9	33.514	126.530	50.337

Table 5. Horizontal and vertical error statistics at each GNSS reference stations (2697 epochs / 2880 epochs).

Site name	Horizontal			Vertical		
	Std. [m]	RMS [m]	Max [m]	Std. [m]	RMS [m]	Max [m]
CHUL	0.4202	0.8857	3.8435	1.0219	1.0276	3.9754
INJE	0.4287	0.8636	5.7658	1.1269	1.1317	10.0602
GANH	0.4686	0.9317	4.6816	1.2085	1.2147	6.1514
HONC	0.4045	0.8197	3.1462	1.0177	1.0239	4.6160
SOUL	0.3746	0.7810	3.6495	0.9918	1.0958	5.3753
DONH	0.3715	0.7515	2.8306	0.8838	0.9107	3.2120
INCH	0.5296	0.9765	4.5056	1.6357	1.6809	13.7194
SUWN	0.4597	0.9104	3.3952	1.1867	1.2582	7.4170
BOEN	0.4357	0.9037	2.8168	1.1417	1.2222	6.2282
KUSN	0.6095	1.0475	6.7553	1.2960	1.4595	8.6851
MUJU	0.5831	0.9558	13.1663	1.6848	1.6846	23.4755
WOLS	1.2822	1.5802	28.6218	2.0497	2.0533	43.7879
PUSN	0.8174	1.1744	14.5710	1.6076	1.6112	29.2361
SONC	0.5416	1.0039	5.9983	1.7611	1.7759	20.1039
GOJE	0.9942	1.4422	12.6941	1.6713	1.7427	11.2583
JAHG	0.5858	1.0592	5.5296	1.3260	1.4009	8.7716
CHJU	1.4705	1.9322	18.9978	2.1544	2.1862	21.2794

Reference Station (GOJE), Jangheung Reference Station (JAHG), Jeju Reference Station (CHJU). Table 4 summarizes latitude, longitude, height, and GNSS receiver used in each reference station. For performance analysis, GPS and GNONASS observation data received at each reference station for 24 hours from 00:00 in September 24 2016 to 24:00 in September 24 2016 were used as GNSS observation data. For SBAS messages, SDCM messages from PRN 140 satellite received at the Navigation System Laboratory in Sejong University at the same time period were used.

3.2 Position Accuracy

Fig. 5 shows a result that projects the Root Mean Squares (RMS) of horizontal and vertical errors of user's position calculated by applying SDCM differential correction and integrity information to the observation data in the reference stations to the Korean Peninsula map in order to verify the correction performance of user positioning error in the GPS/GLONASS Multi-Constellation SBAS according user's position in the Korean Peninsula. Table 5 summarizes standard deviation, RMS, and maximum values of horizontal and vertical errors of user position for each reference station. As presented in Fig. 5 and Table 5, RMSs of horizontal and vertical errors were increased as a latitude is moved from higher latitude to lower latitude in South Korea. In particular, RMSs of horizontal and vertical errors in CHUL Reference Station, which was located in the northernmost part among the selected reference stations, were 0.8857 m and 1.0276 m, respectively, while those in CHJU Reference Station, which was located in the southernmost part, were 1.9322 m and 2.1862 m, verifying that a user positioning error of the GPS/GLONASS Multi-Constellation SBAS was twice that in the high latitude approximately, resulting in a significant decrease in performance.

3.3 APV-I Availability

The ICAO specifies the RNP with regard to accuracy, integrity, continuity, and availability according to a navigation mode in safety facility including the SBAS. The SBAS which is a system

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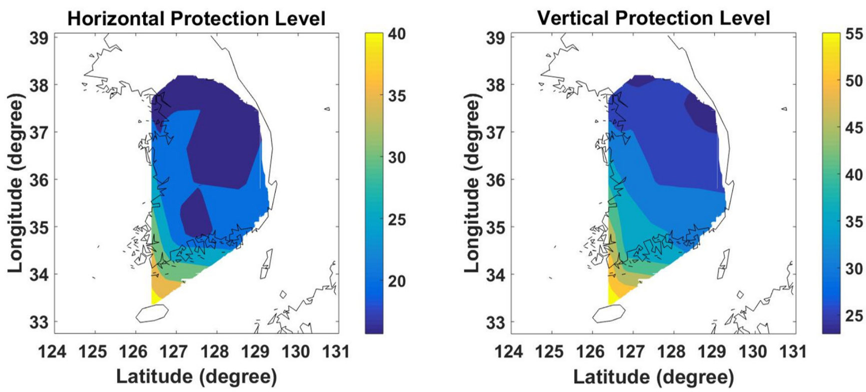
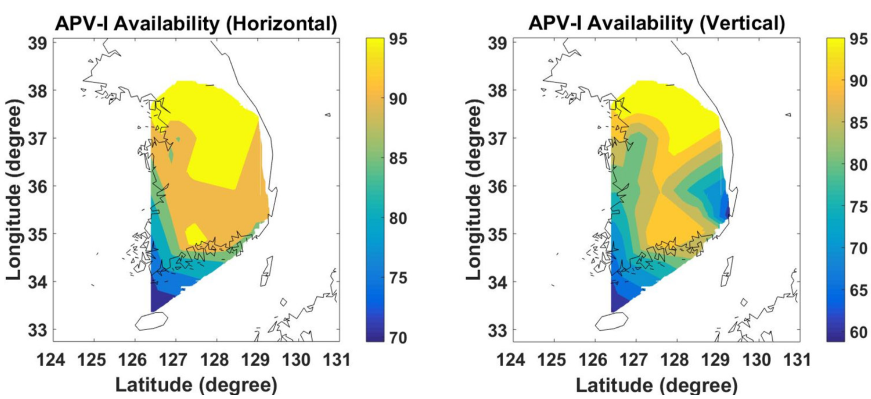


(a) Horizontal (b) Vertical

Fig. 6. Average protection level map of SDCM.



(a) Horizontal (b) Vertical

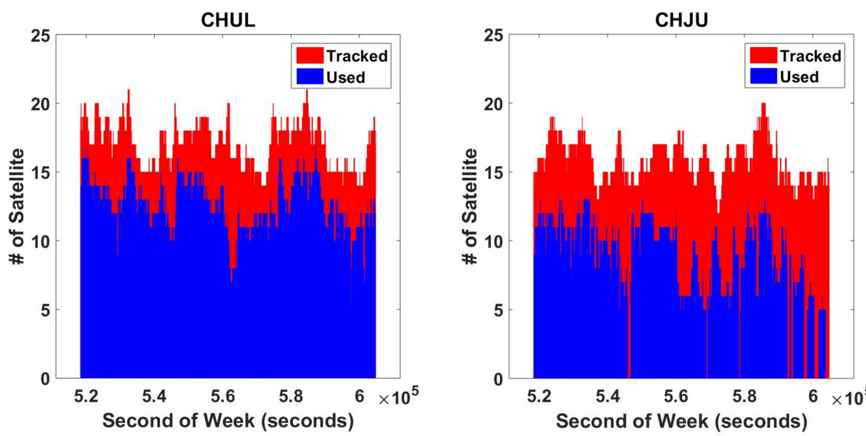
Fig. 7. APV-I availability map of SDCM.

for aviation has been developed to meet the performance requirements of the APV-I level or higher where airplanes can take off and land. It is also necessary for the SBAS to perform performance evaluation and monitoring continuously whether accuracy, integrity, continuity, and availability required before and after system operation are satisfied (ICAO 2006, Kim et al. 2016). Availability, which is one of the SBAS system performance requirements, refers to a requirement of time ratio that meets the performance requirements in relation to accuracy, integrity, and continuity. It is also expressed conventionally as a ratio of time that the protection level (PL) is less than the alert limit (AL). In this paper, we investigated a possibility whether performance of APV-I level is satisfied from viewpoints of AL and horizontal and vertical PL calculated using data collected in 24 hours assuming that accuracy, integrity, and continuity in the SDCM system in South Korea satisfy the performance requirements of APV-I level.

In order to analyze availability of APV-I in the GPS/GLONASS Multi-Constellation SBAS according to user position in South Korea, mean values of Horizontal Protection Level (HPL) and vertical protection level calculated by applying SDCM differential correction and integrity information to observation data in the reference stations are indicated in Fig. 6 and summarized in Table 6 for each reference station. Fig. 7 shows a projection of availability with regard to integrity requirements (Horizontal 40 m / Vertical 50 m) of precision approach (PA) of APV-I

Table 6. Mean value of horizontal and vertical protection level at each GNSS reference stations (2697 epochs / 2880 epochs).

Site name	Horizontal mean [m]	Vertical mean [m]
CHUL	15.9329	23.5342
INJE	16.1806	26.0831
GANH	17.9175	26.9844
HONC	16.2265	25.2107
SOUL	16.9967	26.3453
DONH	15.6189	22.9821
INCH	18.1438	28.0394
SUWN	18.1456	29.2376
BOEN	18.8148	28.1794
KUSN	21.7896	34.9991
MUJU	20.0387	29.8996
WOLS	22.7957	31.3524
PUSN	23.6311	30.9322
SONC	24.3014	36.7476
GOJE	24.2641	32.6797
JAHG	27.1596	37.0806
CHUJ	42.5063	59.0554



(a) CHUL (b) CHJU

Fig. 8. Number of tracked and used satellites at CHUL and CHJU reference stations.

Table 7. Horizontal and vertical APV-I availability at each GNSS reference stations (2697 epochs / 2880 epochs).

Site name	Horizontal availability [%]	Vertical availability [%]
CHUL	99.5139	99.3750
INJE	99.6528	98.4375
GANH	96.6319	95.6597
HONC	99.5139	98.3333
SOUL	99.0278	98.1597
DONH	99.4444	99.6875
INCH	96.5278	95.1389
SUWN	96.7361	92.8472
BOEN	95.1736	93.8194
KUSN	89.7222	80.2083
MUJU	92.3264	89.9653
WOLS	90.1389	88.6806
PUSN	89.6528	89.5139
SONC	87.7431	79.2708
GOJE	87.3611	86.4263
JAHG	82.7083	75.9375
CHUJ	69.4097	58.5764

airplane required by the ICAO to the Korean Peninsula map. Table 7 summarizes detailed results for each reference station. As the same as the analysis result on position errors, horizontal and vertical PLs were increased as a latitude moved from higher to lower latitude in South Korea, and APV-I availability was decreased accordingly. In particular, mean values of horizontal and vertical PLs at CHJU Reference Station were 42.5063 m and 59.0544 m, respectively, which were 2.5 to 2.7 times higher than 15.6189 m and 22.9821 m, which were values at CHUL Reference Station, verifying that the PL was rapidly increased as a latitude moved from higher to lower latitude. Furthermore, APV-I availabilities at CHUL and DONH Reference Stations in the horizontal and vertical directions showed 99.5139% / 99.3750% and 99.4444% / 99.6875%, respectively, which satisfied the required standards (99% ~ 99.999%) of the ICAO, indicating that services of APV-I level can be available to users located in reference stations of high latitude region.

Table 8. Number of fast/long-term/ionospheric corrections at 2016/09/24 18:07.

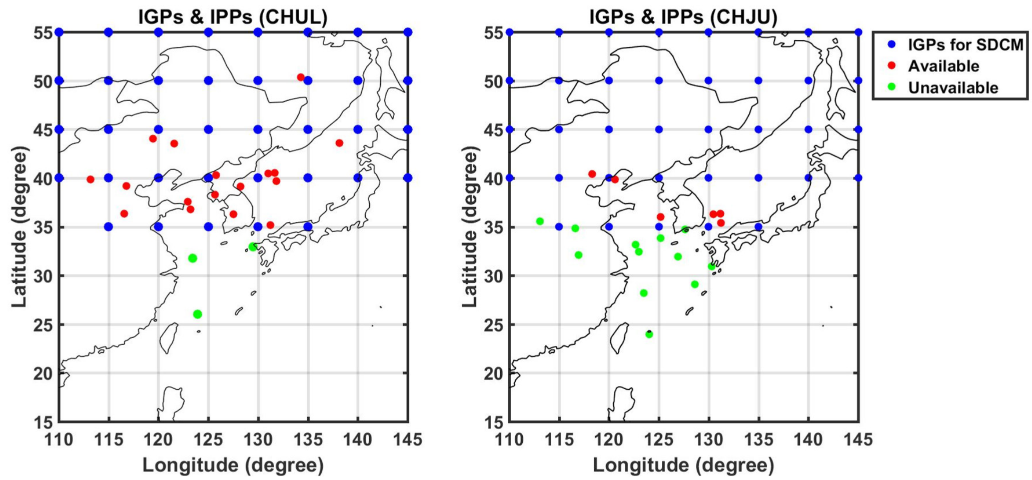
Site name	Fast	Long-term	Ionospheric
CHUL	26	26	17
CHJU	24	26	6

However, reference stations located in mid-to-low latitude regions satisfied the ICAO required standards only at the horizontal or vertical direction but not satisfied in both of the horizontal and vertical directions, which indicated that users in low-to-mid latitude regions may not use services of the APV-I level.

3.4 Differential Correction Analysis

In order to determine the reason for significant performance degradation of GPS/GLONASS Multi-Constellation SBAS as a latitude moved from higher to lower latitude in South Korea, performance was analyzed in terms of fast correction, long-term correction, and ionospheric correction.

Fig. 8 shows comparison of the number of tracked satellites at CHUL and CHJU reference stations and the number of satellites used in user positioning calculation. The mean numbers of tracked satellites at two reference stations were approximately 17 and 16 satellites, which showed no significant difference. However, the mean numbers of satellites used in position calculation were approximately 13 and 9 satellites, which showed a significant difference. In particular, the numbers of satellites used in position calculation showed the most difference between two reference stations as 16 and 6 satellites in 18:07 in September 24 2016. As presented in Table 8, the numbers of satellites that can generate fast correction and long-term correction had no significant difference between two reference stations but the numbers of satellites that can generate ionospheric correction



(a) CHUL (b) CHJU

Fig. 9. IGPs and IPPs distribution at 2016/9/24 18:07.

Table 9. Predefined world-wide IGP spacing – Band 0-8 (RTCA 2006).

Latitude degrees	Latitude spacing degrees	Longitude spacing degrees
N85	10	90
N75 to N65	10	10
S55 to N55	5	5
S75 to S65	10	10
S85	10	90 (offset East)

Table 10. Predefined world-wide IGP spacing – Band 9-10 (RTCA 2006).

Latitude degrees	Latitude spacing degrees	Longitude spacing degrees
N85	10	30
N75 to N65	5	10
N60	5	5
S60	5	5
S75 to S65	5	10
S85	10	30 (offset East)

were 17 and 6 satellites, which have a significant effect on determination of the number of satellites (16 and 6 satellites) used in position calculation in each reference station.

Whether the ionospheric correction information is generated or not is determined by whether the IGPs around the ionospheric pierce point (IPP) provide a sufficient number of vertical ionospheric delay or not. Tables 9 and 10 present IGP latitude and longitude spacing for each band, which are specified in L1 SBAS MOPS. The SDCM employs seven bands (0, 4, 5, 6, 7, 8, and 9) out of a total of 11 bands and the Korean Peninsula is included in Band 7 which provide IGP ionospheric correction information in every 5°. Fig. 9 shows the IGP where the SDCM provides ionospheric correction information at the time of 2016/9/24 18:07 and the IPP of visible satellites at CHUL and CHJU reference stations. The IPP of visible satellites at CHUL reference station was distributed mostly at latitude 35° or higher whereas the IPP of visible satellites in CHJU reference station was distributed mostly over 35° or lower. In addition, the SDCM did not provide ionospheric correction information to regions whose latitude was 35° or lower in the Korean Peninsula. Due to this characteristic, only 17 satellites were able to be used in user positioning calculation because ionospheric correction information about three satellites out of 20 visible satellites cannot be generated at CHUL reference station, and ionospheric correction information about 12 satellites out of 18 visible satellites cannot be generated at CHJU reference station so only six satellites were used in user positioning calculation. From these results, the decrease in the number of satellites that can generate ionospheric correction in low latitude regions was verified as a main reason for performance degradation in the GPS/GLOMASS Multi-Constellation SBAS using SDCM.

4. CONCLUSIONS

In this paper, we generated differential correction and integrity information with regard to GPS and GLONASS by receiving PRN 140 messages from the SDCM satellite of Russia, which has started a test service of SBAS in Russia, and analyzed performance in Multi-Constellation SBAS in the Korean Peninsula utilizing the above information. To do this, 17 reference stations running by the National Geographic Information Institute were selected, and characteristics of messages and accuracy and integrity characteristics received from 2016/9/24 00:00 and 2016/9/24 24:00 were verified thereby performing performance analysis.

The analysis result on correction performance of user positioning showed that horizontal and vertical errors tended to increase as users in South Korea were located in lower latitude. For example, errors calculated in the southernmost reference station amounted to twice of that in the northernmost reference station approximately. The PL also showed the same tendency. For example, the PL in the southernmost reference station amounted to 2.5 times of that in the northernmost reference station approximately. Accordingly, only CHUL and DONH reference stations, which were the northernmost reference stations out of 17 stations, satisfied APV-I availability in terms of PL and AL.

In order to determine the reason for performance degradation in Multi-Constellation SBAS in the SDCM as a latitude moved from higher to lower latitude, fast correction, long-term correction, and ionospheric correction were analyzed. The analysis result showed that the mean numbers of visible satellites were approximately 17 satellites in higher latitude and 16 satellites in lower latitude, which showed no significant difference. However, the mean numbers of satellites used in user positioning calculation were approximately 13 satellites in higher latitude and 9 satellites in lower latitude, which verified the decrease in the number of satellites used in user positioning calculation in lower latitude. To determine the reason for the decrease in the number of satellites, the number of satellites that can generate ionospheric correction with regard to 2016/9/24 18:07 where the number of satellites was the most different between the northernmost CHUL and the southernmost CHJU reference stations were analyzed. The analysis result showed that the number of satellites that can generate ionospheric correction was 17 satellites in CHUL reference station and 6 satellites in CHJU reference station due to the characteristics of the SDCM that did not provide ionospheric correction information with regard to IGP below 35° latitude over the Korean Peninsula. Because most SDCM reference stations were distributed over higher latitudes than that of South Korea so that a distribution of IPPs that can be generated was concentrated in higher latitudes as well, which made difficult to generate vertical ionospheric delay of available IPP in South Korea. As such, a difference in the number of satellites that can generate ionospheric correction was verified as the main reason for the regional difference in performance of GPS/GLONASS Multi-Constellation SBAS using the SDCM. For future study, it is necessary to investigate possibility of improvements on performance degradation through interlink with other systems.

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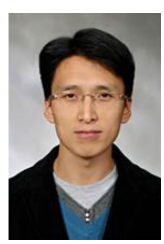

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