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Quality Monitoring Comparison of Global Positioning System and BeiDou System Received from Global Navigation Satellite System Receiver

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ABSTRACT

In this study, we implemented the data quality monitoring algorithm which is the previous step for real-time Global Navigation Satellite System (GNSS) correction generation and compared Global Positioning System (GPS) and BeiDou System (BDS). Signal Quality Monitoring (SQM), Data QM, and Measurement QM (MQM) that are well known in Ground Based Augmentation System (GBAS) were used for quality monitoring. SQM and Carrier Acceleration Ramp Step Test (CARST) of MQM result were divided by satellite elevation angle and analyzed. The data which are judged as abnormal are removed and presented as Root Mean Square (RMS), standard deviation, average, maximum, and minimum value.

Keywords: GPS, BDS, SQM, DQM, MQM

1. INTRODUCTION

Autonomous vehicles have many advantages such as reduction in traffic accidents, promoting mobility for the transportation vulnerable, efficiency in fuel usage, and reduction in pollutant emission, which will increase the social and economic ripple effects positively. Global Navigation Satellite System (GNSS), inertial measurement unit (IMU), vision, and light detection and ranging are some examples of sensors to estimate positioning of Autonomous vehicles and they can be combined to overcome the drawbacks of each sensor.

Global Positioning System (GPS) in the USA is the first of GNSS and GLObal NAvigation Satellite System in the Russia is full operational capability now and BeiDou System (BDS) in the China and Galileo in the Europe are under development. Japan and India are also developing Regional Navigation Satellite System to improve their positioning performance in their countries. With being able to use various systems available, as the number of visible satellites increases, better positioning results of autonomous vehicles are now expected in ground traffic environments where signal blockage frequently occurs.

However, since GNSS positioning algorithms that are generally used in vehicle navigation devices use pseudorange measurements, a positioning error at a level of meter is generated, which is not applicable to autonomous vehicles that requires an error at a level of centimeter such as lane classification and distance from the front or rear cars during car stop or slow-down. To produce a positioning result at a level of centimeter using GNSS, it is recommended to use carrier phase measurements. Real Time Kinematic (RTK) is usually used for centimeter level positioning. To overcome the disadvantage of conventional RTK, using multi-reference station technic has been developed that is called Network RTK. In the Network RTK, a single network is formed using three or more reference stations and correction is generated by calculating and combining the information of the reference stations. Generated correction is transfer to the user that can remove the user errors located in the network.

This study implemented an abnormal detection algorithms of GPS and BDS as pre-processing step to develop a generating real time correction based on GNSS carrier

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Table 1. System difference between GPS and BDS.

	GPS	BDS
Carrier frequency	L1 (1575.42 MHz) L2 (1227.60 MHz)	B1I (1561.098 MHz) B2I (1207.140 MHz)
Satellite orbit	MEO	GEO, IGSO, MEO
MEO orbit period	About 11 hr 58 min	About 12 hr 53min 24 sec
Geocentric gravitational constant	3.986005×10^{14} m^3/s^2	$3.986004418 \times 10^{14}$ m^3/s^2
Rate of earth rotation	$7.2921151467 \times 10^{-5}$ rad/s	7.292115×10^{-5} rad/s
Coordinate system	WGS84	CGCS2000
Time system	GPST	BDT (GPST-14 second)
Subframe frequency	6 second	6 second for D1 (IGSO, MEO) 0.6 second for D2 (GEO)
Broadcast ephemeris update	2 hour	1 hour
Time of ephemeris	After 2 hour from updated time	Updated time
Week over in ephemeris	About GPST 7200 second	About BDT 0 second

phase measurement using multi reference stations to provide correction that vehicles can perform lane-level positioning. The result of this study could be utilized as foundation research for threshold determination in the future work and evaluate the implementation accuracy of the real-time algorithm. The Signal Quality Monitoring (SQM), Data QM (DQM), and Measurement QM (MQM) proposed by Xie (2004) were used.

As previous study, Xie (2004) studied threshold determination for abnormal measurement detection using the Integrity Monitor Testbed that is a prototype of the Local Area Augmentation System (LAAS) Ground Facility (LGF) that is used to evaluate whether the LGF can meet system integrity requirements. In addition, Ahn (2009) conducted performance evaluation by applying artificial errors to the normal measurements in the failure detection algorithm used in the Ground Based Augmentation System reference station. Koenig (2010) improved existing MQM algorithm to apply existing LAAS to the Joint Precision and Approach Landing System program in the US army and compared and analyzed the improved algorithm with the existing algorithm.

Regarding the quality analysis (QA) and comparison of the GPS and BDS, Jan & Tao (2016) performed signal QA, data QA, and measurement QA to detect and remove abnormal measurements prior to integrated positioning of GPS and BDS, and their analysis results verified no significant difference between GPS and BDS.

These previous studies showed only the results analyzed with GPS L1 or BDS B1. Thus, this study presented the results applied to GPS L2 and BDS B2 additionally, and compared the results with those of the previous study results.

2. SYSTEM DIFFERENCE BETWEEN GPS AND BDS

According to the GPS ICD (2014) and BDS ICD (2013), the frequency of the GPS is named as L1 and L2, and that of the BDS is named as B1I and B2I. Although frequencies between the systems are different due to the code division multiple access, frequencies between satellites are the same. In this study, the frequencies of the BDS were named as B1 and B2 for convenience. The satellite orbit in the GPS consists of medium earth orbit (MEO) only and the orbit period is approximately 11 hours and 58 minutes so that the same satellite is observed approximately twice a day. The BDS consists of three orbits: geostationary EO (GEO), inclined geosynchronous satellite orbit (IGSO), and MEO. The MEO orbit period is around 12 hours 53 minutes and 24 seconds. The two systems use a different coordinate system. According to Cheng (2009), the difference in gravity in the two coordinate systems is 0.02×10^{-8} m/s^2, and the difference in latitude and longitude is 0.11 mm. These differences occur because they use a different gravity constant and Earth's rotation angular velocity value. Thus, it is considered that there is no significant difference in World Geodetic System 1984 and China Geodetic Coordinate System 2000.

The time system used in the GPS and BDS are GPS Time (GPST) and BDS Time, respectively. However, the start time of the two systems is different. In 2018, the GPS has a leap second of 18 seconds and the BDS has a leap second of 4 seconds, resulting in 14 seconds difference between two systems. Accordingly, GNSS receivers used generally are synchronized with the GPST. Thus, it should subtract 14 seconds from the GPST when BDS data are processed. In addition, a difference in the GNSS week number between the two systems is 1,356 (Kong et al. 2016).

A subframe that provides real time ephemeris is used for real-time processing of the GNSS. The GPS subframe is provided from one to five in every six seconds, and this is also same with D1 in the BDS. However, D1 data in the BDS provides only the ephemeris of IGSO and MEO satellites, so the ephemeris of GEO satellites should be acquired using D2 data that is provided in every 0.6 seconds. The difference between those two ephemerides is that the GPS is updated in every two hours while the BDS is updated in every hour, and the GPS provides the time of ephemeris (TOE) in ephemeris data after two hours from the updated time, and the BDS provides the TOE in ephemeris data at the updated time (BDS ICD 2013, GPS ICD 2014). If the GNSS week second at the current time is zero, the TOE is 7,200 seconds and 0 seconds are provided in the GPS and BDS, respectively. Thus, the BDS week number in the ephemeris is increased by one when the TOE is 0 seconds. But the GPS week number is not increased when the TOE is 0 seconds and is increased by one when the TOE is 7,200 seconds. The differences between the two systems are summarized in Table 1.

3. COMPARISON OF QUALITY MONITORING BETWEEN GPS AND BDS

The SQM, DQM, and MQM algorithms proposed by Xie (2004) were implemented and applied to GPS L1 and L2 and BDS B1 and B2. The data used in the analysis were received from CHAM, GSNM, and HWSM continuously operating reference stations, which were located in Cheonan, Goesan, and Hwaseong, respectively. Each of the stations was equipped with choke ring antennas that can minimize multipath errors and dual frequency receivers. The measurements were stored in every second and the minimum satellite elevation angle was approximately set to 5°. The analysis period was from day of year (DOY) 223 of 2018 to DOY 229 of 2018. The satellite position was calculated by decoding the subframe to assume the real time, and the data were processed for seven days continuously epoch by epoch. The precise coordinates of the stations were obtained based on Bernese 5.2 which is precise GNSS data processing software and its mean value of the analysis period was used to calculate geometry range etc.

3.1 Signal Quality Monitoring

SQM is used to detect the abnormality due to signal interference and reflection of GNSS signals. It can be divided into correlation peak symmetry test (CPST), signal power test (SPT), and code-carrier divergence test (CCDT) (Xie 2004, Koenig 2010). Among them, the CPST was excluded in this study because it needed an additional receiver that integrated and produced correlation measurements at different locations.

3.1.1 Code-carrier divergence test

The CCDT is used to detect the sudden change of ionospheric errors with a geometric moving averaging method using the pseudorange minus carrier phase measurements assuming that a cycle slip has not occurred in the carrier measurements and changes of ionosphere error is very small in a short period of time (Xie 2004, Koenig 2010). As shown in Eq. (1), a difference between pseudorange and carrier phase measurements is assumed as z, and Eq. (1) is time differenced to produce Eq. (2), resulting in having only changes of ionosphere error. Then, the CCDT can be performed by using Eq. (3). In Eqs. (1) to (3), P is the pseudorange measurement, Φ is the carrier phase measurement, I is the ionospheric error, λ is a wavelength, N is the integer ambiguity, and τ is a mean time constant, which was set to 100 in this study. Since the ionospheric error of L2 (B2) is $\frac{F_1^2}{F_2^2}$ times that of the L1 (B1), when processing the L2 (B2) data, the change in the ionosphere was divided by $\frac{F_1^2}{F_2^2}$.

$$z = \mathrm{P} - \Phi = 2\mathrm{I} - \lambda\mathrm{N} \quad (1)$$

$$\frac{z(t)-z(t-1)}{2} = \dot{\mathrm{I}} \quad (2)$$

$$CCDT(t) = \frac{\tau(t)-\dot{t}}{\tau(t)}\mathrm{CCDT}(t-1) + \frac{\dot{\mathrm{I}}}{\tau(t)} \quad (3)$$

$$\tau(t) = \begin{cases} kt, k < \tau < t \\ \tau, else \end{cases} \quad (4)$$

The CCDT analysis results of BDS Pseudo Random Noise (PRN) 5 were constantly blocked even if it is the GEO satellite whose satellite elevation angle was approximately 30°, resulting in large CCDT values. Jan & Tao (2016) also mentioned about the abnormality of BDS PRN5 but their analysis region was different from that of this study, so their satellite elevation angle was approximately 20° in the BDS PRN 5, indicating that the signal block was due to the low satellite elevation angle. Since the BDS did not implement the abnormality notification system as implemented in the GPS in the Notice Advisory to Navstar Users (NANU), abnormality of satellites cannot be identified. Thus, this study excluded the BDS PRN5 from the analysis.

Since the ionospheric error was related to a satellite elevation angle and rapid changes at a low elevation angle, the CCDT results were analyzed by dividing the satellite elevation angle. Root mean square (RMS) and standard deviation in the CCDT were analyzed by satellite elevation angle; the analysis results showed that there was no significant difference between them. Thus, the mean was close to zero and the results obtained were in accordance with those of the previous study. The GPS result in the CCDT analysis was the largest in a range of 10-15° as shown in Table 2, which required further analysis. The additional analysis result showed that the value was large up to 22° of satellite elevation angle in the GSNM station. The GPS satellite

Table 2. CCDT RMS value of GPS and BDS (unit: 10^{-3} m/s).

Elev	5-10°	10-15°	15-20°	20-30°	30-45°	45-60°	60-75°	75-90°
GPS L1	26.42	32.05	17.59	3.78	0.62	0.62	0.53	0.44
GEO B1	-	-	-	1.26	0.33	0.42	-	-
IGSO B1	7.42	2.49	1.46	1.29	0.92	0.73	1.25	0.64
MEO B1	10.16	2.23	1.60	2.76	1.21	0.83	0.67	0.55
GPS L2	113.79	119.76	77.13	20.16	1.04	0.75	0.06	0.59
GEO B2	-	-	-	8.55	1.15	0.59	-	-
IGSO B2	6.77	2.24	1.74	1.27	0.61	0.32	1.17	0.29
MEO B2	6.07	1.42	1.09	2.97	1.19	0.42	0.34	0.32

Table 3. CCDT RMS value of GPS and BDS without anomaly (unit: 10^{-3} m/s).

Elev	5-10°	10-15°	15-20°	20-30°	30-45°	45-60°	60-75°	75-90°
GPS L1	19.54	1.78	1.39	0.71	0.62	0.62	0.53	0.44
GEO B1	-	-	-	1.26	0.33	0.42	-	-
IGSO B1	7.42	2.49	1.46	1.29	0.92	0.73	1.25	0.64
MEO B1	10.16	2.23	1.60	2.36	1.21	0.83	0.67	0.55
GPS L2	109.92	6.01	3.81	1.29	1.04	0.75	0.60	0.59
GEO B2	-	-	-	8.55	1.15	0.59	-	-
IGSO B2	6.77	2.24	1.74	1.27	0.61	0.32	1.17	0.29
MEO B2	6.07	1.42	1.09	2.50	1.19	0.42	0.34	0.32

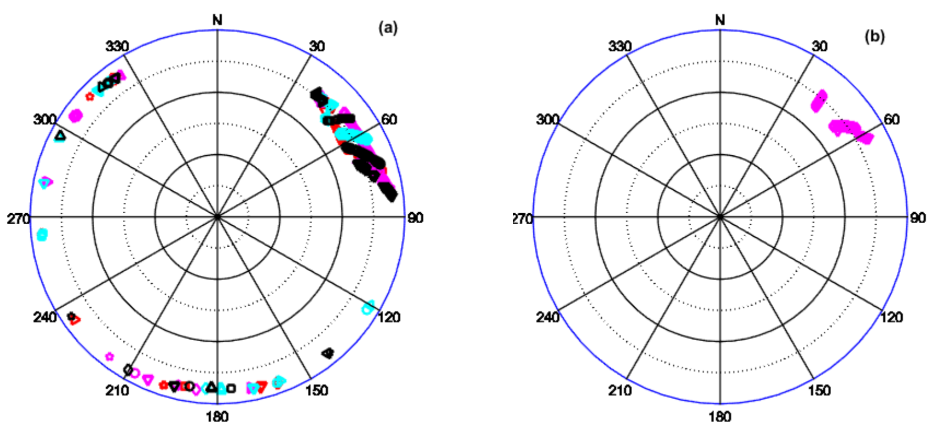

Fig. 1. Skyplot of GSNM station in 7 days: (a) GPS satellite position that could be obstacles that satellite elevation angles are under 22 degrees and CCDT values are bigger than 1m/s, (b) BDS satellite position that satellite elevation angles are under 22 degrees and azimuths are between 30 and 90 degrees.

position whose elevation angle was smaller than 22° and CCDT value was larger than 1m/s was checked to find that the position was concentrated in a range of 30-90° azimuth angle as shown in Fig. 1a, and signal block was found to frequently occur due to the obstacles. The satellite position in sections where signal block was expected in the BDS was also checked; the results showed that there were PRN 12 and 13 as shown in Fig. 1b but the number and range of the azimuth were small compared to those of the GPS.

Table 3 presents the re-calculation results after excluding the sections where signal block was expected frequently in the GSNM stations as shown in Fig. 1. It can be seen from the table that RMSs of both GPS and BDS were reduced, in particular, significant reductions at the section above GPS 10°. The RMSs of the GPS in the section below 10° did not significantly reduce due to the signal block by various azimuth angles and other stations. The results of comparison between the GPS and BDS revealed that L1 (B1) in the GPS was smaller than that of the BDS after 10° of satellite elevation angle while L2 (B2) in the GPS was mostly larger than that of the BDS.

Previous studies did not present the CCDT results in detail by dividing them by elevation angles. However, Xie (2004) set the GPS L1 CCDT threshold value to approximately 0.06 m/s at a low elevation angle and 0.02 m/s at a high elevation angle. As such, the higher the elevation angle was, the smaller the CCDT and threshold values were. In addition, the CCDT value was closer to 0.02 m/s even at a low elevation angle. The CCDT results in this study were similar to those of study by Xie (2004) at a high elevation angle but they were not at

Table 4. Maximum and minimum SPT value of GPS and BDS (unit: dB-Hz).

	Max	Min	Difference
GPS L1	52.8	27.9	24.9
GEO B1	48.4	31.5	16.9
IGSO B1	50.1	29.3	20.8
MEO B1	50.8	27.1	23.7
GPS L2	51.1	12.2	39.9
GEO B2	48.8	35.2	13.6
IGSO B2	50.1	26.6	23.5
MEO B2	51.2	26.1	25.1

a low elevation angle, suggesting that the data used in this study had poorer signal environment at a low elevation angle than that of the data used by Xie (2004).

3.1.2 Signal power test

SPT examines the signal power quality of satellites. The test method utilizes mean values previous and current epoch CN_0 that is produced from the GNSS receiver (Xie 2004, Koenig 2010). The maximum and minimum SPT values are presented in Table 4. The highest value was 52.8 dB-Hz at GPS L1, but for the BDS, it was 51.2 dB-Hz at the MEO satellite B2. The smallest value was 12.2 dB-Hz at GPS L2, and for the BDS, it was 26.1 dB-Hz at MEO satellite B2. The BDS GEO satellites that maintained the similar elevation angle had the smallest deviation between maximum and minimum values at 13.6 dB-Hz at B2, and the deviation of the GPS was larger than that of the BDS.

Table 5 presents the analysis results of SPT, which is related to a satellite elevation angle, by dividing it at a level of 10° unit. The values in the table refer to mean values and the values in the brackets indicate standard deviations. Jan & Tao (2016) presented GPS L1 and BDS B1 analysis results of GPS and BDS CN_0 values by dividing the value at a level of 10° unit. The results of Jan & Tao (2016) also exhibited higher values of the GPS than the BDS at L1 (B1), which was in accordance with the results in this study. This was analyzed to be due to the effect of long signal transmission time resulting from higher orbit of the BDS than that of the GPS. Accordingly, the largest SPT value at B1 in the BDS was found in MEO followed by IGSO and GEO, which reflected the above results. However, for L2 (B2), SPT values in the GPS were smaller than those of the BDS, while at BDS B2, SPT values were larger in the GEO than those in the IGSO. The change of SPT value showed that of GPS was lager than that of BDS at most of satellite elevation angles, but it did not always decrease when it was going to higher elevation angles. The difference between L1 and L2 in the GPS was found to be 8.41 dB-Hz on average, and the difference between B1 and B2 in the BDS was 0.52 dB-Hz (GEO), 1.26 dB-Hz (IGSO), and 0.04 dB-Hz (MEO), respectively, all of which were smaller than the difference between L1 and L2 in the GPS. Based on satellite elevation angle and differences between L1 (B1) and L2 (B2), it is judged BDS has a more stable signal strength than GPS.

3.2 Data Quality Monitoring

DQM examines the satellite orbits constantly and inspects whether the consistence of satellite orbits is maintained using GNSS satellite navigation messages of GNSS. It includes Ephemeris-Ephemeris Test (EET), Ephemeris-Almanac Test (EAT), Yesterday Ephemeris-Today Ephemeris (YE-TE) test (Xie 2004, Koenig 2010). As Xie (2004) stated that the YE-TE test was more accurate than the EAT for newly arisen satellites, the EAT was excluded in this study, and Ephemeris-International GNSS Service (IGS) Test (EIT) was additionally performed.

3.2.1 Yesterday ephemeris-today ephemeris test

The YE-TE test is performed to test the validity of the current ephemeris by comparing it with yesterday ephemeris when a new satellite appears. The yesterday ephemeris requires an assumption that the verification was complete. Thus, the ephemeris of DOY223 was compared with that of DOY222 using the navigation message file of DOY222 in the Receiver INdepent EXchange format 3.03 version provided by the IGS.

Prior to the analysis of the YE-TE test results, the occurrence of large errors was verified in DOY 229 PRN 12 in the GPS and DOY225-226 PRN 6 in the BDS as shown

Table 5. Average and standard deviation SPT value of GPS and BDS (unit: dB-Hz).

Elev (°)	10	20	30	40	50	60	70	80	90
GPS L1	43.09 (2.35)	45.35 (2.19)	47.58 (1.56)	49.04 (1.03)	49.67 (0.82)	50.05 (0.73)	50.40 (0.83)	50.61 (1.06)	50.93 (1.16)
GEO B1	-	-	42.37 (0.99)	45.05 (0.56)	45.75 (0.73)	-	-	-	-
IGSO B1	39.56 (1.53)	41.68 (1.38)	43.77 (0.95)	45.17 (0.87)	46.04 (0.83)	46.56 (0.72)	46.81 (0.70)	47.74 (0.64)	48.18 (0.42)
MEO B1	40.11 (2.04)	42.48 (1.88)	45.05 (1.24)	46.87 (0.83)	47.84 (0.62)	48.25 (0.55)	48.33 (0.60)	48.64 (0.66)	48.80 (0.54)
GPS L2	31.66 (2.41)	34.16 (2.17)	37.31 (1.98)	40.20 (1.58)	42.45 (1.39)	44.07 (1.32)	45.36 (1.25)	46.20 (1.30)	47.18 (1.39)
GEO B2	-	-	42.51 (0.78)	43.67 (0.57)	45.46 (0.59)	-	-	-	-
IGSO B2	36.83 (1.76)	38.96 (1.38)	41.28 (1.08)	43.14 (0.99)	44.76 (0.86)	45.79 (0.74)	46.62 (0.53)	46.95 (0.62)	47.11 (0.48)
MEO B2	39.57 (1.96)	41.94 (1.72)	44.49 (1.13)	46.52 (0.80)	47.82 (0.60)	48.78 (0.46)	49.17 (0.40)	49.31 (0.38)	49.15 (0.35)

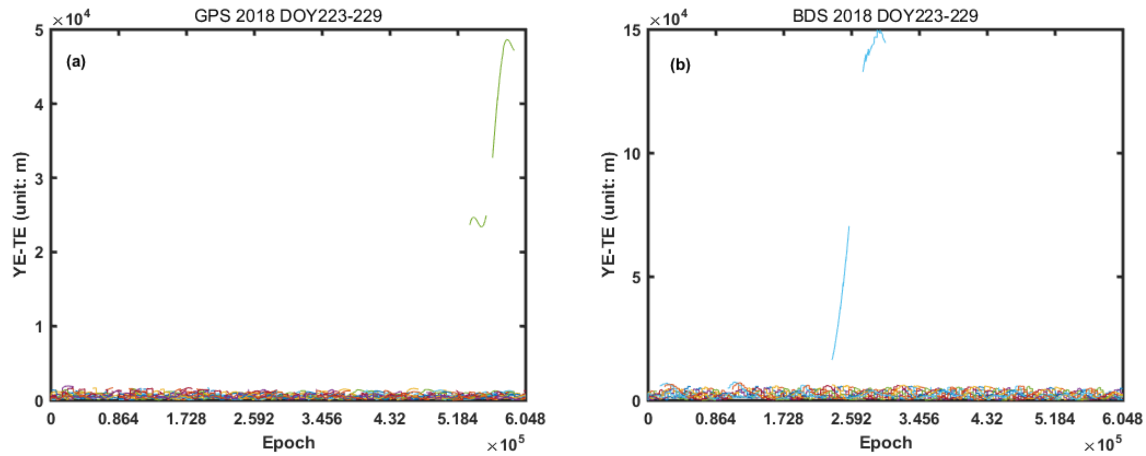

Fig. 2. YE-TE test result and huge error. (a) GPS: PRN12, (b) BDS: PRN6

Table 6. Mean, standard deviation, max, and min value of YE-TE test of GPS and BDS (unit: m).

	GPS	BDS GEO	BDS IGSO	BDS MEO
Mean	599.63	2449.23	2375.42	620.26
Std.	326.61	1429.04	1429.56	403.81
Max	1940.13	6157.22	7391.33	1879.51
Min	14.12	95.37	175.10	80.87

Table 7. Mean, standard deviation and max value of EET of GPS and BDS (unit: m).

	GPS	BDS GEO	BDS IGSO	BDS MEO
Mean	3.37	0.35	0.39	1.71
Std.	7.81	0.45	0.90	2.84
Max	103.69	6.54	21.88	15.02

in Fig. 2. The NANU in the GPS was checked and the satellite maintenance of PRN12 due to the orbit adjustment scheduled from DOY 228 17:21 to 23:06 on the basis of GPST was notified at DOY 222. The analyzed data verified that PRN12 disappeared from the field of vision of the receiver with approximately 5.13° of satellite elevation angle at around DOY228 17:15. After this, PRN12 re-appeared at around DOY229 4:00. Thus, the ephemerides before and after the maintenance were compared, resulting in a large YE-TE error at DOY229. This result implies that the current ephemeris has errors. Therefore, to develop a real-time system, exception handling and additional inspection may be needed to prevent misjudgment of YE-TE test by checking the NANU message.

Table 6 presents the results except for those of GPS PRN 12 and BDS PRN 6 where large errors occurred. The GPS exhibited smaller errors than those of the BDS, except for the maximum value. For the BDS, the MEO had smaller values than those of the GEO and IGSO in terms of maximum, minimum, standard deviation and mean. Compared to the results of EAT by Jan & Tao (2016), means, standard deviations, and maximum values were smaller in the GPS and BDS MEO whereas those were larger in the BDS GEO and IGSO. The difference between the almanac and broadcast ephemeris is that the broadcast ephemeris has a correction coefficient to correct the effect of perturbation whereas the almanac doesn't have one. Thus, almanac's accuracy was lower, but the valid period is longer than broadcast ephemeris. The perturbation correction in the broadcast ephemeris is regarded valid for a day for the GPS and BDS MEO. Thus, since the YE-TE test is not suitable for the BDS GEO and IGSO, other analysis methods are needed.

3.2.2 Ephemeris-ephemeris test

The EET aims to test the consistence of the updated ephemeris by comparing satellite positions using the current and previous ephemeris when the ephemeris is updated (Xie 2004, Koenig 2010). The analysis of the EET showed that the GPS had larger errors than those of the BDS; the GPS updated the ephemeris every two hours thereby calculating the satellite position using the ephemeris up to 4 hours ago. Thus, the GPS errors were larger than those of the BDS that updated the ephemeris every hour. The ephemeris test of newly arisen satellites is not possible in the EET. Thus, errors such as GPS PRN 12 and BDS PRN 6 were not displayed in the EET as shown in the YE-TE test. Table 7 presents the GPS and BDS EET results, in which the minimum value of both of the GPS and BDS display errors at a level of mm.

3.2.3 Ephemeris-IGS test

The Ephemeris-IGS Test (EIT) compares the satellite coordinates in the standard position 3 (SP3) format provided by IGS with the broadcast ephemeris. SP3 is one of the IGS products, which is formed by the weighted averaging of

Table 8. GPS Satellite Ephemerids of IGS products (IGS 2018).

	Orbit accuracy (cm)	Latency	Updates	Sample interval (min)
Ultra-Rapid (predicted half)	~5	real time	at 03, 09, 15, 21 UTC	15
Ultra-Rapid (observed half)	~3	3-9 hours	at 03, 09, 15, 21 UTC	15
Rapid	~2.5	17-41 hours	at 17 UTC daily	15
Final	~2.5	12-18 days	every Thursday	15

solutions submitted by GNSS analysis center such as Center for Orbit Determination in Europe, Jet Propulsion Laboratory, Natural Resources Canada, and Massachusetts Institute of Technology (Ray & Senior 2005). The accuracy, updated period, and latency of the GPS SP3 provided by the IGS are presented in Table 8.

The GeoForschungsZentrum (GFZ) in Germany and WuHan University (WHU) in China analyze and develop the orbits in the BDS, and upload SP3 using the IGS file transfer protocol (Fritsche et al. 2015, Shi et al. 2016). The BDS precise product developed by WHU has errors at a level of 10 cm compared to satellite laser ranging, and the rapid product has errors at a level of 20 cm (Shi et al. 2016).

The GPS provides ultra-rapid product in real time from the IGS whereas the BDS provides only rapid product (Fritsche et al. 2015). Thus, rapid product of GFZ were used. Since GFZ provides rapid product of GNSS synchronized with GPST in every five minutes, re-calculation was done in every second using the 9th-order Lagrange interpolation and compared.

The EIT analysis results showed that the GPS's error was smaller than that of the BDS, and errors in the MEO were smaller than those of the GEO and IGSO in the BDS. The means and minimum values were larger in the GEO that those of the IGSO while the standard value and maximum values were smaller in the GEO. GPS PRN12 and BDS PRN6 that showed large errors in the YE-TE test did not provide the rapid product during the corresponding time. BDS PRN6 showed a relatively large error for three days and then

Table 9. Mean, standard deviation, max, and min value of EIT of GPS and BDS (unit: m).

	GPS	BDS GEO	BDS IGSO	BDS MEO
Mean	1.47	7.04	4.38	2.86
Std	0.69	3.19	4.59	2.18
Max	6.70	15.30	26.08	14.33
Min	0.01	2.16	1.20	0.62

was reduced again at the last day. This indicated that the maintenance for orbit correction was performed the same as in GPS PRN 12. The EIT results are presented in Table 9 and Fig. 3. The accuracy of the broadcast ephemeris in the BDS was lower than that of the GPS, considering the rapid product accuracy of the BDS mentioned by Shi et al. (2016) and broadcast ephemeris and rapid product accuracy of the GPS shown in the IGS.

3.3 Measurement Quality Monitoring

MQM tests whether pseudorange measurement and carrier phase measurements maintain consistence for several seconds without abrupt change due to satellite and receiver's clock errors etc. It is divided into lock time check (LTC), carrier acceleration ramp step test (CARST), and carrier-smoothed code (CSC) innovation test (Xie 2004, Koenig 2010). Among them, since CSC was a test related to pseudorange measurements, it was excluded in this study.

3.3.1 Carrier acceleration ramp step test

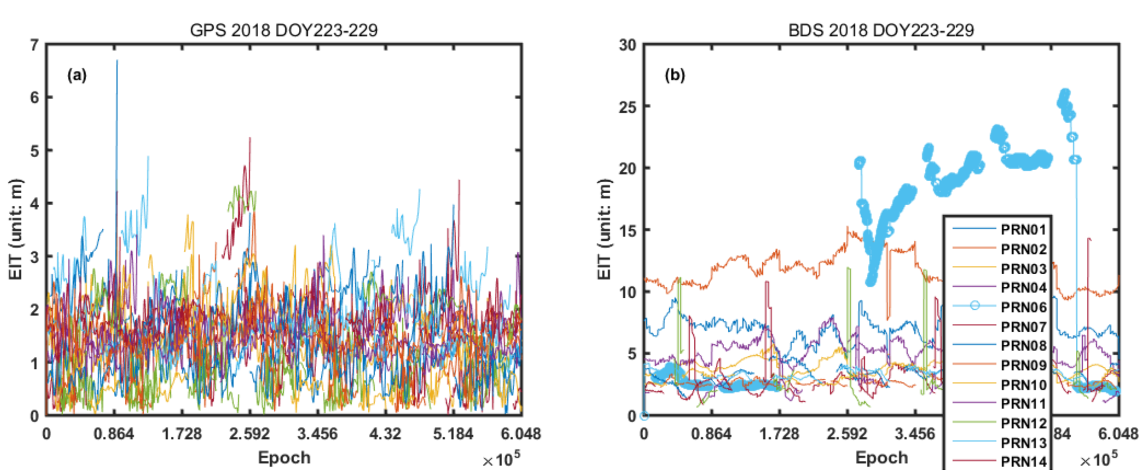

Fig. 3. EIT result. (a) GPS, (b) BDS

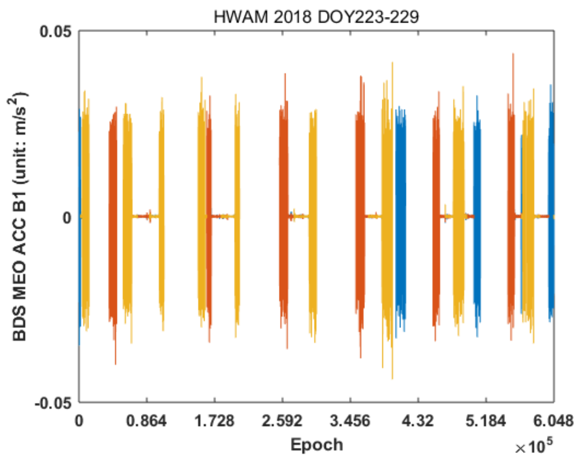

Fig. 4. BDS MEO satellite B1 acceleration of CARST.

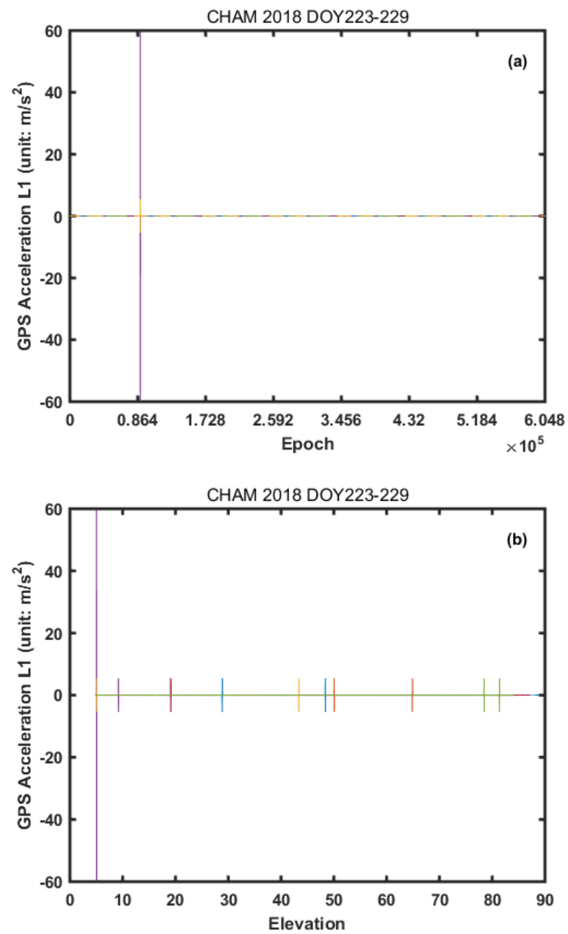

Fig. 5. GPS L1 Acceleration of CARST: (a) arranged by epoch, (b) arranged by satellite elevation angle.

The CARST examines whether carrier phase measurements are abruptly changed. This test sets 10 continuous measurement test windows and estimates each component using the least square method. Without the test window setup, it is difficult to determine whether the failure is due to the sudden change in carrier phase measurements or whether the failure is due to the change of the number of satellites used in the test (Xie 2004). Since the BDS has three satellite orbits, the CARST was separated for each orbit. However, when only one MEO satellite appeared as shown in Fig. 4, the measurement averaging process that removed common terms such as receiver clock error was omitted, thereby producing a large value. Thus, when the number of MEO satellites was only one, it was removed from the analysis.

The CARST examination factors in this study can be ionospheric and tropospheric errors and cycle slip because the stations are fixed. If the cycle slip does not occur, integer ambiguity is not changed as well. Thus, the same method as the CCDT was used in the analysis assuming that the CARST results were related to satellite elevation angle. The GPS during the data analysis process had larger values than those of the BDS in most satellite elevation angles of L1 and L2. The CARST determines that if measurements are suddenly changed in a single satellite due to the measurement averaging process, all satellites were considered to have errors, which occurred continuously in 10 epochs (Xie 2004, Son et al. 2015). The verification results showed that a large value occurred as about 60 m/s^2 in the PRN 3 of CHAM station in DOY 224 as shown in Fig. 5a, and it also affected other satellites as shown in Fig. 5b.

Table 10 presents the calculation results excluding the satellite values that displayed large values in the CARST results of the GPS and BDS. The RMS and standard deviation in the CARST were not significantly different, which were similar to those in the CCDT. Both of the GPS and BDS had the smallest RMS in acceleration and the largest RMS in ramp. According to Xie (2004) and Koenig (2010), each of the values in the CARST becomes smaller when the satellite elevation angle is increased. However, large values were obtained in this study even at some high elevation angles because the measurement values, which were sudden changes in carrier phase measurements, were not removed by removing the large values arbitrarily. For accurate comparison of the CARST results between the GPS and BDS, research on the selection of measurement abnormality determination threshold should be conducted simultaneously.

3.3.2 Lock time check

The lock time is increased with GNSS receiver sampling rate. In this study, it was increased by one in every second since data were received at 1Hz. If the receiver missed the satellite signals, lock time is initialized to zero. In this case, half cycle ambiguity is present in the carrier phase. To

Table 10. RMS value of CARST of GPS and BDS without anomaly.

Elev(°)	Acceleration (10^{-4} m/s^2)								Ramp (10^{-3} m/s)								Step (10^{-4} m)							
	10	15	20	30	45	60	75	90	10	15	20	30	45	60	75	90	10	15	20	30	45	60	75	90
GPS L1	4	5	6	2	2	2	2	2	12	6	4	3	3	3	4	5	18	18	14	8	7	7	8	8
GEO B1	-	-	-	2	2	2	-	-	-	-	-	1	1	1	-	-	-	-	-	10	9	9	-	-
IGSO B1	3	3	4	3	3	3	3	2	6	3	2	3	3	3	3	2	14	12	12	10	10	10	9	9
MEO B1	2	5	1	1	1	2	3	1	8	4	3	2	2	3	2	2	9	8	7	6	6	6	6	6
GPS L2	5	3	3	2	2	2	2	2	12	5	4	3	3	3	4	3	21	15	13	10	8	8	8	8
GEO B2	-	-	-	2	2	2	-	-	-	-	-	1	1	1	-	-	-	-	-	10	9	9	-	-
IGSO B2	12	8	8	5	5	5	4	3	5	3	2	3	3	3	3	2	28	19	19	16	13	13	11	9
MEO B2	2	3	2	1	1	1	2	1	8	4	3	2	2	3	2	2	10	8	7	7	6	6	6	6

Table 11. Max, mean, and standard deviation value of LTC of GPS and BDS (unit: hour).

	Max	Mean	Std
GPS L1	7.50	2.91	1.88
GEO B1	1162.91	224.47	227.22
IGSO B1	18.80	8.22	5.05
MEO B1	8.43	3.03	2.04
GPS L2	7.49	1.88	1.89
GEO B2	275.34	65.97	72.42
IGSO B2	18.80	8.19	5.05
MEO B2	8.43	3.03	2.03

remove this ambiguity, a certain period of time is needed (NovAtel 2017). The continuity of measurements can be easily identified using LTC. Table 11 presents the LTC analysis results. For the GPS, PRN 5 is longest visible and, for the BDS, PRN 4 (GEO), PRN 7 (IGSO), and PRN 11 (MEO) are longest visible in Korea. The BDS MEO was slightly longer than the GPS, which was due to the different orbit period. The GPS, BDS IGSO and MEO's maximum values of L1 (B1) and L2 (B2) were found to have the same PRN whereas the BDS GEO's maximum values had the different PRN.

Jan & Tao (2016) analyzed the continuity and discontinuity of the GPS and BDS in relation to CN_0 and cycle slip. The BDS GEO and IGSO had large CN0 values at high elevation angles thereby generating discontinuity due to the occurrence of cycle slip even if no signal interference occurred. Jan & Tao stated this was due to the problem in the BDS satellites. In this study, B1 of BDS PRN 4 transmitted signals continuously for about 48 days whereas B2 transmitted signals for 11 days. This may be the problem in the signal reception when B1 and B2 were cut off at the same time. It may also be because the BDS was under development.

4. CONCLUSIONS

This study applied the QM algorithm used in previous study to the GPS and BDS and compared and analyzed the results. The GPS and BDS showed similar qualities in all tests. However, the GPS was exposed to the signal disturbance factors more than the BDS as satellites appeared in various directions, as shown in the CCDT results, resulting in low quality results at low elevation angles. The BDS showed more stable results in the SPT in terms of satellite elevation angle and frequency. However, the BDS GEO had a significant difference between B1 and B2 in the LTC. The accurate causes could not be identified in the case of the BDS since the BDS did not implement the maintenance notice system of satellites such as the NANU implemented in the GPS. This was the main difference between completed GPS and BDS which was still under development. This phenomenon was also observed in the DQM. The orbit adjustment maintenance notice of satellites was displayed through the NANU in the case of the GPS. Since the BDS was found to show the similar trend with the GPS through additional tests, it was determined that the BDS was in the orbit adjustment. However, the BDS satellite orbits were found to require more time to reach the stable state. The BDS GEO and IGSO in the YE-TE test had lower accuracy than the EAT of previous study, which required additional studies. In the case of the CCDT and CARST, applying artificial errors or analysis using satellites where real failures occur is needed to determine the sudden change in measurements. The results presented in this study were not significantly different from those of previous studies. Thus, these results are applicable to real-time algorithms, and can be utilized as foundational research data to select the abnormality detection threshold in the BDS.

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REFERENCES

Ahn, J. 2009, Realization and Evaluation of Fault Detection Algorithms for GBAS, Master's Thesis, Konkuk University

BDS ICD 2013, BeiDou navigation satellite system signal,

In Space Interface Control Document, China Satellite Navigation Office, Beijing, China
Cheng, P., Wen, H., Cheng, Y., & Wang, H. 2009, Parameters of the CGCS2000 ellipsoid and comparisons with GRS80 and WGS84, Acta Geodaetica et Cartographica Sinica, 38, 189-194
Fritsche, M., Deng, Z., Uhlemann, M., Nischan, T., Bradke, M., et al. 2015, GFZ Analysis Centre: Multi-GNSS Processing and Products, 5th Galileo Science Colloquium, Braunschweig, DE, 27 Oct 2015
GPS ICD 2014, Global Positioning Systems Directorate System Engineering & Interface Specification IS-GPS-200H, Navstar GPS Space Segment/Navigation User Interfaces, Washington, DC, USA
IGS Products, cited 2018, available from http://www.igs.org/produtcs
Jan, S.-S. & Tao, A.-L. 2016, Comprehensive Comparisons of Satellite Data, Signals, and Measurements between the BeiDou Navigation Satellite System and the Global Positioning System, Sensors, 16, 689, http://dx.doi.org/10.3390/s16050689
Koenig, M. 2010, Optimizing The Decision Rule of A GPS Integrity Monitoring System for Improved Availability, PhD Dissertation, Stanford University
Kong, J., Mao, X., & Li, S. 2016, BDS/GPS Dual Systems Positioning Based on the Modified SR-UKF Algorithm, Sensors, 16, 635. http://dx.doi.org/10.3390/s16050635
NovAtel 2017, OEM6 Family Firmware Reference Manual, Rev 12
Ray, J. & Senior, K. 2005, Geodetic techniques for time and frequency comparisons using GPS phase and code measurements, Metrologia, 42, 215-232. http://dx.doi.org/10.1088/0026-1394/42/4/005
Shi, C., Zhao, Q., Li, M., Guo, J., & Liu, J. 2016, WHU's developments for the MGEX precise products and the GNSS ultra-rapid products, IGS Workshop, Sydney, NSW, Australla, 8-12 Feb 2016
Son, E., Kim, K.-T., Im, S.-H., & Heo M. B. 2015, Threshold Determination of The GPS Carrier Acceleration, Ramp, and Step on the Normal Condition, Journal of Positioning, Navigation, and Timing, 4, 195-203. http://dx.doi.org/10.11003/JPNT.2015.4.4.195
Xie, G. 2004, Optimal On-Airport Monitoring of The Integrity of GPS-Based Landing Systems, PhD Dissertation, Stanford University

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