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Methodology for Evaluating SBAS Satellite Correction

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ABSTRACT

The Satellite-based Augmentation System (SBAS), as a safety critical system, should be verified on an ongoing basis to ensure the adequate performance. This study proposes two methods to evaluate the performance of SBAS satellite correction. Analysis methods based on precise ephemeris and measurement were applied to present an evaluation method for SBAS satellite correction, and a test was performed based on real data. The precise ephemeris-based analysis method had no limitations on the position of the test user and showed a high precision, enabling an accurate performance analysis in various positions. Although the measurement-based analysis method has the advantage of fast data interval, it showed a relatively lower accuracy due to the effects of various error factors. Compared with the precise ephemeris-based analysis method, there was a large difference of more than 5 m at the beginning of smoothing filter, and a difference less than 50 cm when filtered for more than an hour.

Keywords: SBAS, satellite correction, ephemeris, SP3

1. INTRODUCTION

A Satellite-based Augmentation System (SBAS) is a system that improves navigation performance by providing users with correction data on GPS satellite-related errors and ionospheric delay errors. SBAS is used in applications that require high stability such as aircraft take-off and landing since it provides high position accuracy and integrity performance. Since SBAS performance issues are directly related to the safety of users, continuous performance monitoring is required during operation as well as the system development phase.

Among currently operating SBASs, Wide Area Augmentation System (WAAS) in the U.S. and European Geostationary Navigation Overlay System (EGNOS) in Europe continuously monitor and evaluate indicators of position accuracy, availability, and integrity related to the navigation performance of SBAS users. They provide real-time assessment results and periodic statistics through website (European Satellite Service Provider 2018, William, J. and Hughes Technical Center 2018). The EGNOS provides monthly performance evaluation results and mainly presents results in the position domain. The WAAS provides quarterly performance evaluation results while it also presents the results in the final position domain as well as assessment results of satellite and ionospheric correction. Although there are no problems found in the final position domain, the satellite correction or the ionospheric correction may contain excessive errors that do not comply with the error levels of User Range Differential Error and Grid Ionospheric Vertical Error, respectively. Failure to properly detect this may lead to potential problems. In addition, if each analysis is not performed, when a problem occurs in the position domain, it is difficult to identify in which part the problem was occurred.

This paper describes evaluation methods for SBAS satellite correction. There are two methods for analyzing satellite-related errors, the precise ephemeris-based analysis method and the measurement-based analysis method (Gao et al. 2009, Rho & Langley 2009, Heng 2012). This study describes the issues to consider when using the methods to evaluate SBAS satellite correction. In addition, the results of applying

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each method were compared using real SBAS data and reference station data.

Chapter 2 describes an overview of SBAS satellite correction and the analysis methods accordingly. Chapter 3 describes the two methods of evaluating the performance of SBAS satellite correction. Chapter 4 presents the results of processing real data by each method. Chapter 5 draws conclusion from the analysis results.

2. OVERVIEW OF SBAS SATELLITE CORRECTION

The orbit and clock data calculated from GPS broadcast ephemeris have errors of several meters (Kaplan & Hegarty 2006). The SBAS provides correction data by estimating the error of broadcast ephemeris using the measurements collected from several reference stations (Kee & Parkinson 1996). The principle of satellite-related error estimation is taking advantage of the principle of GPS. Unlike calculating user positions from multiple GPS satellites that know the position, SBAS estimates the precise GSP satellite orbit and clock from reference stations that know the position. The estimated 3D orbit error and clock error are delivered to the user as a vector quantity, and the user generates and applies a pseudo-range correction value that matches its position (RTCA 2001).

As the geometry of GPS satellites has a significant influence on the accuracy of navigation solution, the geometry of reference stations has a great influence on SBAS satellite error estimation. As SBAS reference stations are distributed in a very limited area when viewed from the satellite, the DOP becomes very large. Therefore, this causes difficulties in estimating the exact error vector, which makes it difficult to distinguish between the satellite orbit error and clock error (Tsai 1999, Kim 2007). A valid error correction value in the range direction around the service area is provided even if accurate vector estimation is not achieved. Considering the characteristics of SBAS satellite correction, the analysis of correction data should be analyzed in terms of the total sum where the orbit error and clock error are projected in the range, rather than the error vector.

SBAS correction data is referenced to SBAS network time (SNT) rather than GPS time (GPST). SBAS adjusts to maintain the difference within 50 nanoseconds to prevent excessive differences between the two times (Griffith et al. 1999). Due to this time difference, a common bias occurs for all of the satellites. These biases are terms that are absorbed by the receiver clock error during the navigation solution calculation process and do not affect actual navigation performance. In order to analyze only the values that affect the actual navigation performance, this study performed analysis by eliminating the common bias in every epoch for all satellites.

3. METHODOLOGY

3.1 Precise Ephemeris-based Method

The International GNSS Service (IGS) agencies and the National Geospatial-Intelligence Agency provide precise products of GPS satellite orbits and clock data. These data are widely used as reference data for analyzing satellite-related errors (Rho & Langley 2009, Heng 2012). The provided precise ephemeris is divided into ultra-rapid, rapid, and final data. Among these, the final data, which is calculated most precisely by post-processing, has a satellite orbit error within 2.5 cm and RMS error of clock data is very accurate at a 75 ps level (IGS 2018). Therefore, it has enough accuracy for analyzing SBAS satellite correction data. The precise ephemeris is available in the SP3 format through an FTP server (Kouba 2003).

When using the precise ephemeris, the coordinates and time standards may vary from one institution to another, so this should be considered (Heng 2012). The orbital data provided by GPS and SBAS defines the coordinates based on the Antenna Phase Center (APC) of the satellite, while the precise ephemeris is provided by APC or Center of Mass (CM). Therefore, if the precise ephemeris is provided by CM, it should be converted to APC for an accurate analysis. In terms of the time reference, SBAS correction is provided for use with GPS L1 C/A code measurements, whereas the precise ephemeris is tailored to GPS P1/P2 iono-free combination and must be corrected using P1-C1 bias value (Rho & Langley 2009). The precise ephemeris data is provided at 5 or 15-minute intervals. Therefore, the data should be interpolated for every second processing. Fig. 1 is a diagram that shows the process of analyzing SBAS satellite correction based on the precise ephemeris.

First, by comparing the difference of orbit and clock between the precise ephemeris and broadcast ephemeris, the error vector of the broadcasting ephemeris can be calculated as shown in Eqs. (1) and (2).

$$\delta R^j_{BRDC} = R^j_{TRUE} - R^j_{BRDC} \tag{1}$$

$$\delta b^j_{BRDC} = b^j_{TRUE} - b^j_{BRDC} \tag{2}$$

where R^j_{TRUE} and b^j_{TRUE} are the true values of GPS satellite orbit and clock, respectively. In the precise ephemeris-based

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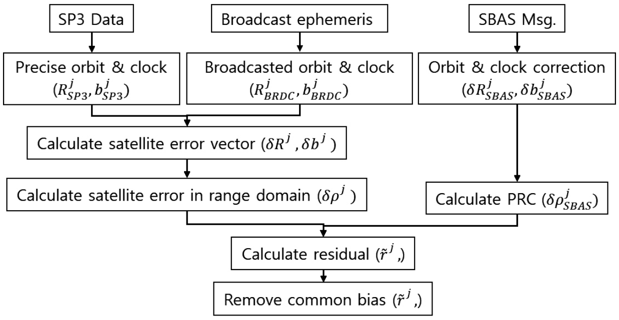

Fig. 1. Flow chart for precise ephemeris-based method.

analysis method, the orbit and clock data calculated from the precise ephemeris are processed as true values. R^j_{BRDC} and b^j_{BRDC} refer to the orbit and clock data calculated from the broadcasting ephemeris, and superscript j is for distinguishing the satellites. From the difference between the two values, the orbit and clock errors are defined as δR^j_{BRDC} and δb^j_{BRDC}. As mentioned above, the error analysis is performed in the range domain, so a conversion should be made as shown in Eq. (3).

$$\begin{aligned}\delta\rho^j &= \left(R^j_{SP3} - R^j_{BRDC}\right)\cdot e^j - \left(b^j_{SP3} - b^j_{BRDC}\right) \\ &= \delta R^j_{BRDC}\cdot e^j - \delta b^j_{BRDC}\end{aligned} \tag{3}$$

where $\delta\rho^j$ is the sum of the satellite orbit and clock errors calculated in the range domain, and e^j is the Lin of Sight (LOS) vector. In order to see the effect of SBAS correction, the correction value to be applied to the pseudorange should be calculated from the broadcasted SBAS message as shown in Eq. (4).

$$PRC_{Sat} = -\delta R^j_{SBAS}\cdot e^j + \delta b^j_{SBAS} \tag{4}$$

where PRC_{Sat} is the SBAS satellite correction in range, δR^j_{SBAS} is the satellite orbit correction, and δb^j_{SBAS} is the satellite clock correction. The residual error $\tilde{r}^j$ after applying SBAS correction from Eqs. (3) and (4), is calculated as shown in Eq. (5).

$$\tilde{r}^j = \delta\rho^j + PRC_{Sat} \tag{5}$$

The residual error has common bias for all satellite because of the difference between SNT and GPST. To eliminate this common bias, we subtract the average of the residual errors for all satellites in every epoch as shown in Eq. (6).

$$r^j = \tilde{r}^j - \frac{1}{N}\sum_{i=1}^{N}\tilde{r}^i \tag{6}$$

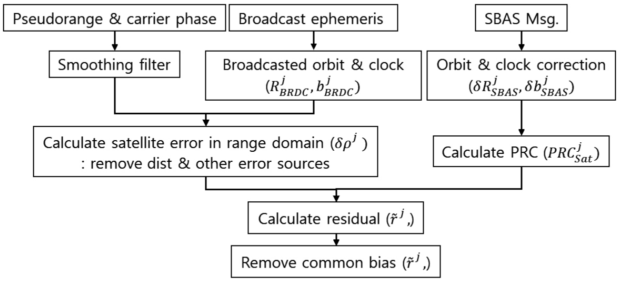

Fig. 2. Flow chart for measurement-based method.

where r^j is the residual error from which the common bias is removed, that is subject to final analysis.

The precise ephemeris provides precise satellite orbit vectors and satellite clock data, which enable performance analysis at any user location. Compared to the measurement-based method, there are fewer other error factors in the analysis process, which allows more accurate analysis.

Since the ultra-rapid ephemeris provides predicted orbit and clock of GPS satellites, it can be used in real time but the accuracy is relatively low. The satellite orbit shows a similar accuracy as the precise ephemeris with an error level of about 5 cm, but the RMS error is about 3 ns for clock data (IGS 2018). In addition, it is difficult to analyze any problems that occur in a shorter period of time than the data interval due to a long time interval in providing data (Gao et al. 2009).

3.2 Measurement-based Method

If measurements from a reference station that knows the exact position are available, the performance of the satellite correction may also be analyzed through the measurement-based analysis. Fig. 2 is a diagram that shows the process of analyzing SBAS satellite correction based on pseudorange measurements.

The pseudorange measurements collected at the reference station are configured as shown in Eq. (7).

$$\begin{aligned}\rho^j &= \left(R^j_{BRDC} + \delta R^j_{BRDC} - R_u\right)\cdot e^j \\ &\quad - \left(b^j_{BRDC} + \delta b^j_{BRDC}\right) + I^j + T^j + B + \varepsilon^j\end{aligned} \tag{7}$$

where R^j_{BRDC} and b^j_{BRDC} are the satellite orbit and clock calculated by the broadcasting ephemeris, and δR^j_{BRDC} and δb^j_{BRDC} are the respective errors. R_u is the reference station position, I^j is the ionospheric delay error, T^j is the tropospheric delay error, B is the receiver clock error, and ε^j is the measurement noise and multipath error. Among the above factors that compose the pseudorange, if the remaining factors are removed except for the satellite-related error, only the terms due to satellite-related errors remain, which may be used to perform the analysis. In order to calculate the distance between the receiver and the satellite, the exact position of the reference station is required. The tropospheric delay errors can be removed by using the model because of its high accuracy (Kim et al. 2016). The ionospheric delay errors can be estimated from the dual frequency measurements (Kaplan & Hegarty 2006). The noise and multipath can be mitigated through filtering using carrier phase such as hatch filters (Kee et al. 1997). Eq. (8) is the calculation of satellite-related errors in range domain.

$$\delta\rho^j = \delta R^j_{BRDC} \cdot e^j - \delta b^j_{BRDC} + B + \varepsilon_{\delta\rho}{}^j \tag{8}$$

where $\varepsilon_{\delta\rho}{}^j$ is the error remaining after removing other error factors. Next, the residual errors after applying SBAS is calculated through the same process as shown in Eqs. (5) and (6). The receiver clock error remains in Eq. (8), but it is erased by removing the common bias of all satellites in the final step Eq. (6).

The measurement-based analysis method can use both real-time and post-processing and analysis can be performed every second. However, there is a limitation that the analysis requires reference station data that knows the exact position, and it is impossible to completely eliminate other error factors in the analysis process.

4. TEST RESULTS

In order to confirm the results of the proposed analysis method, this study performed a test using actual data. Among currently operating systems, this study processed data and analyzed the results for EGNOS during the day on August 9, 2016. The SBAS message used data broadcasted on the PRN 120 satellite. The measurements used 1-second interval data collected from the TLS reference station located in Toulouse, France, among the IGS reference stations. Fig. 3 shows the position of the TLSE reference station.

First, this study calculated the satellite-related errors in the range domain calculated by each analysis method, and compared the results. Next, the residual errors presented by applying SBAS correction were compared. In addition, the precise ephemeris-based analysis method shows the results that can be calculated assuming users are distributed service area.

Figs. 4 and 5 show satellite-related errors in the range domain calculated from the precise ephemeris-based analysis method and the measurement-based analysis method, respectively. For all satellites, the errors in the LOS direction of the reference station were calculated and the time history were shown. The measurement-based method presented the results before and after the hatch filter.

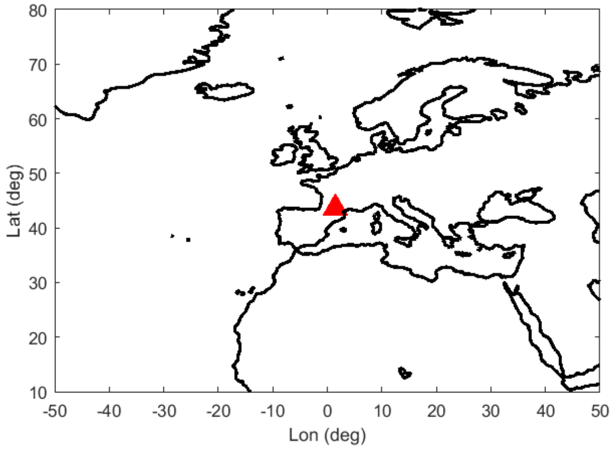

Fig. 3. The reference station for testing EGNOS.

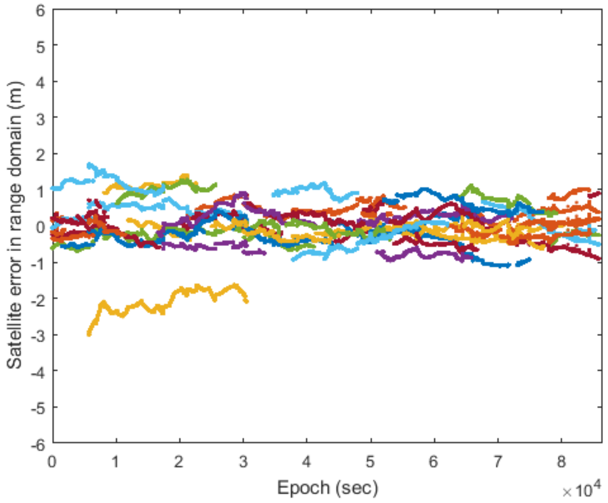

Fig. 4. Satellite orbit and clock error calculated by precise ephemeris-based method.

When using the measurement-based method, it was difficult to compare because the noise levels were very large without filtering, but the filtered result showed a bias trend similar to the precise ephemeris-based analysis method. Fig. 6 is a graph showing the average value of errors for each satellite. The measurement-based analysis method calculates the average value of the hatch filter measurement results. The average error value of each satellite calculated by the two methods was within 30 cm.

The RMS values of the total calculated data were 0.62 m for the precise ephemeris-based analysis and the measurement-based analysis using hatch filter showed a larger value of 0.73 m. This is because the measurement-based analysis method does not eliminate the remaining errors completely. In particular, the noise level is higher than that of the precise

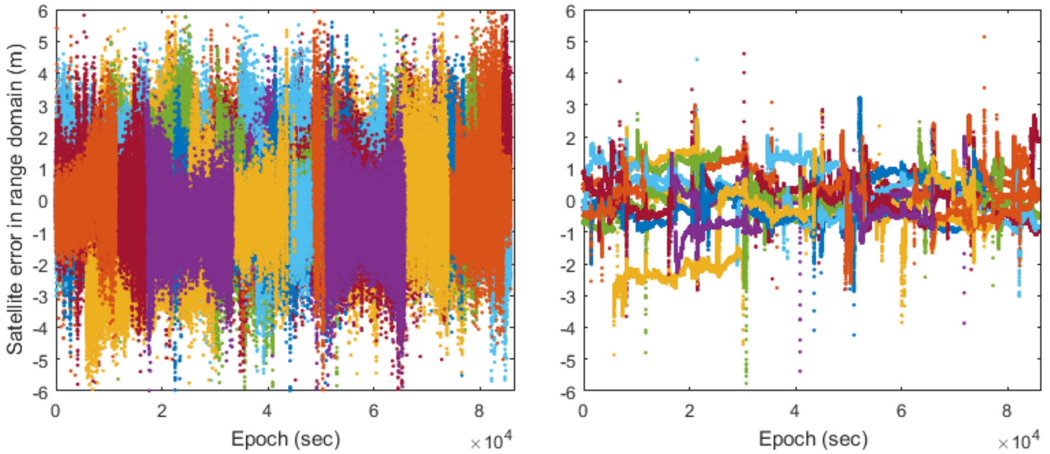

Fig. 5. Satellite orbit and clock error calculated by measurement-based method (left: raw measurement, right: smoothed measurement).

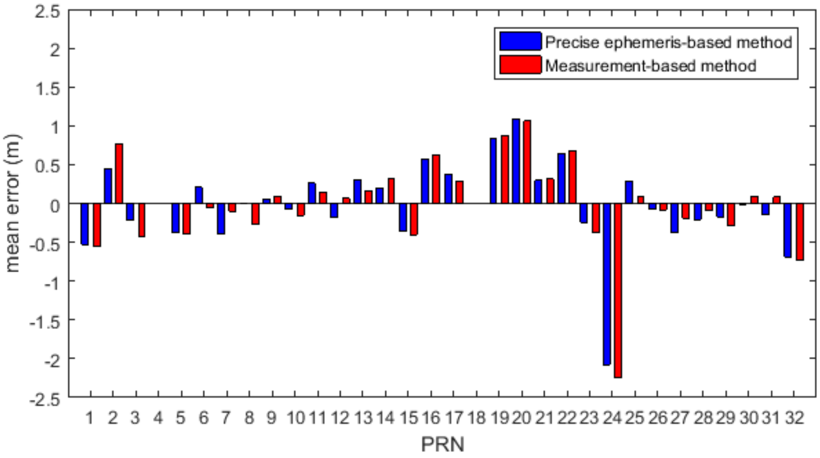

Fig. 6. average satellite orbit and clock error in range domain.

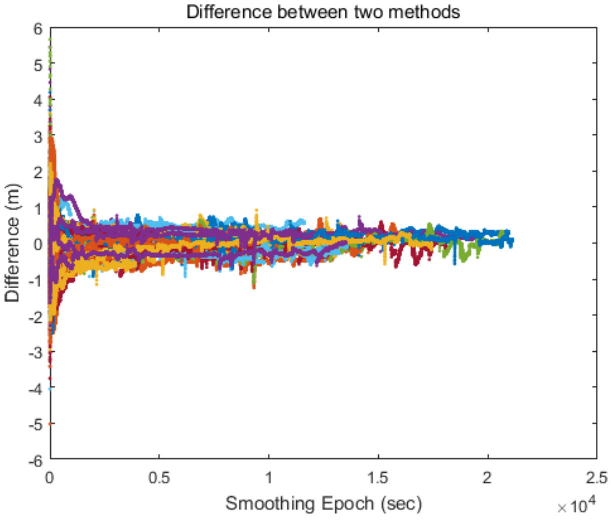

Fig. 7. Difference between two methods.

ephemeris-based analysis method even after smoothing. Fig. 7 is a graph showing the difference between the two methods according to the smoothing epoch to further analyze this.

Fig. 7 shows that the difference between the two methods is inversely proportional to the smoothing epoch. This is due to the characteristics of hatch filtering the pseudo-range measurements, which result in large pseudo-range noise and multipath errors until convergence is achieved for a certain period of time. At the beginning of the filter, the difference is more than 5 m, but after an hour, most of the difference is within 50 cm. In order words, in terms of the measurement-based method, the initial results of hatch filter may have a large error, but accurate results can be obtained after a certain degree of convergence.

Next, the residual error remaining after applying SBAS correction was confirmed in the range domain as above. Figs. 8 and 9 show the residual errors that occur when SBAS correction is applied to satellite-related errors presented in Figs. 4 and 5.

Figs. 8 and 9 show that the bias errors existing in each satellite are mostly eliminated by applying SBAS correction. The RMS values of the total data were 0.33 m for the precise

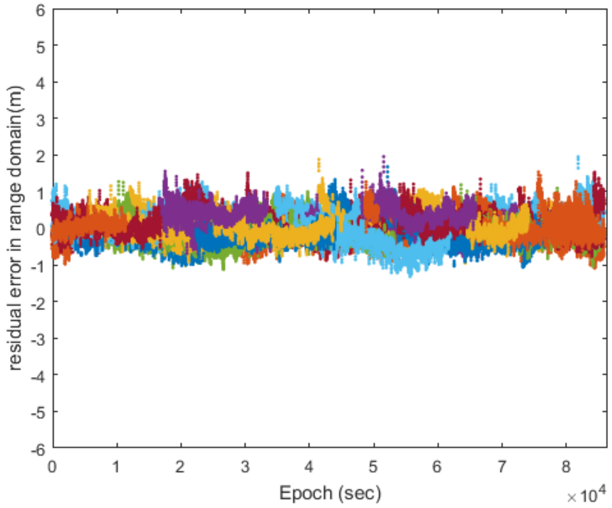

Fig. 8. Residual error calculated by precise ephemeris-based method.

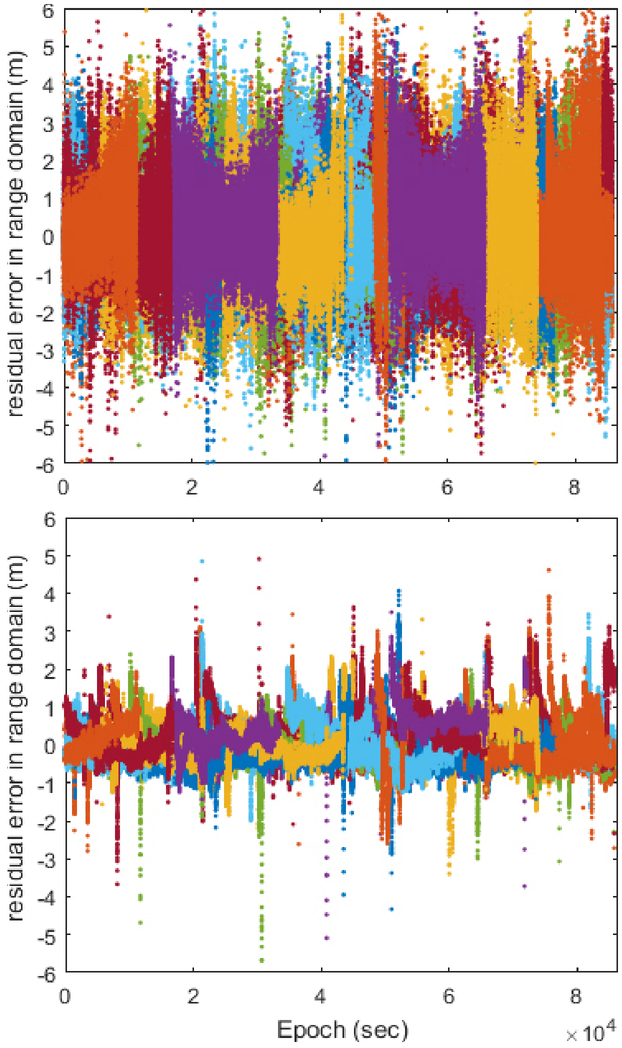

Fig. 9. Residual error calculated by measurement-based method (top: raw measurement, bottom: smoothed measurement).

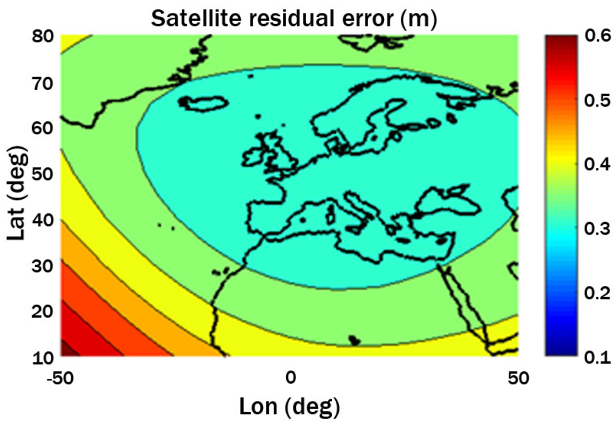

Fig. 10. RMS of residual error.

ephemeris-based analysis method and 0.46 m for the measurement-based method. From these results, in terms of the measurement-based analysis method, the error of the correction can be assessed to be larger due to the measurement noise, multipath error, and other error factors.

It is difficult to estimate the exact error vector since SBAS estimates the errors using reference stations distributed in a specific area. As a result, the residual error will increase as user deviate beyond the reference station. Therefore, it is favorable to use the precise ephemeris to identify the degree of performance degradation according to the user position. Since the precise ephemeris-based analysis method does not require actual reference station measurements, there are no limitations on the user position to be analyzed. Therefore, there is a benefit that the results can be checked while randomly changing the user position. Fig. 10 is a graph that shows the performance of the SBAS satellite correction for EGNOS service region. The user grids were created at the intervals of 5 in the range of latitude 10 ~ 80° and longitude -50 ~ 50°. The RMS values of the residual errors after applying SBAS correction for 24 hours in each user grid are shown as a contour.

As shown in Fig. 10, performance evaluation is also available in marine areas where it is difficult to install reference stations and areas outside the reference station network. This can be used to analyze the performance degradation that occurs when the user position deviates beyond the reference station network.

5. CONCLUSIONS

For a thorough SBAS performance analysis, analysis at the correction stage is required as well as analysis at the final position domain. This paper proposed a method to verify the performance of SBAS satellite correction and presented the results of testing based on real data.

Both methods have strength and weakness therefore, the application should be considered according to the purpose. In terms of the precise ephemeris, analysis can be performed more accurately since fewer errors occur in the analysis process than the measurement-based method, and it is also available to conduct performance analysis in areas where it is difficult to install reference stations. Therefore, there is an advantage of being able to evaluate the overall performance of the service more accurately. In case of using the ultra-rapid ephemeris, a real-time application is available, but the accuracy may be lower than the post-processing precise ephemeris.

For the purpose of monitoring real-time integrity performance, the measurement-based method is considered to be favorable because it is difficult to identify problems that occur during the period smaller than the data interval of the precise ephemeris. However, care must be taken as the measurement-based method can estimate the residual errors to be greater than the actual value.

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