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Performance Analysis of a Satellite-Based Ionosphere Model for WADGPS under Disturbed Ionosphere Condition

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ABSTRACT

The satellite-based ionospheric model consists of local first-order plane function parameters for individual satellites and provides excellent accuracy in the flat ionospheric environment of the Korean Peninsula. This paper analyzes the performance of such model under the rapid changes in the ionosphere. Rapid changes in the ionosphere were observed in Korea from September to October 2014, and a satellite-based ionosphere model was applied to Wide Area Differential GPS (WADGPS) to analyze the navigation performance and the performance of estimating ionospheric delay errors. After processing the test data, it was confirmed that there was a deterioration in navigation performance and extrapolation performance in low-latitude areas and analyzed the cause.

Keywords: WADGPS, ionosphere, satellite-based model

1. INTRODUCTION

Wide Area Differential GPS (WADGPS) uses multiple ground-based satellite navigation reference stations to provide satellite-related and ionospheric delay errors to users in the service area. The ionospheric delay accounts for the largest portion of error factors in satellite navigation and is also an important factor in improving GPS accuracy using WADGPS (Kaplan & Hegarty 2006).

Many prior studies related to WADGPS have applied grid ionospheric models to compensate for ionospheric errors in satellite navigation (Chao 1997). The grid ionospheric model defines a virtual grid point on the ionosphere concentrated altitude and provides a vertical ionospheric delay at the corresponding grid point. In this case, errors such as the Nugget Effect may occur in the process of calculating the vertical ionospheric delay at the grid point by using all of the ionosphere measurements observed around the grid point (Blanch 2003). The satellite-based ionospheric model was proposed to overcome these weaknesses and improve the accuracy of compensating ionospheric delay errors (Stanford University 2015).

The satellite-based ionosphere model provides ionospheric delay error data for individual satellites in the form of a function. Using the ionospheric delay and the ionospheric pierce point data observed by multiple reference stations for each satellite, the model defines a function for the ionospheric delay around the ionospheric pierce point and provides the parameters of the defined function to the user. In this case, the ionosphere model for each satellite only uses the measurements from the corresponding satellites, which eliminates error sources such as the Nugget Effect, thus improving the accuracy compared to the grid ionospheric model. In particular, a good accuracy performance was even confirmed when the ionospheric model was extrapolated to service users located outside WADGPS ground-based reference stations (So et al. 2016).

This study is about verifying the performance and improving the satellite-based ionosphere model under disturbed ionosphere conditions. The Korea Kk-Index,

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released by the National Radio Research Agency on September 25, 2014, reached up to 9. On the other hand, the Korea Kk-Index on September 20, 2014, was only 4. This shows that the ionosphere was more active than usual during this period, so this study examined the performance of a satellite-based ionospheric delay model before and after this period. To identify the characteristics of the ionosphere in the Korean Peninsula, the Global Ionosphere Model (GIM) IONosphere EXchange (IONEX) data of the International GNSS Service (IGS) was used and it was confirmed that the ionosphere was more active than usual. To verify the performance of the satellite-based ionosphere model under these conditions, a WADGPS was configured by using the satellite navigation data from 8 reference stations of the National Geographic Information Institute and used a satellite-based model as the ionosphere model. By applying the generated ionospheric error corrections to domestic and international reference station data, this study examined the performance accuracy of estimating the ionospheric delay using a satellite-based ionospheric model compared to the ionospheric delay that was estimated using dual-frequency.

This study is structured as follows. Chapter 2 provides a brief introduction to the satellite-based ionosphere model. Chapter 3 describes the configuration of WADGPS applied in this study and Chapter 4 shows the performance of the satellite-based ionospheric model and the performance of WADGPS using it when the ionosphere is active. Chapter 5 presents the results of analyzing the extrapolation performance of the satellite-based ionosphere model and the conclusions are presented in Chapter 6.

2. BRIEF REVIEW OF SATELLITE-BASED IONOSPHERE MODEL

The satellite-based ionosphere model is a concept proposed by Stanford University that provides functional ionosphere parameters for individual satellites (Stanford University 2015). Fig. 1 illustrates the concept of a satellite-based ionospheric model, which only uses the ionosphere observations by ground-based reference stations for individual satellites to create an ionosphere model for a region where ionospheric pierce points are distributed locally.

In this study, the average ionosphere distribution in Korea was analyzed using the ionospheric observation data in Korea and selected a first-order plane function as the local ionosphere model. Eq. (1) shows the first-order plane function model of the vertical ionospheric delay I_v for the latitude and longitude (ϕ, λ) of the ionosphere piece point.

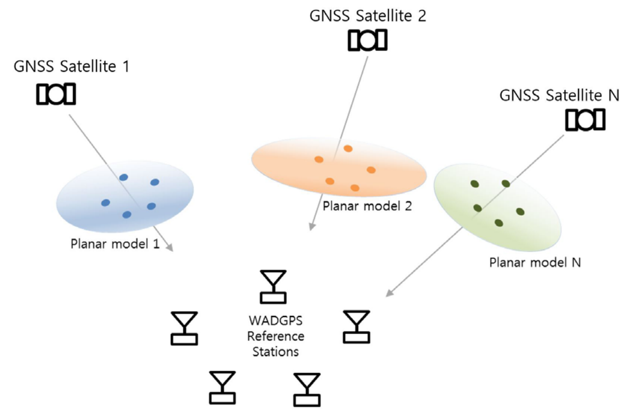

Fig. 1. Conceptual view of satellite-based ionosphere model.

Here, $I_{v,\,ref}$ is the vertical ionospheric delay for the ionosphere concentrate altitude random reference point latitude and longitude $(\phi_{ref}, \lambda_{ref})$, and $Grad_{lat}$, $Grad_{lon}$ are the slopes in the latitude and longitude directions, respectively (So et al. 2016a).

$$I_v(\phi, \lambda) = I_{v,\,ref} + Grad_{lat}(\varphi - \varphi_{ref}) + Grad_{lon}(\lambda - \lambda_{ref}) \qquad (1)$$

The user receives the plane function parameters of Eq. (1) for each satellite, and estimates the vertical ionospheric delay for the ionospheric pierce point of each satellite.

3. WADGPS SYSTEM USING SATELLITE-BASED IONOSPHERE MODEL

The satellite-based ionosphere model was applied to WADGPS to examine the correction performance in the Korean Peninsula during various periods. This study used 8 reference stations in Sejong, Ganghwa, Kwangju, Jeju, Woolsan, Wuljin, Inje, and Cheolwon of the National Geographic Information Institute to generate WADGPS data. Fig. 2 shows the operating screen of WADGPS operated by post-processing (So et al. 2016b).

4. PERFORMANCE ANALYSIS OF SATELLITE-BASED IONOSPHERE MODEL UNDER DISTURBED IONOSPHERE CONDITION

To verify the performance of WADGPS using a satellite-based ionosphere model configured as above, the navigation performance was examined using the post-processing method by choosing a period when the ionosphere was

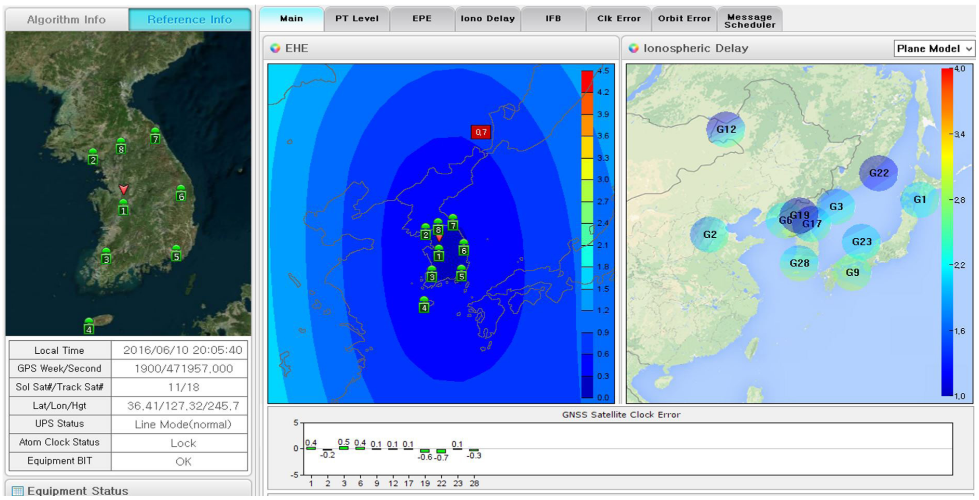

Fig. 2. Screen shot of operation status of WADGPS master station.

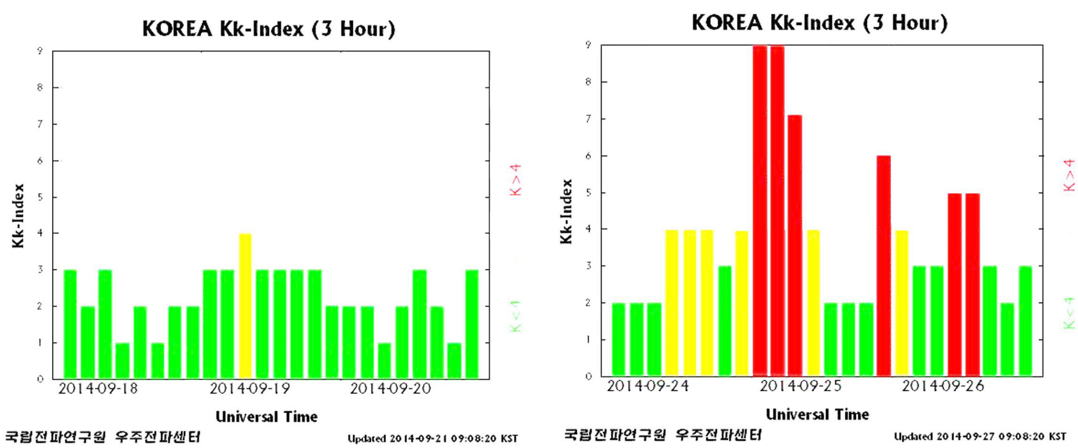

Fig. 3. Korea Kk-Index plots on normal (left) and disturbed (right) ionosphere condition (Courtesy: Korean Space Weather Center, National Radio Research Agency).

active. This study referred to the Korea Kk-Index values provided by the Korean Space Weather Center of the National Radio Research Agency to check the ionosphere characteristics as shown in Fig. 3. After comparing two periods in September 2014, it was found that the magnetic field changes over the Korean Peninsula were active on September 25 compared to September 18-20. Through this, the rapid changes in the ionosphere before and after September 25, 2014 can be expected, and as a result of processing GPS data, it was confirmed that the largest impact on navigation performance was on October 3, 2014.

Table 1 compares the horizontal navigation solutions of receiver stand-alone navigation and aided navigation in each reference station for 24 hours on October 3, 2014. In Jeju, the stand-alone navigation 95% horizontal navigation solution error increased up to 10 m, and the performance of aided navigation also dropped to 1.7 m, which shows that the navigation performance declined due to the influence of the ionosphere.

Table 1. Horizontal positioning errors for 24 hours at reference stations on Oct. 3rd, 2014.

Reference stations	Standalone horizontal positioning error (95%, meter)	WADGPS horizontal positioning error (95%, meter)
Sejong	6.40	1.31
Ganghwa	4.97	0.87
Kwangju	5.02	0.80
Jeju	10.62	1.69
Woolsan	5.79	1.22
Wuljin	6.23	1.32
Inje	4.92	0.98
Cheolwon	4.14	0.57

The accuracy of the satellite-based ionosphere model was analyzed to find the cause of the deterioration in performance as shown in Table 1. In terms of the true value, the ionospheric

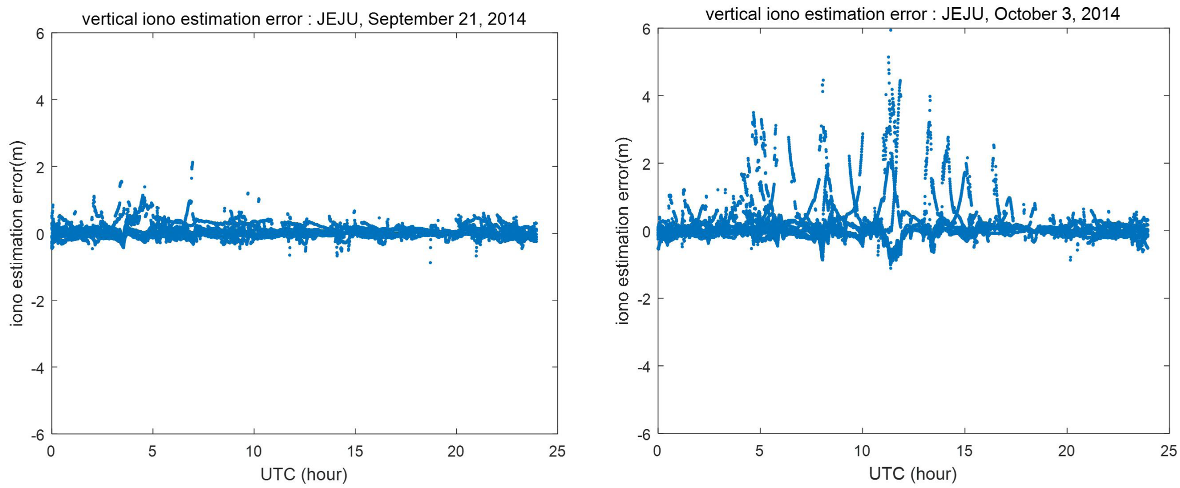

Fig. 4. Error plots of satellite-based ionosphere model under normal (left) and disturbed (right) ionosphere condition.

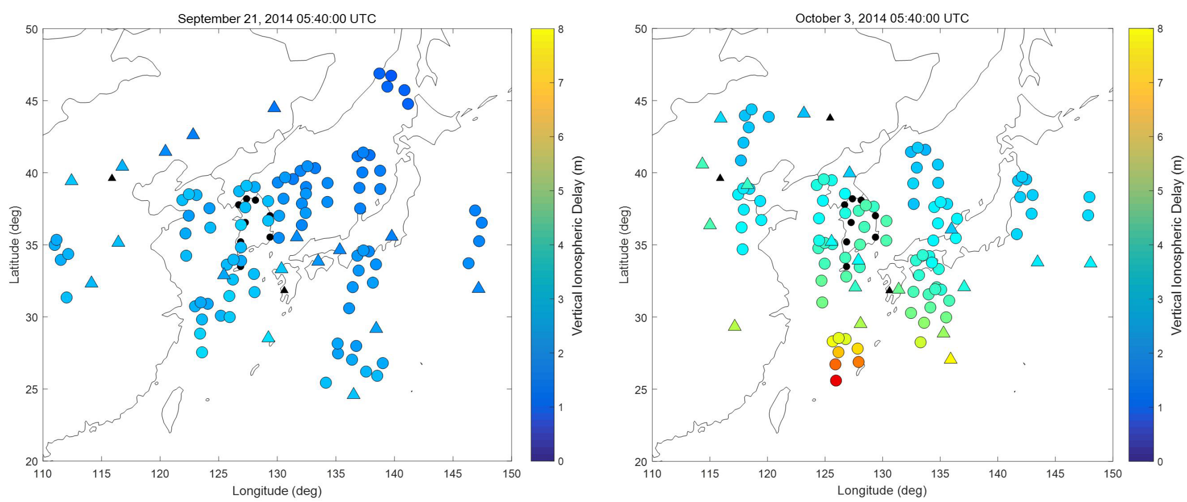

Fig. 5. Observed vertical ionospheric delay on normal (left) and disturbed (right) ionosphere condition.

delay was converted using dual-frequency measurements into a vertical delay and compared it with the vertical delay estimated by the satellite-based ionosphere model. Fig. 4 shows the error of the satellite-based ionosphere model at the Jeju reference station calculated in this way over time, where the average ionosphere estimation performance of September 21, 2014, was around 1 m and up to 2 m, but the estimation error on October 3, 2014 increases to around 6 m. From this, it is estimated that the deterioration in navigation performance in Table 1 was caused by the ionosphere estimation error.

The satellite-based ionosphere model used in this study is a first-order plane function as shown in Eq. (1), which has been confirmed by prior studies to be most suitable for the ionosphere distribution characteristics in the Korean Peninsula (Stanford University 2015). This analysis may be suitable for the average ionospheric environment in Korea, but showed a significant performance deterioration during certain periods when the ionosphere was very active, including September and October 2014.

This is because the satellite-based ionosphere model assumes that the distribution of the ionosphere in the ionospheric pierce point area generated by the observation reference station in Korea has linear characteristics. Fig. 5 shows the vertical ionospheric delay at the ionospheric pierce point observed by the observation reference station on October 3, 2014. On September 21, 2014 (left), the magnitude of the ionospheric delay at the ionospheric pierce point for individual satellites has linear characteristics, but on October 3, 2014 (right), the ionospheric delay at the ionospheric pierce point in the southern region changes significantly. In this case, the basic assumption of linear ionospheric distribution does not hold, therefore, it causes significant errors as shown in the figure to the right of Fig. 4.

5. EXTRAPOLATION PERFORMANCE OF SATELLITE–BASED IONOSPHERE MODEL

As above, the performance of the satellite-based ionosphere model when using an observation reference station that constitutes WADGPS as a user was analyzed. In comparison with the performance of WADGPS using a satellite-based ionospheric model from prior studies, the performance deteriorated from September to October 2014 when the ionosphere was active. This is due to the performance limitations of satellite-based ionosphere models which model the ionosphere as a first-order plane function.

In this chapter, the reference station data located outside the observation reference station was applied as the user in order to verify the extrapolation performance using a satellite-based ionosphere model. The satellite-based ionosphere model showed an excellent extrapolation performance since it can individually model local ionosphere distributions in the ionospheric pierce point area (Stanford University 2015).

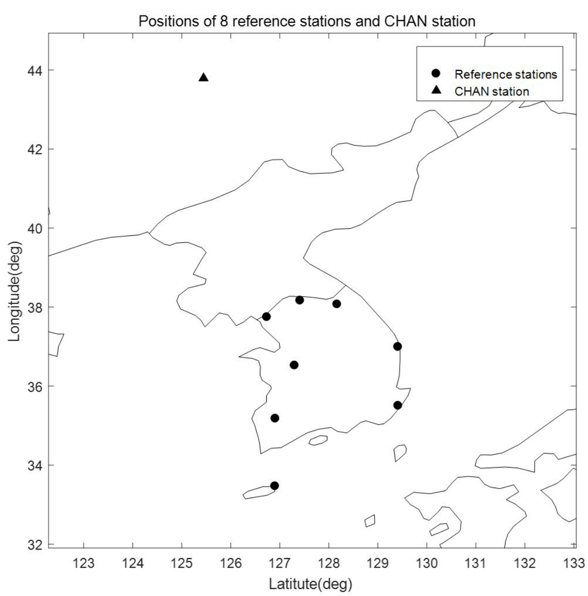

Fig. 6. Positions of 8 reference stations and CHAN station.

In terms of the reference station outside the observation reference station, the IGS reference station (CHAN) data of Changchun, China was applied as the user, and applied the ionospheric correction data generated from the same WADGPS described in Chapter 3. Fig. 6 shows the locations of the 8 observation stations that were used to process the data and the location of Changchun (CHAN) reference station in China. Fig. 7 shows the ionospheric delay error estimated over time using the satellite-based ionosphere model at Changchun reference station. On September 21, 2014, the error level was within 1 m for 24 hours, but on October 3, 2014 (right), the error increased by up to 5 m.

This is because the extrapolation was performed using a model assumed as a first-order plane function under the circumstances where the correlation between the active ionosphere distribution characteristics in lower latitudes and the flat ionosphere distribution characteristics in higher latitudes is reduced, as shown in Fig. 5. Fig. 8 shows the GIM provided by IGS, where the rapid changes in the ionosphere according to the latitude can be confirmed again as shown in the observation of individual ionosphere pierce points in Fig. 5.

As shown in Fig. 8, there are uncorrelated characteristics of the ionosphere according to space in the north-south direction, but the ionosphere showed flat characteristics in high latitudes even when the ionosphere was active on October 3, 2014. By considering these distribution characteristics, an improvement in the extrapolation

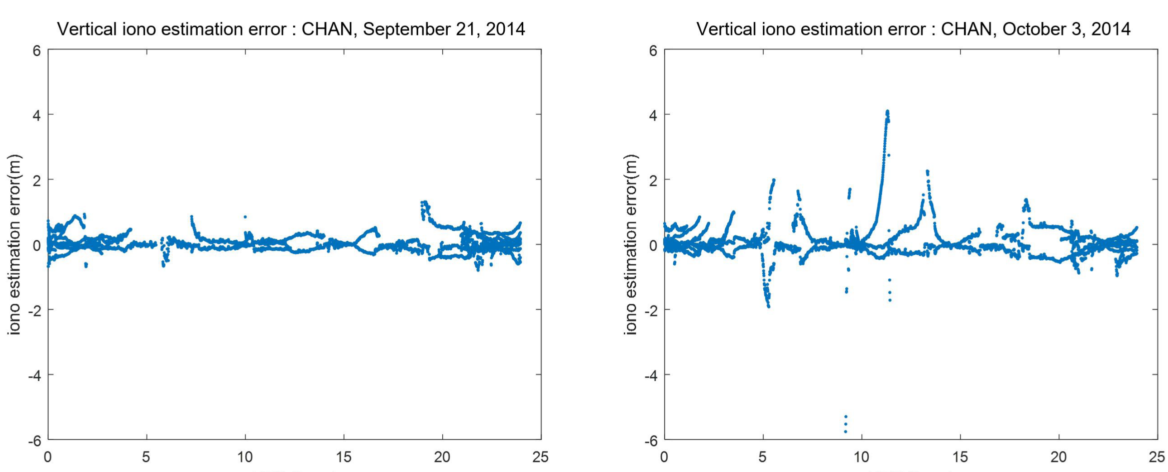

Fig. 7. Error plots of satellite-based ionosphere model under normal (left) and severe (right) ionosphere condition

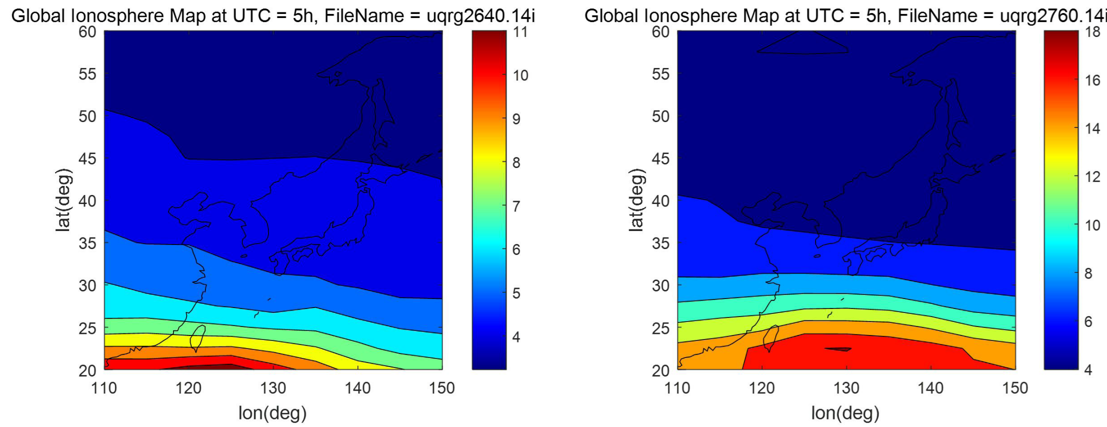

Fig. 8. Ionosphere distribution on September 21, 2014 (left) and October 3, 2014 (right) from IGS GIM.

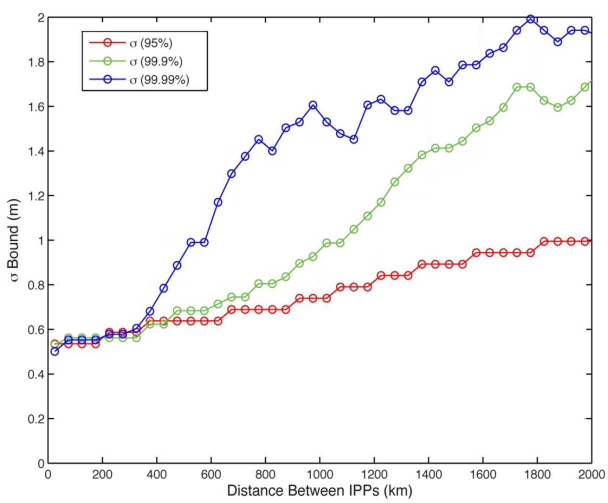

Fig. 9. Differences in vertical ionospheric delay with respect to the distance between ionosphere pierce points (Stanford University 2015).

performance is expected by reflecting less of the low latitude ionosphere measurements showing rapid changes when extrapolating in the direction of high latitude where the ionosphere is relatively flat.

Fig. 9 shows the distribution of the differences (as 95%, 99.9%, and 99.99%) in the vertical ionospheric delay for the distance of the ionosphere pierce points over the Korean Peninsula, which shows a 0.25 mm/km rate of change based on 95%. By reflecting these characteristics, in terms of applying the ionospheric observations of the observation stations to estimate the satellite-based ionospheric model parameters at the wide-area processing station, this study reduced the weight by applying standard deviation values corresponding to 0.25 mm/km depending on the distance for low-latitude ionospheric observations with respect to the estimated reference point. Fig. 10 shows the results of applying the extrapolation model to the IGS Changchun

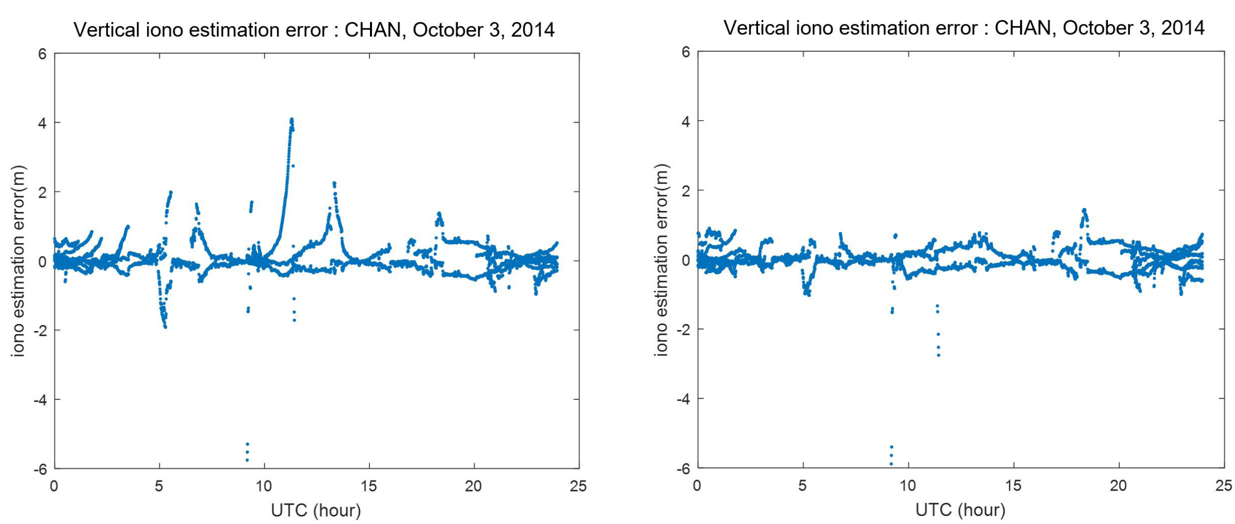

Fig. 10. . Error plots of conventional satellite-based ionosphere model (left) and weighted model (right).

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Reference Station (CHAN) in China in Fig. 7, by lowering the weight for low-latitude observations. The left of Fig. 10 is the same image as the right of Fig. 7, which is the estimation results of the conventional satellite-based ionosphere model, and the right of Fig. 10 shows the results of applying the weighted model. While the conventional model shows deterioration in performance such as errors of about 5 m after UTC 10h, these errors are improved on the right of Fig. 10, which reduces the influence of low latitude by reflecting weights. From the analysis results above, it was confirmed that the spatial separation uncorrelated characteristics of ionosphere distribution should be considered according to the latitude in order to improve the extrapolation performance of the satellite-based ionosphere model.

6. CONCLUSIONS

In this study, the performance of a satellite-based ionosphere model was examined when there are rapid changes in the ionosphere environment. Prior studies configured a WADGPS using 8 reference stations in the Korean Peninsula and applied a satellite-based ionospheric model to compensate for ionospheric errors. The results showed a performance level where the horizontal navigation solutions showed errors within 1 m. Meanwhile, highly active ionosphere characteristics were confirmed in October 2014, in which the horizontal accuracy of stand-alone navigation increased up to 10 m (95%) in Jeju, Korea. The performance of WADGPS using a satellite-based ionospheric model deteriorated to 1.7 m (95%) in Jeju, which was the worst performance in this environment. Through the distribution of ionosphere in Korea and the error characteristics of the satellite-based ionosphere model during this period, it was found that the reason for such deterioration was because the satellite-based ionosphere model was configured as a first-order planar function, which confirmed the limitations of the model.

This study also examined the ionospheric estimation accuracy by using Changchun IGS reference station data to examine the extrapolation performance of using a satellite-based ionosphere model. In October 2014, when the ionosphere of Korea was active, rapid changes in the ionosphere were observed in low latitudes, but linear distributions were maintained in high latitudes. Due to these uncorrelated characteristics according to spatial separation, the extrapolation performance also deteriorated significantly. This study showed that the accuracy of extrapolation ionospheric estimation could be improved by reducing the weight of the ionospheric observations in low latitudes by considering the change of ionosphere by distance.

Through the above post-processing data analysis results, the performance of a satellite-based ionosphere model during rapid changes in the ionosphere was confirmed. As a result, it was found that the performance will deteriorate under disturbed ionosphere conditions because the satellite-based ionosphere model models the ionosphere of Korea as a first-order plane function. To overcome these limitations, it is necessary to develop an adaptive model that changes according to the distribution characteristics of the ionosphere in the future.

AUTHOR CONTRIBUTIONS

Algorithm development and performance analysis, H. So; validation, K. Lee; project administration K. Kim; supervision, J. Park.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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