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Test Results of WADGPS System using Satellite-based Ionospheric Delay Model for Improving Positioning Accuracy

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ABSTRACT

Most existing studies on the wide-area differential global positioning system (WADGPS) employed a grid ionosphere model for error correction in the ionospheric delay. The present study discusses the application of satellite-based ionospheric delay model that provides an error model as a plane function with regard to individual satellites in order to improve accuracy in the WADGPS. The satellite-based ionospheric delay model was developed by Stanford University in the USA. In the present study, the algorithm in the model is applied to the WADGPS system and experimental results using measurements in the Korean Peninsula are presented. Around 1 m horizontal accuracy was exhibited in the existing planar fit grid model but when the satellite-based model was applied, correction performance within 1 m was verified.

Keywords: ionospheric delay model, DGPS, WADGPS, SBAS

1. INTRODUCTION

The wide area differential global positioning system (WADGPS) is a differential global positioning system (DGPS) that services a relatively large range of user areas using a number of global navigation satellite system (GNSS) observation reference stations. Generally, DGPS that uses a single reference station employs a pseudorange error observed by a reference station as correction information of scalar type whereas the WADGPS employs satellite-related error correction information of vector type and grid ionosphere model in order to service a wide range of area with uniform performance (Chao 1997).

The grid ionosphere model is a method that sets a virtual ionospheric concentrated altitude over the service area sky and provides a vertical ionospheric delay estimation with regard to a grid point that has a predefined gap (Kaplan & Hegarty 2006). A number of existing studies on the WADGPS and satellite-based augmentation systems (SBAS) employ a grid ionospheric delay model (RTCA 2001). A grid ionosphere model employs ionospheric delay observed with regard to a number of satellites at multiple reference stations as basic observation. Each of the observed values is observed via combination of satellites and each reference station, and an ionospheric pierce point (IPP) of the observed value refers to a point where a line that connects reference station and satellite is passed through the virtual ionospheric concentrated altitude. An ionospheric delay at the grid point defined in advance in the grid ionosphere model is estimated from the ionospheric delay measurement of multiple IPPs distributed around the corresponding grid point.

Recently, Stanford University in the USA conducted a study on satellite-based ionospheric delay model, which was better than grid ionosphere model, in terms of improvements on accuracy (Stanford University 2015). According to their study result, since a grid ionosphere model using a general planar fit employs a mixture of measured values observed from multiple satellites during the delay estimation with regard to each grid point, inevitable errors such as nugget effect are involved (Blanch 2003). The nugget effect means that a number of vertical ionospheric delays estimated at the IPP at the same or very

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short distance have a different value one another. Stanford University proposed a satellite-based ionospheric delay model using only measurements with regard to individual satellites to improve accuracy.

The purpose of the present study is to apply the satellite-based ionospheric delay model developed by Stanford University to the WADGPS, and analyze performance using a WADGPS testbed of the Korean Peninsula consisting of eight reference stations and one master station. Only the accuracy of the WADGPS was considered as a target of performance analysis. For the experiment results, post-processing performance of actual observation data and real-time correction performance results were presented.

This paper is organized as follows. In Chapter 2, an overview of the satellite-based ionospheric model is explained. In Chapter 3, a configuration of the WADGPS testbed and how to apply the satellite-based ionospheric model is discussed. In Chapter 4, the post-processing results of the WADGPS and real-time experimental results are presented followed by conclusions in Chapter 5.

2. OVERVIEW OF STANFORD SATELLITE-BASED IONOSPHERIC DELAY MODEL

In the present chapter, a brief explanation about the satellite-based ionospheric delay model is presented based on the research report of Stanford University (2015). The satellite-based ionospheric delay model defines an ionosphere model of function form with regard to individual satellites. A linear planar function was used as an ionosphere model with regard to individual satellites considering the characteristic of gradual distribution of the ionosphere in Korea. Eq. (1) shows the linear planar function model of vertical ionospheric delay l_v with regard to latitude and longitude (ϕ, λ) in the IPP. Here, $l_{v,ref}$ refers to a vertical ionospheric delay with regard to latitude and longitude (ϕ_{ref}, λ_{ref}) at an arbitrary reference point in the ionospheric concentrated altitude, and $Grad_{lat}$, $Grad_{lon}$ refers to a gradient in the latitude and longitude directions, respectively.

$$l_v(\phi, \lambda) = l_{v,ref} + Grad_{lat}(\phi - \phi_{ref}) + Grad_{lon}(\lambda - \lambda_{ref}) \qquad (1)$$

In the present paper, a WADGPS system consisting of eight observation reference stations was set as a target of the satellite-based ionospheric delay model. IPP reference points (ϕ_{ref}, λ_{ref}) are determined using only eight measurements of ionospheric delay for each satellite at each time are employed in the satellite-based model, and vertical ionospheric delay $l_{v,ref}$ at the reference point as well as gradients $Grad_{lat}$, $Grad_{lon}$ in latitude and longitude are estimated. Once each parameter of Eq. (1) is broadcast to a user after estimating it for each visible satellite, a user can estimate vertical ionospheric delay of corresponding satellite using input value of IPP for each individual satellite.

3. APPLICATION OF SATELLITE-BASED IONOSPHERIC DELAY MODEL ON WADGPS SYSTEM

3.1 Overview of WADGPS testbed

A WADGPS testbed consisting of eight observation reference stations and one master station installed in the Korean Peninsula was used to verify the performance of the WADGPS (So 2016). Fig. 1 shows a layout of the observation reference stations and conceptual diagram of operation. The satellite-based ionospheric delay model was implemented in the master station installed in Daejeon and generated correction values were sent to a user after defining an additional message format (Park 2015). An additional message type includes parameters in Eq. (1) and variances of each parameter. A single satellite has 93-bit data. Thus, a single message includes information about two satellites. A transmission cycle of message format was set to 30 sec. for each satellite. A testbed in Fig. 1 is operated in real time and correction information generated at the master station is transferred to a user using the Internet or Long-Term Evolution (LTE) modem.

3.2 Implementation of satellite-based ionospheric delay model

The satellite-based ionospheric delay model employs ionospheric delay with regard to individual satellites observed by a number of observation reference stations as measurement thereby estimating a parameter in the linear planar function with regard to vertical ionospheric delay. In order to integrate and use ionospheric delays measured at multiple observation reference stations, the inter-frequency bias (IFB), which is hardware propagation delay according to L1/L2 frequency difference at receivers of each reference station, shall be estimated and removed (Yun et al. 2011). Thus, IFB at multiple observation reference stations shall be able to be estimated in real time in order to apply the Stanford satellite-based model to the WADGPS operated in real time.

The present study employed an estimation method of IFB

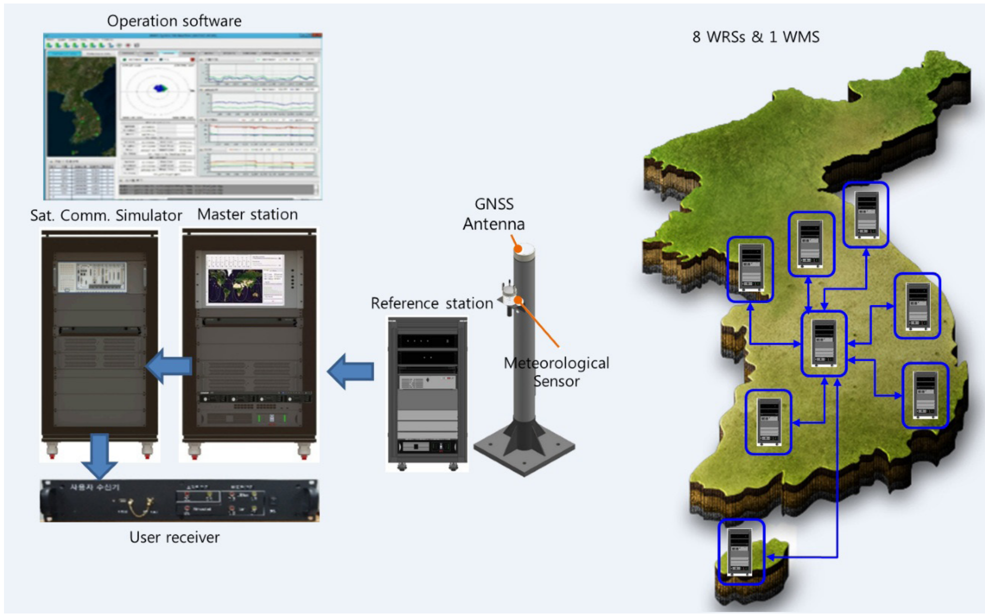

Fig. 1. Conceptual view of WADGPS testbed.

by using observed values of ionospheric delay with regard to all visible satellites at all reference stations and modeling an ionospheric distribution into quadratic spherical harmonics to estimate the IFB (Kim 2007). The slant ionospheric delay observation $i_{i,s}^{j}$ with regard to the j-th satellite at an arbitrary i-th reference station can be expressed via vertical delay $i_{i,v}^{j}$ due to the ionosphere, obliquity factor Q_i^j, and i-th reference station receiver IFB $i_{b_{Rx},i}$, and IFB $i_{b_{Tx}}^{j}$ at the j-th satellite, which are modeled as presented in Eq. (2). The superscript in the above equation refer to classification of satellite, and the subscripts refer to classification of ground receives.

$$i_{i,s}^{j} = i_{i,v}^{j} \cdot Q_i^j + i_{b_{Rx},i} - i_{b_{Tx}}^{j} \tag{2}$$

The satellite IFB $i_{b_{Tx}}^{j}$ in Eq. (2) can be corrected with T_{GD} value that is transferred through navigation message of the corresponding satellite, and vertical delay $i_{i,v}^{j}$ is assumed as quadratic spherical harmonics in Eqs. (3) and (4). Assuming observed values from N reference stations with regard to M satellites, nine quadratic spherical harmonics coefficients and the IFBs of N reference stations can be estimated from NM measured values (Kee 2014). ϕ_M, λ refer to latitude and longitude at the IPP, respectively, and C_{nm}, S_{nm} refers to coefficients of quadratic spherical harmonics.

$$i_v(\phi_M,\lambda) = \sum_{n=0}^{2}\left[\sum_{m=0}^{n}\{C_{nm}\cdot\cos m\lambda + S_{nm}\cdot\sin m\lambda\}\cdot P_{nm(\sin\phi_M)}\right] \tag{3}$$

$$P_{nm}(x) = \frac{1}{2^n\cdot n!}(1-x^2)^{\frac{m}{2}}\cdot\frac{d^m}{dx^m}\left[\frac{d^n}{dx^n}(x^2-1)^n\right] \tag{4}$$

The IFB-removed vertical ionospheric delay $i_{i,v}^{j}$ is divided by individual satellites through the above process and linear planar function model in Eq. (1) can be applied. Using measurements from N reference stations with regard to arbitrary satellite, coefficients $l_{v,ref}$, $Grad_{lat}$, and $Grad_{lon}$ of planar function in Eq. (1) can be estimated by applying a least square method. An arbitrary reference point (ϕ_{ref}, λ_{ref}) at the ionospheric concentrated altitude with regard to individual satellites in Eq. (1) was calculated by using an arithmetic mean of the observed pierce point in the ionosphere at all reference stations with regard to a corresponding satellite.

4. TEST RESULTS

4.1 Post-processing test results

A testbed of the WADGPS in Fig. 1 consisted of eight observation reference stations. For post-processing performance analysis, about 20-hour correction data were generated using a total of seven observation reference stations except for one station installed in Gimhae. Data from the receivers at the observation reference stations in Paju, Daejeon, and Jeju were assumed as measured values from user receivers in order to verify the correction performance, and three positioning results of single positioning result, planar fit grid ionosphere model-applied WADGPS, and satellite-based ionosphere model-applied WADGPS were compared. For satellite-related

Table 1. Post-processing test results.

	Horizontal position error (95%, m)			Vertical position error (95%, m)		
	Standalone L1 only	Grid model	Satellite-based model	Standalone L1 only	Grid model	Satellite-based model
Paju	3.37	0.90	0.63	3.36	1.73	1.25
Daejeon	3.43	1.12	0.88	3.70	1.90	1.48
Jeju	3.81	0.99	0.54	2.90	1.66	0.90

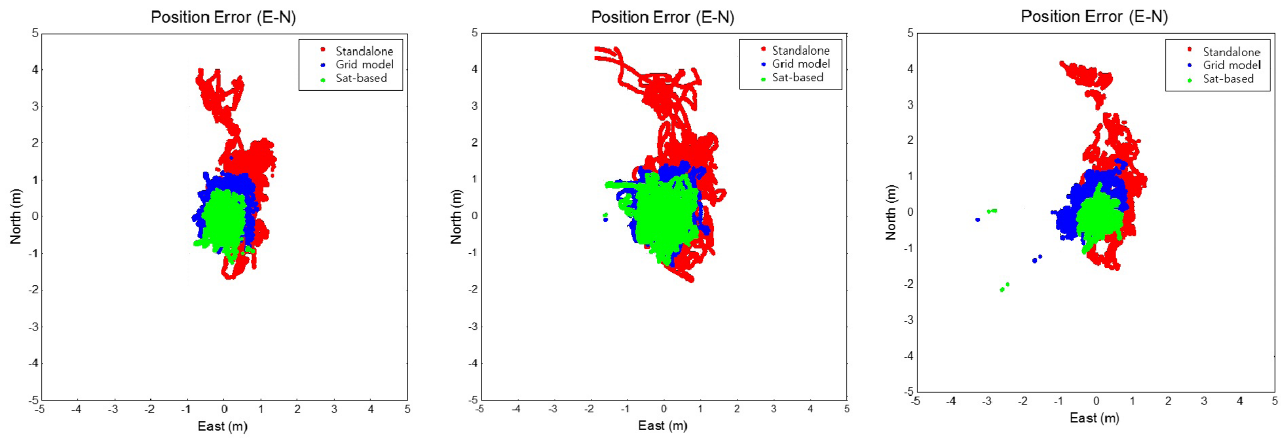

Fig. 2. Post-processing test results for 3 user receivers (left : Paju, middle : Daejeon, right : Jeju), where red dots mean standalone, blue dots mean WADGPS with grid ionospheric delay model, and green dots mean WADGPS with satellite-based ionospheric delay model.

errors, a minimum variance estimator was applied, and for tropospheric delay, the Wide Area Augmentation System (WAAS) model was applied (Tsai 1999). In Table 1, horizontal and vertical navigational solution results at three reference stations assumed as users are summarized. The horizontal positioning result had accuracy around 1 m when the grid ionospheric delay model was applied, and it had accuracy of less than 1 m when the satellite-based model is applied. A level of improvement on accuracy was about 20% in Daejeon and about 45% in Jeju. Improvements on performance in vertical positioning result were similar to that of the horizontal positioning result. Fig. 2 shows the results of the horizontal positioning result from three user receivers.

4.2 Accuracy of satellite-based ionospheric delay model applied on WADGPS system

In order to verify the performance of accuracy of the satellite-based ionospheric delay model applied to the WADGPS, an error of slant ionospheric delay estimated with the satellite-based model compared to slant ionospheric delay estimated using L1/L2 dual frequency measurements at user receivers of the observation reference station was estimated. The reference station IFB included in the L1/L2 measurements employed IFB estimation filter results at the master station, which was discussed in Section 3.2.

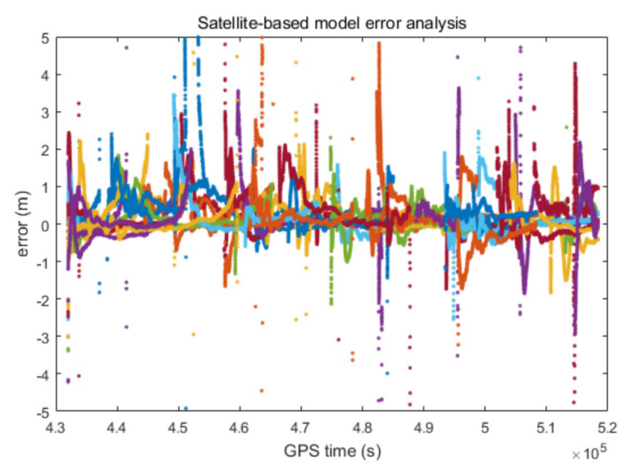

Fig. 3. Satellite-based ionospheric delay model error which is the difference between estimated slant ionospheric delay from satellite-based model and L1/L2 dual frequency ionospheric delay measurement.

Fig. 3 shows errors of the satellite-based ionospheric delay model error with regard to all ionospheric delay measurements observed in Daejeon reference station for 24 hours. Table 2 shows statistics of errors shown in Fig. 3, in which a level of 50 cm of RMS is exhibited. Fig. 4 shows the errors of the satellite-based ionospheric delay model with regard to time axis for a specific satellite, estimated variance of pseudo-range, and elevation angle of the satellite. The top and bottom results in Fig. 4 show that when an elevation angle of the satellite exceeds 10°, the satellite-

Table 2. Statistics of test results of satellite-based ionospheric delay model.

Mean (cm)	Std (cm)	RMS (cm)
18	47	50

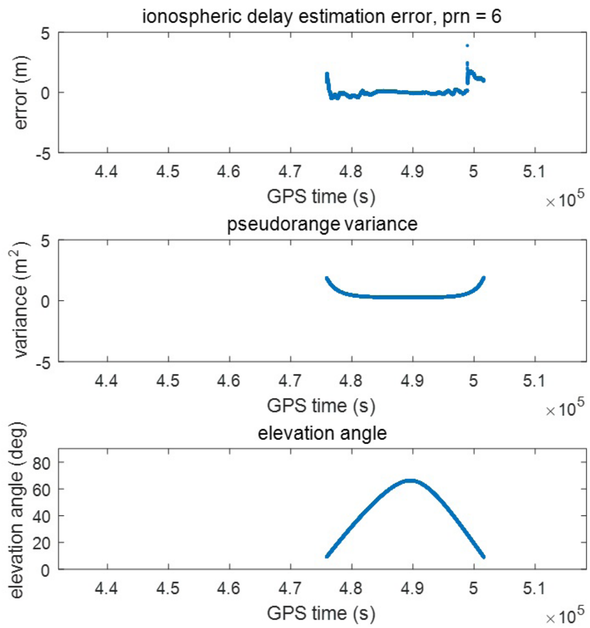

Fig. 4. Satellite-based ionospheric delay model error for a certain satellite (top: ionospheric delay estimation error, middle: estimated variance of pseudorange, bottom: elevation angle of GPS satellite).

based ionospheric model works normally. However, when the satellite rises and sets, an error increases rapidly. This is because all measurements used in parameter estimation in the linear planar function of Eq. (1) at the corresponding time have large errors due to a low elevation angle thereby inducing errors in the parameter estimation results. As shown in the middle of Fig. 4, an estimation value of error level with regard to pseudorange becomes also large. Thus, since a weight of positioning result is decreased with regard to measurements when an error level is large because of applying a weighted least square method to calculate a positioning result, the effect on final positioning result is limited.

4.3 Real-time test results

Fig. 5 shows a screen shot of the master station display in the WADGPS system. The left figure of Fig. 5 shows locations of observation reference stations in the map of the Korean Peninsula and communication states and the middle figure shows a level of accuracy in horizontal positioning result estimated using correction information. The right side of Fig. 5 shows a circular shape of the linear planar function

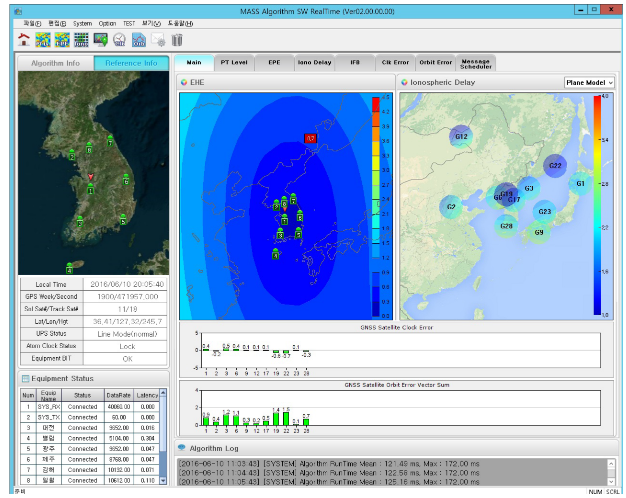

Fig. 5. Screen shot of WADGPS master station display.

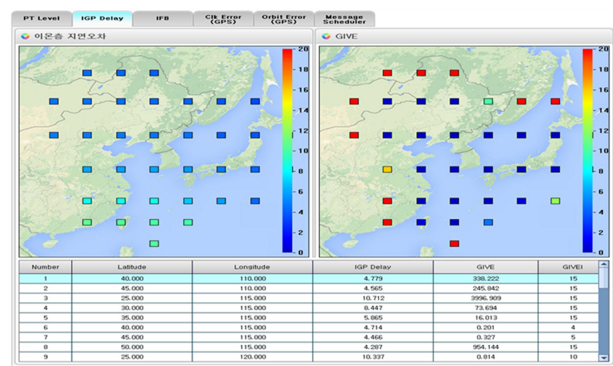

Fig. 6. Screen shot of grid ionospheric delay model of WADGPS master station display.

estimated using the satellite-based ionospheric delay model at the IPP locations of individual satellites. Fig. 6 shows the screen shot of the grid ionospheric model operated in the WADGPS system master station. The currently implemented WADGPS system estimates both of grid ionosphere model and satellite-based model internally and can send correction message optionally. Fig. 7 shows the screen shot of the navigation accuracy analysis function operated in the WADGPS system master station. The implemented WADGPS master station transfers generated correction messages to each of the observation reference stations, and each observation reference station performs a function of user receiver thereby providing correction information-applied positioning results. Fig. 7 shows the performance of navigation accuracy at the reference station. Results of standalone positioning result and correction information-applied positioning result are revealed with regard to the selected region from the reference stations in the left side. The middle in Fig. 7 shows the horizontal positioning result, in which green color indicates standalone result and blue

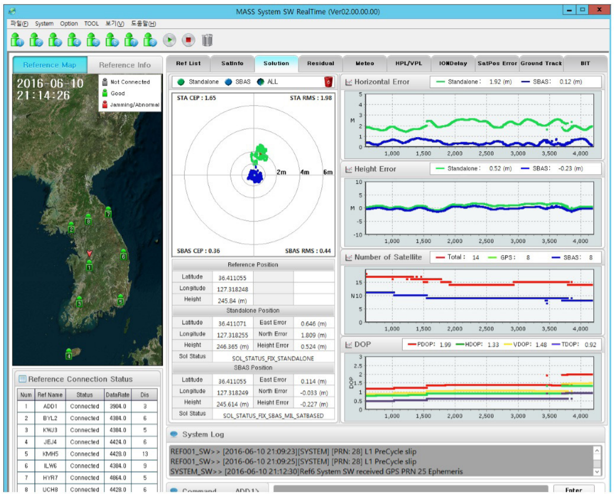

Fig. 7. Screen shot of positioning results of WADGPS master station display.

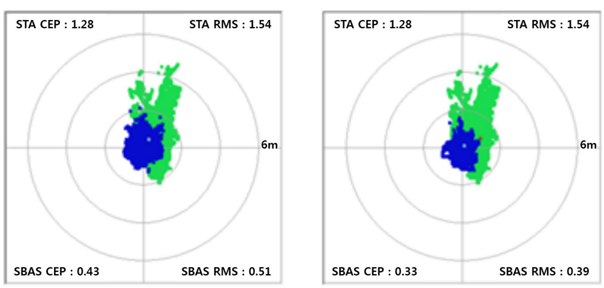

Fig. 8. Screen shot of horizontal positioning error where green dots mean standalone position and blue dots mean WADGPS position (left: WADGPS with grid model, right: WADGPS with satellite-based model).

color indicates WADGPS correction-applied positioning result.

Fig. 8 shows the results of horizontal positioning result of WADGPS operation in real time in Daejeon, in which the left side shows positioning errors in the standalone and WADGPS when the grid ionosphere model is applied and the right side shows positioning errors of standalone and WADGPS when the satellite-based ionospheric delay model is applied. Statistics was marked inside the horizontal positioning figure and as shown in Fig. 8, the grid ionospheric delay model-applied WADGPS had horizontal accuracy performance of CEP 0.43 m and the satellite-based ionospheric model-applied WADGPS had horizontal accuracy performance of CEP 0.33 m.

5. CONCLUSIONS

In the present paper, application of satellite-based ionospheric delay model developed by Stanford University in the USA and experimental results were discussed in order to improve the performance of accuracy in WADGPS. The existing planar fit grid ionospheric delay model employed all measurements in the ionosphere around the grid point when ionospheric delay was estimated thereby inducing inevitable errors such as nugget effect in terms of accuracy. On the other hand, the satellite-based ionospheric delay model employed only measurements of individual satellite to estimate a function model for each satellite thereby improving performance in terms of accuracy.

In this paper, the satellite-based ionospheric delay model was applied to a real time WADGPS system. The WADGPS system consisted of eight observation reference stations in the Korean Peninsula. For the function that was applied to the satellite-based ionospheric delay model, linear planar function was assumed in consideration of gradual distribution of the ionosphere in the Korean Peninsula, and IFB estimation and smoothing were applied to enable real time operation. In order to verify the performance of accuracy in the WADGPS system, the ionospheric delay model of the WADGPS was divided into grid model and satellite-based model to compare positioning performance. The comparison result showed that corrected positioning performance was within horizontal 95% 1 m with about 45% performance improvement.

For estimation performance of ionospheric delay in the satellite-based model, results estimated using L1/L2 dual frequency measurements and results estimated via the model were compared. The comparison result showed that excellent estimation performance was exhibited in general but a significant error was verified when an elevation angle of satellite was low. This was because when an elevation angle of satellite was low, errors and noise level of all measurements used to estimate the linear planar function became larger thereby making estimation performance unstable. This phenomenon occurred when a satellite rose and set. Since a variance of pseudorange measurement reflected this at the corresponding time, the effect on the final positioning result was limited.

REFERENCES

Blanch, J. 2003, Using Kriging to bound satellite ranging errors due to the ionosphere, Ph.D. Dissertation, Stanford University

Chao, Y.-C. 1997, Real Time Implementation of the Wide Area Augmentation System for the Global Positioning System with an Emphasis on Ionospheric Modeling, Ph.D. Dissertation, Stanford University

Kaplan, E. D. & Hegarty, C. J. 2006, Understanding GPS: Principles and Applications. 2nd ed. (Boston: Artech House)

Kee, C. 2014, Lectures on SBAS System Design, Lecture Notes of GNSS Laboratory in Seoul National University

Kim, D. 2007, A study on correction generation algorithms for wide area differential GNSS, Ph.D. Dissertation, Seoul National University

Park, B. 2015, A study on WADGPS message structure and design, Internal report, Sejong University

RTCA Special Committee 159 Working Group 2 2001, Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, Radio Technical Commission for Aeronautics Document Number DO-229C

So, H., Jang, J., Lee, K., Park, J., & Song, K. 2016, Performance analysis of WADGPS system for improving positioning accuracy, Journal of Positioning, Navigation, and Timing, 5, 21-28. http://dx.doi.org/10.11003/JPNT.2016.5.1.021

Stanford University 2015, A study on GNSS ionospheric delay estimation for extending the coverage of WADGPS, Internal report, Stanford University

Tsai, Y.-J. 1999, Wide Area Differential Operation of the Global Positioning System : Ephemeris and Clock Algorithms, Ph.D. Dissertation, Stanford University

Yun, H., Kee, C.-D., & Kim, D.-Y. 2011, Korean Wide Area Differential Global Positioning System Development Status and Preliminary Test Results, International Journal of Aeronautical & Space Science, 12, 274-282. http://dx.doi.org/10.5139/IJASS.2011.12.3.274

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