JPNT 3(1), 17-23 (2014)
http://dx.doi.org/10.11003/JPNT.2014.3.1.017

JPNT Journal of Positioning, Navigation, and Timing

Considerations on Ionospheric Correction and Integrity Algorithm for Korean SBAS

Eugene Bang, Jiyun Lee†
Division of Aerospace Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea

ABSTRACT

Satellite Based Augmentation Systems (SBAS) provide ionospheric corrections at geographically five degree-spaced Ionospheric Grid Points (IGPs) and confidence bounds, called Grid Ionospheric Vertical Errors (GIVEs), on the error of those corrections. Since the ionosphere is one of the largest error sources which may threaten the safety of a single frequency Global Navigation Satellite System (GNSS) user, the ionospheric correction and integrity bound algorithm is essential for the development of SBAS. The current single frequency based SBAS, already deployed or being developed, implement the ionospheric correction and error bounding algorithm of the Wide Area Augmentation System (WAAS) developed for use in the United States. However, the ionospheric condition is different for each region and it could greatly degrade the performance of SBAS if its regional characteristics are not properly treated. Therefore, this paper discusses key factors that should be taken into consideration in the development of the ionospheric correction and integrity bound algorithm optimized for the Korean SBAS. The main elements of the conventional GIVE monitor algorithm are firstly reviewed. Then, this paper suggests several areas which should be investigated to improve the availability of the Korean SBAS by decreasing the GIVE value.

Keywords: grid ionospheric vertical error (GIVE), integrity, satellite based augmentation system (SBAS)

1. INTRODUCTION

Global Navigation Satellite System (GNSS), which is represented by the Global Positioning System (GPS) of the U.S., has been used in various areas of the modern society and has become an essential part of the global social infrastructure. However, in aircraft precision approach and landing, applying GNSS alone may not satisfy the high navigation performance and safety requirements. Therefore, Satellite Based Augmentation System (SBAS) was developed for such applications.

As the demand for airspace capacity, efficiency, and safety is increasing in the modern society, the need for navigation systems with higher performance and stability also grows. The operation of U.S. Wide Area Augmentation System (WAAS) was initiated in 2003, and other similar navigation systems are currently under test operation or development. These include: Multi-functional Satellite Augmentation System (MSAS) of Japan; European Geostationary Navigation Overlay Service (EGNOS) of the Europe; and GPS Aided GEO Augmented Navigation (GAGAN) of India. In Korea, Korean SBAS research and development project will be conducted from 2014. The first objective will be the development of a single frequency-based operation system with Approach Procedures with Vertical guidance (APV-I) capability and the final objective will be the realization of Category I experimental operation system by 2021.

The largest error source that may affect the accuracy of GNSS user positioning and threaten the safety of GNSS users comes from the ionosphere. Therefore, the SBAS allows the user to correct for the ionosphere induced error by providing ionospheric delay estimates at Ionospheric Grid Points (IGPs) and confidence bounds of the ionospheric delay estimates, called Grid Ionospheric Vertical Errors (GIVEs).

Received Jan 24, 2014 Revised Feb 06, 2014 Accepted Feb 17, 2014
†**Corresponding Author**
E-mail: jiyunlee@kaist.ac.kr
Tel: : +82-42-350-3725

http://www.gnss.or.kr pISSN: 2288-8187

The ionospheric correction procedure implemented in the existing SBAS is based on the GIVE monitor algorithm of the WAAS developed for use in the Conterminous United States (CONUS). However, South Korea is located at low geomagnetic latitude in comparison to the US CONUS region. Thus Korea is likely to be affected by equatorial anomaly (Saito & Fujii 2010) and plasma bubble (Maruyama et al. 2013) which frequently take place in the equatorial region. If an ionospheric correction and error bounding algorithm for the Korean SBAS is designed by assuming the same ionospheric activity in the CONUS region, it may difficult to realize the optimum performance. Furthermore, due to the limited number of reference stations and narrow distribution of reference stations in South Korea, if the conventional GIVE algorithm for WAAS is applied to the Korean SBAS without any modification, the optimum availability of the system may not be achieved.

Therefore, this paper discusses key components that should be taken into consideration for the development of the ionospheric correction and error bounding algorithm optimized for the Korean SBAS. The main elements of the conventional GIVE algorithm are firstly reviewed. Then, essential factors to be considered to improve the availability of the Korean SBAS are described. This paper includes following Sections: Section 2 explains the ionospheric delay estimation methods used in the conventional GIVE algorithm; Section 3 describes the GIVE value that is the integrity bound on the calculated ionospheric delay estimate; Section 4 describes an irregularity detector for detection of ionospheric irregularities which may occur under disturbed ionospheric conditions; and Section 5 summarizes the analysis and discussion in each Section, and suggests several factors that should be taken into account in the ionospheric correction and error bounding algorithm design for the Korean SBAS.

2. IONOSPHERIC DELAY ESTIMATION

This Section describes methods of estimating a vertical ionospheric delay at each IGP based on the ionospheric delay measurements at SBAS reference stations.

2.1 Planar Fit Estimation

In the standard planar fit algorithm, the ionosphere around an IGP is modeled under nominal ionospheric conditions as follows (Walter et al. 2000):

$$\hat{I}_v(\Delta x, \Delta y) = \hat{a}_0 + \hat{a}_1 \Delta x + \hat{a}_2 \Delta y \tag{1}$$

In Eq. (1), Δx and Δy denote the relative coordinates of an ionospheric pierce point (IPP) around the IGP. The origin of the relative coordinates is the position of the IGP. The planar model coefficients, $(\hat{a}_0, \hat{a}_1, \hat{a}_2)$, are estimated through the least square fit performed based on the vertical ionospheric delay measurements at IPPs around the IGP. The vertical ionospheric delay estimate at the IGP is given as follows (Walter et al. 2000):

$$\hat{I}_{v,IGP} = \hat{a}_0 \tag{2}$$

In the case of the WAAS, in order to obtain required performance, the minimum number and the maximum number of the ionospheric measurements to be used for the planar fit are limited to N_{min}=10 and N_{max}=30 (Pandya et al. 2007, Sparks et al. 2011a). In addition, the ionospheric measurements of the target number are searched within the predefined radius from the IGP. Currently, the minimum search radius and the maximum search radius of the planar fit are R_{min}=800 km and R_{max}=2100 km, respectively (Pandya et al. 2007, Sparks et al. 2011a).

2.2 Kriging Estimation

Kriging based methodology used to estimate the vertical ionospheric delay at IGPs was introduced in the WAAS Follow-On Release 3 to replace the planar fit (Sparks et al. 2011a, Blanch 2003). Kriging is a minimum mean square estimator that estimates characteristics at a point of concern on the basis of the weighted linear combination of the values at the nearby points of which characteristic values are known (Eq. (3)) (Sparks et al. 2011a). Blanch (2003) used ionospheric observables at SBAS reference stations as the known characteristic values.

$$\hat{I}_v(\Delta x) = \sum_{k=1}^{N} w_k \, I_{meas}(\Delta x_k) \tag{3}$$

In Eq. (3), Δx indicates the relative coordinate of each IPP whose origin is at each IGP, I_{meas} denotes the ionospheric delay measurement at each IPP, and w_k indicates the weight coefficient applied to each measurement. The weight coefficient, w_k, are determined primarily by the detrended ionospheric delay covariance between measurement locations (Sparks et al. 2011a). In particular, the detrended ionospheric delay covariance is calculated based on variogram (Cressie 1993). The variogram characterizes spatial structure of the nominal ionosphere

http://dx.doi.org/10.11003/JPNT.2014.3.1.017

(Sparks et al. 2011a, Blanch 2003). In the Kriging based estimation, constraints on the number of the ionospheric measurements and the search radius for measurements are the same with those of the planar fit algorithm described in Section 2.1. Sparks et al. (2011a) compared the root mean square (RMS) errors of the ionospheric delay obtained by the planar fit algorithm and the Kriging method during disturbed ionospheric conditions Sparks et al. (2011a) also reported that the performance of the Kriging-based estimation was better than that of the planar fit algorithm by up to 15%.

3. INTEGRITY BOUND ON THE IONOSPEHRIC CORRECTION

As mentioned earlier, SBAS provides not only the ionospheric delay estimates at IGPs but also GIVE values, the integrity bounds on the estimates. The GIVE value whose magnitude has major contribution to the magnitude of the protection level of the SBAS user is calculated based on the uncertainties associated with the fit plane, nominal ionospheric decorrelation, and undersampled threat model contributions (Pandya et al. 2007). Section 3 reviews each element of the GIVE value and discusses factors which should be taken into consideration in designing the ionospheric correction and error bounding algorithm of the Korean SBAS.

3.1 Formal Estimation Error

The formal estimation error term in the GIVE calculation is defined to consider the uncertainty inherent in the planar fitting procedure (Cormier et al. 2003). Under quiet ionospheric conditions, the planar fit estimation error can be sufficiently bounded by this formal error variance, and the GIVE value is computed based on the formal error variance (Sparks et al. 2011b).

3.2 Nominal Ionospheric Decorrelation

When the ionospheric delay estimation is performed through the fitting, the fit model may never be consistent with actual data perfectly. To consider the spatial decorrelation of the planar fit, σ_{decorr}^{nom} is used which represents the standard deviation of residuals between the fit model and actual data under nominal ionospheric conditions (Altshuler et al. 2002). In the current WAAS, the value is calculated through a correlation analysis performed based on the CONUS ionospheric data under nominal ionospheric conditions (Walter et al. 2000, Hansen et al. 2000a,b).

Since the ionospheric phenomena are correlated with the geomagnetic activity, the ionospheric behaviors are known to be significantly dependent on the geomagnetic latitude. In the equatorial regions, it is difficult to model the ionosphere due to the equatorial anomaly whose peak ionospheric plasma densities form about 15 degrees magnetic latitude (Cormier et al. 2003, Saito & Fujii 2010). In the case of the WAAS, the ionospheric decorrelation analysis was performed for the region of Brazil to extend the coverage of WAAS to Latin America (Cormier et al. 2003). Countries in low latitude regions such as India conducted studies to redefine σ_{decorr}^{nom} to establish SBAS of their own countries (Sarma et al. 2009). Therefore, considering the geographic characteristics of Korea which is closer to the geomagnetic equator than the CONUS region, a different σ_{decorr}^{nom} value should be defined instead of the σ_{decorr}^{nom} value for the CONUS.

3.3 Undersampled Ionospheric Threat Model

The GIVE based on the formal error variance should be large enough to bound the ionospheric estimation error at an IGP. However, when the ionospheric irregularities may form between the IPPs and are not observed by the SBAS reference stations, the GIVE should be increased to ensure the integrity of the user position solution. When calculating GIVE, the increment is derived from an undersampled ionospheric threat model. Fig. 1 shows an example result from populating data to threat space using the data observed at reference stations in Korea on November 6, 2001. The undersampled irregularities are estimated using data from all ionospheric storm days to construct an undersampled

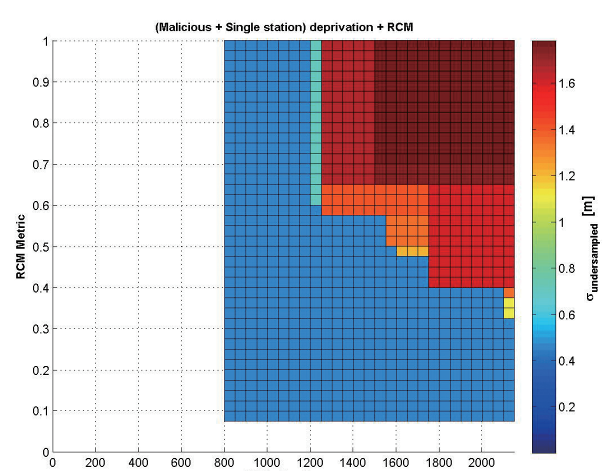


Fig. 1. An example of populating undersampled irregularity data to ionospheric threat model.

threat model. $\sigma_{undersampled}$ represents the uncertainty bound due to undersampling (Pandya et al. 2007, Sparks et al. 2011b).

As shown in Fig. 1, $\sigma_{undersampled}$ is a function of fit radius and Relative Centroid Metric (RCM). The fit radius and RCM represent the density and uniformity of the ionospheric measurements used in the planar fit, respectively (Pandya et al. 2007). As the density or uniformity of the ionospheric measurements decreases, the risk of undersampling increases. Therefore, an undersampled threat model is defined in such a threat metric domain (Sparks et al. 2005, Pandya et al. 2007).

An undersampled threat model is established with post-processed ionospheric storm data using a data deprivation method that simulates the worst case undersampling conditions (Pandya et al. 2007, Sakai et al. 2008, Sparks et al. 2005). When the data deprivation method is performed, the potential ionospheric threats are better identified as the number of reference stations is greater. In the construction of an ionospheric threat model for the MSAS, Sakai et al. (2008) showed that more undersampled ionospheric threats could be identified through an oversampling method. The oversampling method uses not only the ionospheric measurements at the six MSAS reference stations in Japan but also those of additional reference stations (Sakai et al. 2008). Since the number of Korean SBAS reference stations would be similar to that of MSAS, it would be beneficial to introduce the oversampled method to establish a reliable ionospheric threat model in Korea.

Although it is necessary to build an ionospheric threat model for the single frequency SBAS, an excessively conservative threat model may rather decrease the system availability. The threat model contribution to the GIVE computation is determined by the distribution of the ionospheric measurements used in fitting. The design of a threat model metric that may precisely characterize the spatial distribution of measurements with which undersampled ionospheric threats can be generated is thus a key factor for increasing the SBAS availability.

4. IONOSPHERIC STORM DETECTORS

In the WAAS GIVE algorithm, the ionospheric irregularity detector monitors whether the ionospheric fitting model well reflects the actual ionosphere by performing a chi-square consistency check (Sparks et al. 2011a, Walter et al. 2000). When the irregularity detector is tripped by the existence of the ionospheric irregularities, the GIVE value at the IGP is set to be 45 m (the maximum possible GIVE value) to guarantee the integrity of the user navigation solution (Sparks et al. 2011b). Even though the trip of the irregularity detector would ensure safety of the user under the ionospheric disturbances, the false alarm given by the storm detector could rather damage the system availability. The irregularity detector performs differently based on the number of IPPs used in fitting, the distribution of the IPPs, and the accuracy of the ionospheric delay estimation (Sparks et al. 2011a). Therefore, if the conventional planar fit algorithm is applied without any modification to the Korean region where a smaller number of ionospheric measurements are available, the poor performance is expected due to the increased false alarm rate of the irregularity detector. Hence, further studies need to be conducted on the design of the irregularity detector to improve system performance.

5. DISCUSSION

Beginning with a single frequency system supporting APV-I precision approach, the Korean SBAS development plan is aimed at the development of a dual frequency-based CAT-I experimental operation system. According to Bang et al. (2013), it is expected that the required availability is achievable as shown in Fig. 2 when an ionospheric threat model that reflects the ionospheric activity in the Korean region is applied. However, the expected performance is too poor to support LPV-200 precision approaches (Bang et al. 2013).

If CAT-I operations or near CAT-I capability with single-frequency based SBAS could be achieved through the

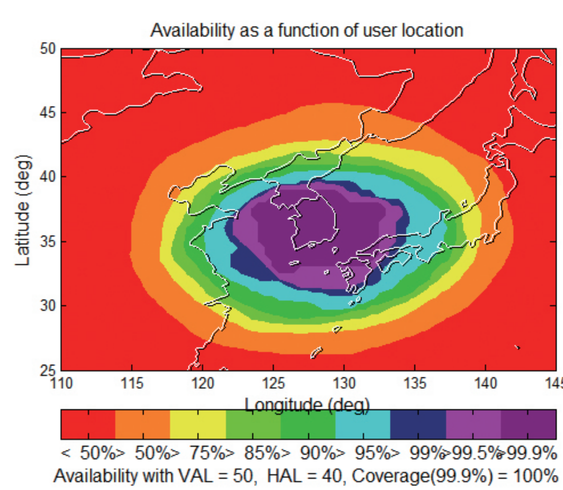


Fig. 2. Expected availability performance of single-frequency SBAS for APV-I (HAL=40, VAL=50) operations in the Korean region.

improvement of the ionospheric correction and error bounding algorithm including the ionospheric threat model, the use of the single frequency SBAS would increase as a primary mean and also as a backup system for a future dual frequency-based CAT-I operational system. Thus, it is necessary to study methodologies of improving each element of the ionospheric correction and integrity bound algorithm in order to improve the Korean single frequency SBAS performance.

As described above, there are two major challenges to the ionospheric correction and error bounding algorithm design for the Korean SBAS. First, due to formation of reference stations in the small territory, the number and the coverage of the ionospheric measurements obtained from those reference stations are limited. Second, since Korea is located in lower geomagnetic latitude than that of the CONUS region, the effects of the ionospheric phenomena that are rarely observed in the CONUS region could be continuously observed in Korea. These ionospheric phenomena include equatorial anomaly (Saito & Fujii 2010) and plasma bubble (Maruyama et al. 2013). However, the conventional GIVE algorithm was developed based on the historical observation of the ionospheric activities over the CONUS region. Thus, this section suggests several areas that should be revisited for the development of the ionospheric correction and error bounding algorithm to improve the performance of the Korean SBAS, as described below.

The number of the ionospheric measurements used in the planar fit method (Walter et al. 2000) or Kriging method (Blanch 2002, 2003) not only has a direct effect on the formal estimation error but also affects the ionospheric irregularity detector trip rate. In particular, when the number of the ionospheric measurements is insufficient to perform a reasonable fit, the irregularity detector is frequently tripped despite the nominal ionospheric conditions. Such false alarm of the irregularity detector results in degradation of the nominal performance of the SBAS. Therefore, a study needs to be conducted on the design of the IPP search parameters by considering that a small number of ionospheric measurements are available in the Korean region. Along with the consideration on the number of reference stations, a study on determining a trip threshold of the irregularity detector is also needed in order to reduce a false alarm rate of the irregularity detector.

The performance of the irregularity detector varies depending on the number of the ionospheric measurement as well as the accuracy of the ionospheric delay estimation (Sparks et al. 2011b). When the accuracy of the delay estimation increases, the formal estimation error may decrease and the false alarm rate of the irregularity detector may also decrease (Sparks et al. 2011b). Thus, if the Kriging method (Blanch 2002, 2003) is applied to estimate the vertical ionospheric delay at IGPs, better system availability is expected in comparison with the planar fit-based algorithm.

Next, unlike the ionosphere over the CONUS region, the ionosphere in the region of Korea may include local ionospheric irregularities caused by equatorial anomaly (Saito & Fujii 2010) or plasma bubble (Maruyama et al. 2013). These local ionospheric phenomena may increase the uncertainty of ionosphere modeling. Therefore, it is required to define a σ_{decorr}^{nom} value reflecting the ionosphere in the region of Korea by performing a nominal ionospheric decorrelation analysis (Hansen et al. 2000a, Sakai et al. 2004). In addition, it is necessary to study a method of applying the σ_{decorr}^{nom} value in a different manner according to the phase of the ionospheric activities in the Korean region.

As described above, the ionospheric threat model, which is another contribution to the GIVE computation, is defined in the threat metric (i.e., Rfit and RCM) domain. If the threat metric fails to characterize the geometries of IPPs at which ionospheric measurements are used for ionospheric delay estimation, an excessively conservative $\sigma_{undersampled}$ value may be applied to the GIVE computation. Thus, to reduce the unnecessarily large contribution of the threat model to the GIVE value, a threat metric which accurately characterizes the IPP distribution needs to be developed. In addition, as mentioned in Section 3.3, an oversampling method (Sakai et al. 2008) needs to be introduced, considering the insufficient number of reference stations in Korea.

6. CONCLUSIONS

This paper discussed several factors that should be taken into consideration for the development of the ionospheric correction and integrity bound algorithm of the Korean SBAS. First, the key elements of the conventional SBAS ionospheric correction and error bounding algorithm were discussed. On the basis of the analysis, factors which should be considered to improve the availability of the Korean SBAS are suggested as follows:

- Improvement of ionospheric delay estimation and fitting method (including Kriging algorithm)
- Selection of IPP search parameters by considering the insufficient number of reference stations in Korea
- Design of the irregularity detector by considering the insufficient number of reference stations in Korea
- Determination of a nominal ionospheric decorrelation

value reflecting the ionospheric conditions in the region of Korea

- Construction of an ionospheric threat model that covers ionospheric irregularities in the Korean region and development of threat model metric that precisely identifies characteristics of IPP geometries

In addition, further works needs to be conducted to perform the simulation to which the analytical results of this paper may be applied. Through the simulation, the effect of the individual analytical results on the accuracy, integrity, and availability of a single frequency-based SBAS should be analyzed to verify the suggestions described above. This work would be useful for the design of the Korean SBAS architecture if deployed in the future.

ACKNOWLEDGMENTS

This work has been supported by National GNSS Research Center program of Defense Acquisition Program Administration and Agency for Defense Development.

REFERENCES

Altshuler, E., Cormier, D., & Go, H. 2002, Improvements to the WAAS ionospheric algorithms, Proceedings of the 15th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2002), Portland, OR, Sep. 2002.

Bang, E., Lee, J., & Lee, J. 2013, Construction of undersampled ionospheric threat model for preliminary assessment of SBAS availability in the Korean region, in proceedings of the Korean GNSS Society Conference, Jeju island, Nov. 2013.

Blanch, J. 2002, An Ionosphere Estimation Algorithm for WAAS Based on Kriging, Proceedings of the 15th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2002), Portland, OR, Sep. 2002.

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

Cormier, D., Altshuler, E., & Shloss, P. 2003, Providing Precision Approach SBAS Service and Integrity in Equatorial Regions, Proceedings of the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS/GNSS 2003), Portland, OR, Sep. 2003

Cressie, N. A. C. 1993, Statistics for spatial data, revised ed. (New York: John Wiley)

Hansen, A., Peterson, E., Walter, T., & Enge, P. 2000a, Correlation Structure of Ionospheric Estimation and Correction for WAAS, in proceedings of ION NTM, Anaheim, CA, Jan. 2000

Hansen, A., Walter, T., Blanch, J., & Enge, P. 2000b, Ionospheric Spatial and Temporal Correlation Analysis for WAAS: Quiet and Stormy, in proceedings of ION GPS, Salt Lake City, UT, Sep. 2000

Maruyama, T., Ma, G., & Tsugawa, T. 2013, Storm-induced plasma stream in the low-latitude to midlatitude ionosphere, J. Geophys. Res. Space Physics, 118, doi:10.1002/jgra.50541

Pandya, N., Gran, M., & Paredes, E. 2007, WAAS Performance Improvement with a New Undersampled Ionospheric Gradient Threat Model Metric, Proceedings of the 2007 National Technical Meeting of The Institute of Navigation, San Diego, CA, Jan. 2007

Saito, S. & Fujii, N. 2010, Impact of the low ionosphere disturbances on GNSS studied with a three-dimensional ionosphere model, ENRI International Workshop on ATM/CNS (EIWAC), Tokyo, Japan, Nov. 2010

Sakai, T., Matsunaga, K., Hoshinoo, K., & Walter, T. 2004, Evaluating Ionospheric Effects on SBAS in the Low Magnetic Latitude Region, Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2004), Long Beach, CA, Sep. 2004

Sakai, T., Matsunaga, K., Hoshinoo, K., & Walter, T. 2008, Modeling Ionospheric Spatial Threat Based on Dense Observation Datasets for MSAS, Proceedings of the 21st International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2008), Savannah, GA, Sep. 2008

Sarma, A. D., Ratnam, D. V., & Reddy, D. K. 2009, Modeling of Low-latitude Ionosphere Using Modified Planar Fit Method for GAGAN, IET Radar, Sonar & Navigation, 3, 609-619

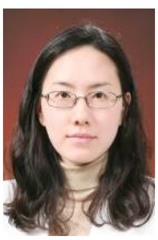
Sparks, L., Komjathy, A., & Mannucci, A. J. 2005, Extreme Ionospheric Storms and Their Impact on WAAS, Ionospheric Effects Symposium 2005, Alexandria, VA, 3-5 May 2005

Sparks, L., Blanch, J., & Pandya, N. 2011a, Estimating ionospheric delay using kriging: 1. Methodology, Radio Sci., 46, RS0D21, doi:10.1029/2011RS004667

Sparks, L., Blanch, J., & Pandya, N. 2011b, Estimating ionospheric delay using kriging: 2. Impact on satellite based augmentation system availability, Radio Sci., 46, RS0D22, doi:10.1029/2011RS004781

Walter, T., Hansen, A., Blanch, J., Enge, P., Mannucci, T., et al. 2000, Robust Detection of Ionospheric Irregularities, Proceedings of the 13th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2000), Salt Lake City, Utah, 19-22 Sep. 2000

Eugene Bang received his B.S. in Aerospace Engineering from Korea Aerospace University in 2010 and received M.S. in the Department of Aerospace Engineering from Korea Advanced Institute of Science and Technology (KAIST) in 2012. He is currently a Ph.D. student in the Department of Aerospace Engineering at KAIST. His research interests include GNSS augmentation system and Receiver Autonomous Integrity Monitoring (RAIM).



Jiyun Lee is an Associate Professor in the School of Mechanical Aerospace and Systems Engineering at Korea Advanced Institute of Science and Technology. She has supported the GBAS and SBAS program over the past six years as a consulting professor at Stanford University and a Principal GPS Systems Engineer at Tetra Tech AMT. She received her B.S. degree from Yonsei University, M.S. degree from the University of Colorado at Boulder, and her Ph.D. from Stanford University (2005) in aeronautics and astronautics. Prior to joining AMT, she worked for SiRF Technology, Inc. as a Senior GPS systems engineer.