INTERNATIONAL CIVIL AVIATION ORGANIZATION
ASIA AND PACIFIC OFFICE

GBAS safety assessment guidance
related to anomalous ionospheric conditions

Edition 1.0 – September 2016
Adopted by APANPIRG/27

Intentionally left blank

Records of amendments

Amendment Number	**Date**	**Amended by**	**Comments**

TABLE OF CONTENTS FOR GUIDANCE ON GBAS THREAT MODEL

Introduction

1.1. GBAS and its fundamental principles

GNSS (Global Navigation Satellite System) is expected to support seamless and flexible aircraft guidance in all flight phases. However, the current GNSS lacks safety performances to support precision approaches because it does not have any functions to timely detect its failure and alert it to aviation users. ICAO defines safety requirements for navigation system as accuracy, integrity, availability and continuity for each flight phases, which are en-route, terminal, non-precision approach (NPA) and precision approach in Annex 10 to the Convention International Civil Aviation [1]. To satisfy the requirements, three types of GNSS augmentation systems are introduced. Ground-Based Augmentation Systems (GBAS) is one of them and its SARPs (Standards And Recommended Practices) are defined in the Annex 10.

GBAS is a navigation system to support aircraft precision approach and landing. SARPs for CAT-I precision approach has been effective since 2001, and ones for CAT-III (GAST-D; GBAS Service Type D) is now under the final validation [2, 3]. GBAS is based on the "local" differential positioning method which subtracts common error components from each GNSS ranging source signals received at a user's onboard system. The GBAS ground subsystem generates differential correction and integrity messages from three or more (usually four) sets of ground GNSS antenna and receivers (see Figure 1). As major error sources, it is well known that there are satellite ephemeris and clock errors, propagation delays due to the ionosphere and troposphere, where the refractivity is more than one. It is important that these remaining errors in each ranging source after the correction are increased in accordance with distance from the GBAS ground subsystem, namely the centroid of the ground GNSS receivers. Multipath effects are also an error factor for GNSS differential technique on both ground and aircraft that do not increase with distance. However, they can be reduced by averaging measurement data of ranging sources among the multiple ground receivers.

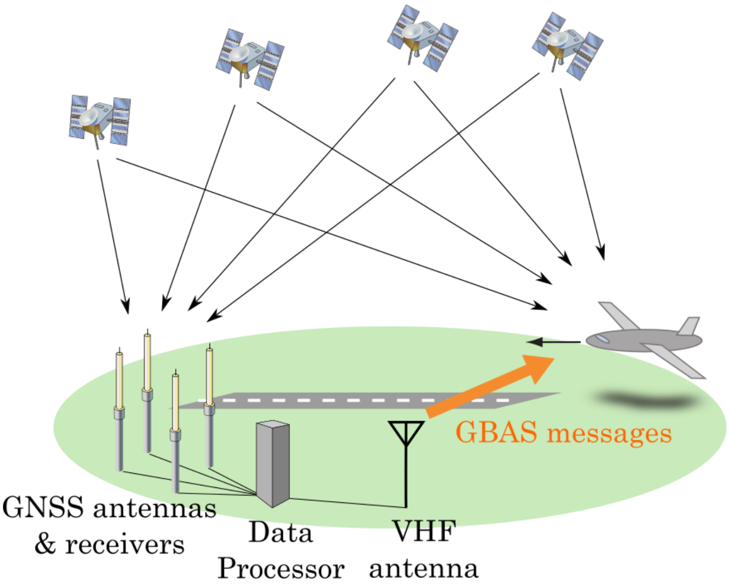

Figure 1. GBAS outline

Because it is necessary for an operational GBAS ground subsystem to meet the extreme safety requirements defined by the SARPs in Annex 10, its validation only by monitoring continuous run behavior is not enough for operational approval. Service provider has to prove the system is enough safety to meet the safety requirements, and each country or regional regulator has to judge whether it satisfies them or not.

1.2. Scope: GBAS threat model to mitigate anomalous ionospheric conditions

Although GBAS is designed to subtract common error components, spatial decorrelation of ionospheric propagation delay is one of error sources for GBAS precision approaches as mentioned the above. Namely, effects of GBAS correction for ionospheric delay are worse at far points from GBAS ground station than near. Therefore, GBAS takes its effects into account as evaluation parameters, which are broadcasted from ground subsystem to airborne, to be used for calculation reliability of user's final positioning solution. In other words, GBAS protect users from the spatial decorrelation effects of ionospheric delay under "nominal" condition within a certain range that is covered by the evaluation parameters. However, a large spatial changes of ionospheric delay which exceed the range assured by the broadcasted evaluation parameters cloud cause loss of integrity. Figure 2 shows an example scenario of ionospheric delay anomaly, which cannot be detected by GBAS ground subsystem. GBAS ground subsystem should protect users from any ionospheric anomaly in a case of CAT-I approach service in contrast to CAT-III (GAST-D), which requires ionospheric anomaly monitors onboard in addition to ground subsystem.

Although a system is safer with consideration of more ionospheric anomalous cases and scenarios, there should be an appropriate safe level enough to meet the targeted requirements. An ionospheric threat model is used to analyze and evaluate impacts of the ionospheric effects on GBAS. The threat model is developed based on ionospheric effects on GBAS considering actual ionospheric characteristics. It also describes threat space for safe GBAS design such as ranges of related parameters to consider. Using the threat model, it is required to evaluate users' remaining integrity risk including simulation analysis. If GBAS could not protect users with a targeted safe level against all possible cases, it is also needed to develop mitigation methods to satisfy the requirements. An integrity monitor to detect and exclude anomalous ranging source affected by ionospheric disturbances is one of such mitigation methods. Because GBAS safety requirements not only integrity but also continuity, required performances of an integrity monitor contain a false alert rate as well as a missed detection rate. Note that decrease in available ranging sources due to satellite exclusion by integrity monitor degrades system availability. Thus, the ionospheric threat model is used for evaluation of impacts, development of mitigation method and validation of the final performances. It is important to develop ionospheric threat model appropriate and enough for safe system design [4].

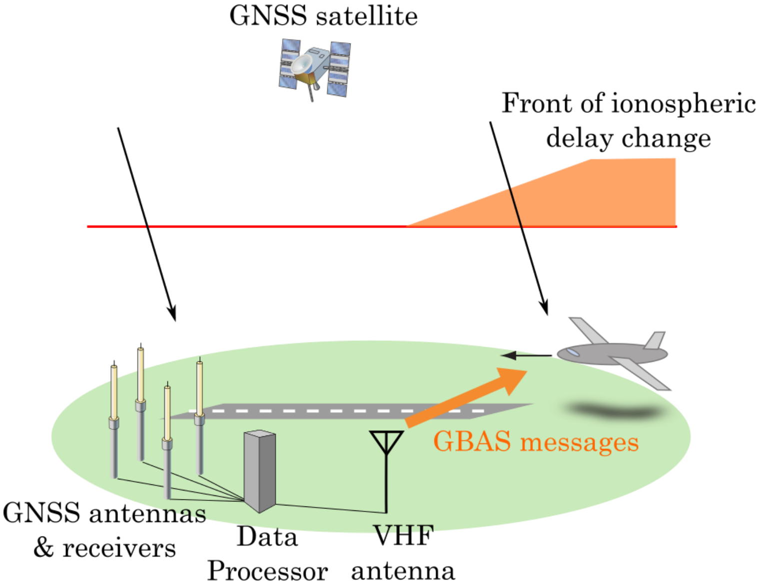

Figure 2. An example scenario of ionospheric delay anomaly for GBAS.

1.3. Ionospheric effects on GBAS

1.3.1. Propagation delay

In GBAS, the application of differential corrections by users almost completely removes ionospheric delay under nominal condition. However, range errors due to ionospheric delay can become significant if there is a large spatial gradient between ground station and user. If this gradient is large enough, it can create a large differential error (e.g., greater than 1 meter) in between the several kilometers separating the ground system and users. This error is increased through "carrier smoothing”, where carrier-smoothed pseudorange is calculated using changes in the carrier-phase measurement to reduce the random noise in the code measurement [5]. This process increases ionospheric range error because the ionosphere delays code pseudorange, whereas it advances carrier phase. Because the absolute magnitudes of both effects are almost the same, ionospheric error almost doubles in carrier-smoothed code under steady-state conditions. Also, the “memory” in this filter extends the effective separation between ground station and user by a quantity roughly equal to the distance the user aircraft moves horizontally (toward the ground station) over two smoothing time constants. As mentioned above, the following equation gives us a typical magnitude of ionospheric range error δI in slant direction under steady-state conditions:

$$\delta I \cong \frac{dI}{dx}\,(x + 2\,\tau\,v)$$

, where x, dI/dx, τ and v are separation distance between aircraft and ground station along approach direction, ionospheric delay gradient, a time constant of carrier smoothing filter and aircraft velocity, respectively. For example, a large ionospheric delay gradient of 425 mm/km could produce a range error of about 8.5 meters in a case that a point of CAT-I decision height (DH) is 6 km away from GBAS ground station [4].

1.3.2. Scintillation effects

It is known that active ionosphere often causes scintillation effects which disturbs power and phase of GNSS signals. The strong scintillation sometimes causes loss of lock on GNSS signals from multiple satellites simultaneously. The GBAS is not a countermeasure against scintillation and users should be aware that availability and continuity of navigation may be degraded due to scintillation effects. A useful guidance is: 'Guidance material on scintillation measurements', ISTF/3-WP/9 [6].

2. Ionosphere conditions to consider for GBAS safety analysis

2.1. Overview of relationship between GBAS safety assessment and ionospheric conditions

GBAS protects users under "nominal" or “typical” ionosphere conditions by differential correction messages and an evaluation parameter for ionospheric error (σ_{iono}), which is derived from the broadcast parameter σ_{vig} (sigma vertical ionospheric gradient). However, it is required to account for anomalous ionosphere conditions in GBAS ground subsystem safety design. Anomalous conditions are those that generate spatial gradients that are larger than 6 times the value of σ_{vig} after converting σ_{vig} from vertical (zenith) to slant gradients (i.e., multiplying by the satellite-elevation-dependent “obliquity factor” given by the RTCA LAAS MOPS, DO-253C [7]). Under anomalous ionospheric conditions, positioning errors larger than the computed protection levels may occur, where these user-computed protection levels indicate upper bounds of user positioning error for lateral and vertical directions derived from evaluation parameters broadcast in GBAS messages [8, 9]. To mitigate this ionospheric threat on GBAS, it is necessary to detect and exclude the affected ranging sources at GBAS ground stations or to adjust the parameters broadcast by GBAS to reflect possible anomalies. Therefore, it is important to evaluate both nominal and anomalous conditions for a safe system design against ionospheric effects.

2.2. Nominal conditions bounded by PL (protection level)

Regarding nominal conditions, the equatorial anomaly is a dominant factor in determining background ionospheric conditions in the low magnetic latitude region. Ionospheric delay dynamically changes during both day time and night time. It has seasonal variation, with spring and autumn being more active seasons. It also depends on solar activity, which has a cycle of about 11 years [10]. These effects should be covered by the parameter σ_{vig} broadcast by GBAS, although the details depend on the approach to system safety design. In general, σ_{vig} should be determined to bound a large population of observed data [11]. Note that an analysis limited to observational data collected during low solar activity period could lead underestimation of the appropriate value of σ_{vig} during more active periods.

2.3. Anomalous conditions and ionospheric disturbances to consider

2.3.1. Storm enhanced density

Storm Enhanced Density (SED) is an extreme ionospheric density enhancement associated with severe magnetic storms. It generally occurs in mid- to high latitude regions, and its occurrence rate is relatively rare [12].

2.3.2. Plasma bubble

Plasma bubble phenomenon is another type of disturbance that can be summarized as a depletion (rather than enhancement) of ionospheric density relative to the surrounding environment. It has a structure spread along the North-South direction and can produce steep ionospheric spatial gradients and scintillation on GNSS signals [13,14]. It frequently occurs after sunset in high solar activity periods. In the Asia Pacific (APAC) region, its frequency of occurrence is most frequent during equinox seasons from March to April and from September to October.

2.3.3. Other

It is known that there are several phenomena with spatial ionospheric gradients such as TID (Traveling Ionospheric Disturbance) and disturbances in sporadic E layer. However, these phenomena do not produce significant effects on GBAS because of their variation amplitude including spatial scales.

2.4. Ionospheric threat model for GBAS safety analysis

The definition of an ionospheric threat model that includes all possible ionospheric anomaly conditions is required for a safe system design. An ideal threat model should satisfy a necessary and sufficient condition for ionospheric effects on GBAS. Note that underestimation of the threat model bounds might expose users to unmitigated (and therefore unsafe) conditions, whereas overestimation of these bounds may degrade system availability. An Ionospheric front is a model with an ionospheric spatial gradient, and is referred as wedge model [15]. The model enables us to perform quantitative analysis on range error impacted by ionospheric disturbances. Moreover, the model is required to find the worst case because an induced range error depends on not only ionospheric delay spatial gradient but also geometrical relationship among aircraft, ground station, ionospheric front and GNSS satellite path on equivalent ionospheric layer. The primary parameters of the ionospheric flront model are summarized as four parameters, which are spatial gradient, front moving speed, width and drop. The last parameter means the maximum ionospheric delay difference of ionospheric front, and it is also given by combination of upper bounds for both spatial gradient and width [16]. Ddefinition of the ionospheric front model is important to describe threat space for GBAS safe system design.

2.5. Evaluation of requirements and performance, including integrity monitoring

Because ICAO SARPs defines safety requirements of integrity and continuity for GBAS ground subsystem together with accuracy and availability, it is important to evaluate ionospheric anomaly impacts on such requirements with the ionospheric threat model. For example, integrity requirement is defined to assure user's safety for any approach. In order to satisfy the requirements, it is needed to implement appropriate mitigation methods for ionospheric anomaly if it causes Hazardous

Misleading Information (HMI) for GBAS users. In general, integrity monitors to detect and exclude fault satellites are simple methods to mitigate ionospheric threat. However, it is notable that false alarm in the mitigation degrades continuity performance. Because integrity and continuity risks is not only ionospheric anomaly, it is required to allocate a targeted level for each risk through GBAS safety design to satisfy the requirements in total system. This risk allocation depends on each GBAS system including threat models for integrity risks. For issues on ionospheric anomaly, allocated target is converted to performance requirement for each integrity monitor in system design. Finally, total of remaining risk should be less than the targeted level.

2.5.1. Ranging errors induced by ionospheric anomaly

Because estimated user's range error is different among various scenario with the four parameters, it is important to identify ranges for the four parameters to cover actual conditions with a certain safety margin and find the worst case scenario. Simulation analysis provides ranging errors induced by ionospheric anomaly using defined wedge model [8].

2.5.2. Positioning errors in the final implementation

Regarding CAT-I GBAS, because ground subsystem has to evaluate not only user’s ranging source errors but also their final positioning errors, it performs a kind of position domain monitoring in real time called geometry screening in addition to integrity monitors for ranging source anomalies [16,17,18]. Geometry screening is based on “potential” remaining ranging source error using the threat model and it validates various satellite geometry subsets which include impacted satellites. Since GBAS parameters are set against potential error based on threat model, the system availability also depends on threat model. To reduce potential remaining ranging source error, far filed monitor is one of solutions [19].

2.6. Other important descriptions

2.6.1. Except the four parameters of the ionospheric front model, there are some important parameters originated form characteristics of each ionospheric disturbance. For examples, locations, dominant season and/or time, occurrence rate and number of impacted satellites are key parameters. Using these characteristics, it is capable to construct threat models with certain flexibilities.

3. Development and validation of the threat model

The development and utilization of the ionospheric threat model occurs in two stages. The first stage is observation, in which data accumulated over a lengthy period is collected to describe and cover the features of ionospheric impacts on GBAS. The results of observation are used to estimate the bounding parameters of the threat model. The second stage is simulation, in which the completed threat model is used in a simulation of GBAS ground station and user operation. The user errors resulting from these simulations provide a basis for estimating the GBAS integrity risk and determining the impacts of changes to the ground and airborne monitors.

3.1. Observation stage

In the observation stage, networks of GNSS stations located close together (e.g., within 10 to 50 km) are needed. Each observation is based on the difference in ionospheric delays between two nearby GNSS stations. In the case of dual frequency measurements for estimating ionospheric delay, inter-frequency biases must be corrected before ionospheric delay differences can be calculated.

It is well known that the error component of the estimated gradient increases in short baseline analysis because the gradient is calculated from difference of ionospheric delay divided by the baseline length (separation between stations) [11]. Moreover, where possible, the baseline length should be comparable with or smaller than the spatial scale of disturbances. Because SEDs are related to magnetic storms, data filtering based on indices caused by magnetic storms are useful for extraction of events, meaning identifying the times when large gradients are most likely to occur [15,20]. Plasma bubbles are created by different ionospheric mechanisms. Therefore, such index parameters are not enough to extract events, but local time filtering remains useful because plasma bubbles occur during local nighttime. Solar activity with a period of about 11 years is also an important factor for observation-based approach. To the degree possible, measurements should be taken near to the peak of this cycle (maximum solar activity)and in the several years following it, as the largest gradients are likely to occur during this period.

3.1.1. Tools like LTIAM (Long Term Ionospheric Anomaly Monitor)

It is important to construct database for safety analysis maintaining their compatibility and qualities through long term monitoring of ionospheric anomalies [20]. A LTIAM tool has been developed and used for the analysis [21]. The tool enable us to search events and extract important parameters for ionospheric threat mode. One of the advantages to use such a tool is to maintain the same quality for data process. Cross validation is also important issues and there is another evaluation tool based on Single Frequency Carrier Based Code-Added (SF-CBCA) measurement [22]. This tool requires only single frequency measurement data.

3.1.2. Time Step method

In general, ionospheric gradients are calculated from measurement data with a pair of station with appropriate baseline length to targeted ionospheric disturbances. However, time step method is also useful as an alternative method to station pair analysis especially for regions without dense GNSS networks with consideration on its characteristics [11].

3.2. Simulation approach

In order to translate ionospheric threat model bounds into GBAS errors, simulations of GBAS ground station and user operations (e.g., airborne precision approaches) are required. In these simulations, the threat model is used to construct anomalous distributions of electron density according to the “front” or “wedge” model described in Section 2.6 above. As this front and approaching aircraft both move relative to the (static) ground station and the orbiting GNSS satellites, the impact of the ionospheric anomaly on ground measurements, user measurements, and ground and user monitor algorithms are recorded and evaluated. At the end of each approach simulation, the differential range and position errors along the approach can be evaluated with respect to the integrity requirements for that operation. If one or more monitors would have detected the anomalous ionospheric conditions prior to the occurrence of hazardous errors, those errors would have been mitigated by the exclusion of the affected GNSS satellite.

3.2.1. Three dimensional analysis

The ionospheric front model is based on two dimensional plan. However, actual distribution of electron density in ionosphere is more complicated. Therefore, it was pointed out that data analysis of SED with satellite signals from low elevation angle [23], simulation analysis concerning plasma bubble [24].

3.3. Validation

Threat model should cover observational and simulation results with appropriate safety margin.

4. Post-implementation activities

Because safety management requires monitoring and improvement even after implementation, long term validation of ionospheric threat model has to be addressed. This means that additional observation data should be collected and analyzed over time after the establishment of the original threat model. Through this process, there are possibilities not only to find new ionospheric events outside the original threat model but also to reduce threat space with improved safety margin (e.g., if later observations suggest that the original bounds were too conservative). Solar cycles with different levels of maximum activity are also an important viewpoint, considering the fact that dense networks of GNSS continuous stations have only been deployed since the solar peak around 2000.

4.1. Monitoring of ionospheric activity

For long-term monitoring, it is important to consider solar cycle of about 11 years with consideration of characteristics of the targeted ionospheric disturbances. Additionally, information on occurred events are very important and useful for search similar events over neighbor area. Such an event list gives candidate dates for another area.

4.2. Maintenance of threat model

There are two view points. The one is to search new events which are not covered by the current threat model. Another is reconsideration of safety margin.

5. References

[1] International Civil Aviation Organization, Annex 10 to the Convention on International Civil Aviation, Volume I, Radio Navigation Aids, Amendment 89, Applicable: 13 November 2014.

[2] ICAO/NSP WGW May 2010 Report – Attachment G, MSP May 10 / Flimsy 29, Navigation Systems Panel (NSP) Working Group of the Whole Meeting, Montreal, 17-28 May 2010, Agenda

Item 3: SARPs for GNSS Elements and Signals (GBAS), Development Baseline SARPs Proposal, Presented by Tim Murphy and Stefan Naerlich.

[3] ICAO/NSP WGW Nov 2009 Report – Attachment D, NSP Nov 09 / Flimsy6, Navigation Systems Panel (NSP) Working Group of the Whole Meeting, Montreal, 8-18 Nov 2010, Agenda Item 3: SARPs for GNSS Elements and Signals (GBAS), Conceptual Framework for the proposal for GBAS to Support CAT III Operations, Presented by CSG Rapporteur.

[4] S. Pullen et al., "The Impact and Mitigation of Ionospheric Anomalies on Ground-Based Augmentation of GNSS", *Radio Sci.*, 44, RS0A21, doi:10.1029/2008RS004084, 2009.

[5] J. Christie et al., "Analytical and Experimental Observations of Ionospheric and Tropospheric Decorrelation Effects for Differential Satellite Navigation during Precision Approach", Proc. the ION GPS, pp.739-747, Sept., 1998.

[6] ISTF/3-WP/9 Guidance material on scintillation measurements

[7] Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment, RTCA/DO-253C, December 16, 2008.

[8] M. Luo et al., "Ionospheric Spatial Gradient Threat for LAAS: Mitigation and Tolerable Threat Space", Proc. of the ION NTM 2004, pp 490-501, Jan., 2004.

[9] M. Luo et al., "LAAS Study of Slow-Moving Ionosphere Anomalies and Their Potential Impacts", Proc. ION GNSS 2005, pp.2337-2349, Sept. 2005.

[10] T. Yoshihara et al., "A Study of Nominal Ionospheric Gradient for GBAS (Ground-based Augmentation System) in Japan", proc. ION GNSS 2010, Sept. 2010.

[11] J. Lee et al., "Assessment of Nominal Ionosphere Spatial Decorrelation for LAAS", Proc. IEEE/ION PLANS 2006, pp.506-514, Apr. 2006.

[12] Pullen et al., "Prior Probability Model Development to Support System Safety Verification in the Presence of Anomalies", Proc. IEEE/ION PLANS, pp.1127-1136, Apr. 2006.

[13] T. Yoshihara et al., " Preliminary Analysis of Ionospheric Delay Variation Effect on GBAS due to Plasma Bubble at the Southern Region in Japan" Proc. of NTM 2007, pp. 1065-1072, San Diego, CA, January 2007.

[14] S. Saito et al., "Development of an Ionospheric Delay Model with Plasma Bubbles for GBAS," Proceedings of the 2009 International Technical Meeting of The Institute of Navigation, pp. 947-953, Anaheim, CA, January 2009.

[15] A. Ene et al., "A Comprehensive Ionosheric Storm Data Analysis Method to Support LAAS Threat Model Development," Proc. ION NTM 2005, pp.110-130, Jan. 2005.

[16] J. Lee et al., "Position-Domain Geometry Screening to Maximize LAAS Availability in the Presence of Ionosphere Anomalies", Proc. ION GNSS 2006, pp., Sept. 2006.

[17] S. Ramakrishnan et al., "Targeted Ephemeris Decorrelation Parameter Inflation for Improved LAAS Availability during Severe Ionosphere Anomalies," Proc. ION NTM 2008, pp.354-366, Jan. 2008.

[18] J. Lee, J. Seo, Y. Park, S. Pullen, and P. Enge, " Ionospheric Threat Mitigation by Geometry Screening in Ground-Based Augmentation Systems", Journal of aircraft, vol.48, No.4, 2011.

[19] H. Konno et al., “Analysis of Ionosphere Gradient Using Japan GEONET Data”, Proc. ION NTM 2005, pp.1118-1129, Jan. 2005.

[20] K. Lee, et. al, "Long Term Monitoring of Ionospheric Anomalies to Support the Local Area Augmentation System," Proc. of ION GNSS 2010, pp. 2651-2660, Sept. 2010.

[21] M. Kim, et. al, "Data Quality Improvements and Applications of Long-Term Monitoring of Ionospheric Anomalies for GBAS," Proc. of ION GNSS 2012, pp. 2159-2174, Sept. 2012.

[22] S. Fujita et al., “Determination of Ionosphere Gradient in Short Baselines by Using Single Frequency Measurements”, Proc. IGPS/GNSS, pp.439-444, Oct. 2010.

[23] G. Zhang, "Low-Elevation Ionosphere Spatial Anomalies Discovered from the 20 November 2003 Storm", Proc. of ION ITM 2007, Jan. 2007.

[24] S. Saito et al., “Study of Effects of the Plasma Bubble on GBAS by a Three-Dimensional Ionospheric Delay Model”, Proc. ION GNSS 2009, pp.1141-1148, Sept. 2009.

[25] S. Saito, "Three-dimensional ionospheric delay model with plasma bubbles for GBAS", I-GWG meeting, WS3.4, Palo Alto, CA, Nov. 2009.

[26] C. Mayer, et. al, "Ionosphere Threat Space Model Assessment for GBAS", Proc. of ION GNSS 2009, Sept. 2009.

6. Annexes

6.1. CONUS model

CONUS model is described in [4].

6.2. Safety analysis for GBAS prototyping in Osaka

Ionospheric threat model is described in [25]

6.3. Other

Ionospheric threat model analysis is performed in such as [26].