INTERNATIONAL CIVIL AVIATION ORGANIZATION
ASIA AND PACIFIC OFFICE

SBAS safety assessment guidance related to anomalous ionospheric conditions

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Records of amendments

Amendment Number	Date	Amended by	Comments

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Chapter 1 Introduction

1.1 Background

1.1.1 GNSS is today widely used for civil aviation and GNSS-based operations with additional efficiency and flexibility are being implemented. A major advantage of GNSS, in comparison with conventional navaids, might be its accuracy and compactness; Users need only a small receiver set to have their accurate positions.

1.1.2 It is important to recognize that many error sources could affect GNSS. Among them, the ionosphere, existing at 300-400km above the ground, is a major error source which is not corrected enough by the GNSS core constellation. Invisible radio signals from GNSS space elements are affected by the ionosphere during propagation and thus have ranging delays.

1.1.3 A function of the augmentation system, including SBAS, is to provide users with better ionospheric corrections based on real time observation of ionosphere to improve position accuracy as well as availability of the system. Various ionosphere models, both theoretical and empirical, have been developed to provide information on ionospheric activities and ranging delays. Augmentation systems need to generate ionospheric corrections meeting integrity requirements.

1.1.4 The most important feature of an augmentation system for civil aviation is to provide position information with the integrity required for the intended operation. In other words, integrity is an essential element of an SBAS safety case, which must be met anytime and anywhere in the service area. A common application is the use by aircraft of GNSS-based vertical guidance to conduct RNP APCH operations down to LNAV/VNAV minima (LPV approach).

1.1.5 As per ICAO Document 9613 (PBN Manual), Part C, Chapter 5, Section B relating to RNP APCH operations down to LP and LPV minima, the State must verify that the augmented GNSS system and that the service provider of the GNSS system, used to support RNP APCH operations, are approved according to the appropriate regulation. ICAO Document 9849 (GNSS Manual), Section 1.5 also notes that by approving GNSS operations, a State accepts responsibility to ensure that such operations can be completed safely. Thus the responsible airspace authority should assess the integrity of the SBAS system in particular before its use by LPV procedures in the intended service area.

1.1.6 In such an activity, ionosphere is a potential problem because its behavior depends upon many factors such as user location, local time, season of year, and solar activity. As a matter of fact, typical errors experienced due to anomalous ionospheric propagation can be 5-10 meters in vertical guidance, which constitute severe operational hazards particularly when they occur in the final approach segment. In this connection it is recognized by ICAO Doc 9613 that at some airports, it may not be possible to meet the requirements to publish an approach procedure with LPV vertical guidance. This may be due to the inability of SBAS to provide the desired availability of vertical guidance (i.e. an airport located on the fringe of the SBAS service area).

1.1.7 Generally an SBAS system should be validated to ensure that it meets ICAO Annex 10 requirements, including integrity requirements for operations within the airspace of the responsible airspace authority, but may not meet those requirements outside the airspace. Therefore any previous activity conducted for another airspace may not be valid enough for the intended airspace. Considering that the Asia Pacific Region is diagnosed with a number of anomalous ionospheric phenomena, this activity should contain an evaluation of the magnitude of error due to irregularity of ionosphere.

1.1.8 Where there is no standardized process to assess the ionospheric error, the present document can provide further guidance.

1.2 Purpose and scope of this document

1.2.1 The purpose of this document is to provide guidance to evaluate ionospheric error in use of the current (single-frequency) SBAS as a part of integrity assessment. States might use information of this document for:

(i) approval of SBAS system implemented by the State itself;
(ii) approval of an SBAS service provider operating from another State; or
(iii) assessment of GNSS SBAS vertical guidance availability.

1.2.2 Disclaimer. Note that this document gives guidance information only and is not a regulatory basis for approval of SBAS system or service provision.

Chapter 2 Overview of GNSS

2.1 Overview of GNSS

2.1.1 As per ICAO Document 9849 (GNSS Manual), the concept of GNSS means the system consisting of core constellations, augmentation systems, and GNSS avionics (user receivers). Core constellation are GPS and GLONASS operated by the United States of America and the Russian Federation, respectively.

2.1.2 Each core constellation has 24-32 ranging satellites orbiting around the Earth. Such ranging satellites are broadcasting radio signals for navigation use from the space. The typical altitude of the ranging satellites varies from 19,000 to 20,200 km above the ground.

2.1.3 The existing core constellations alone do not meet requirements of ICAO Annex 10 GNSS SARPS. To meet such requirements specific for aviation, core constellations need to be augmented in terms of accuracy and integrity of navigation.

2.1.4 Currently three augmentation systems are standardized by ICAO GNSS SARPS: aircraft-based augmentation system (ABAS), satellite-based augmentation system (SBAS), and ground-based augmentation system (GBAS).

2.1.5 ABAS achieves the required level of integrity only with onboard equipment, while the other two augmentation systems rely upon monitoring by the ground receivers. SBAS transmits augmentation information via geostationary satellite (GEO), while GBAS uses VHF data broadcast (VDB) for communication with user avionics.

2.2 Satellite-Based Augmentation System (SBAS)

2.2.1 Currently there are four SBAS systems in operation: US WAAS (Wide Area Augmentation System), Japanese MSAS (MTSAT-based Satellite Augmentation System), European EGNOS (European Geostationary Navigation Overlay Service), and Indian GAGAN (GPS Aided GEO Augmented Navigation). All SBAS systems are continuously broadcasting augmentation information via GEO (geostationary satellite).

2.2.2 The SBAS system monitors GPS signals by the network of ground stations. For radio signals transmitted from satellites in core constellations, the SBAS master station computes the ranging error and checks health status of signals. Based on the results, it generates correction and integrity information and broadcast them on the SBAS signal via the uplink station.

2.2.3 The SBAS signal is broadcast at the center frequency of 1575.42MHz, same with GPS L1. The onboard avionics receives the SBAS signal via RF antenna and front-end circuit both common with GPS.

2.2.4 The SBAS signal can be received over the coverage area, but the service area is determined for each SBAS as a part of the coverage area. The performance of the SBAS is assured within the service area but might not for the whole of the coverage area.

2.2.5 The SBAS broadcast augmentation information for each ranging satellite per error sources, such as fast correction (FC), long-term correction (LTC), and ionospheric correction (IC) in case of the single-frequency SBAS. FC and LTC represent satellite clock and orbit errors and accompanied by the associated UDRE (user differential range error) parameter. IC consists of vertical delay for correction and GIVE (grid ionosphere vertical error) parameter representing the uncertainty of the correction. Additionally tropospheric correction (TC) is made inside user receivers by applying the tropospheric propagation error model.

2.2.6 IC is given as a set of propagation delays, converted into vertical, at the IGP (ionospheric grid point). IGP is located with the interval of 5 degrees in latitude and longitude for low- and mid-latitude regions and with 10-degree interval at high-latitude regions. Users should apply the appropriate interpolation and vertical-to-slant conversion to broadcast IC in order to obtain the correction added to the measured range. Both interpolation and vertical-to-slant conversion procedures are defined in the GNSS SARPS.

2.2.7 The usage of IC (and GIVE) is mandate for users in operations with vertical guidance, i.e., LNAV/VNAV and LPV operations, while it is optional for users in operations with horizontal navigation only. In fact, some SBAS system is approved only for horizontal navigation.

2.3 Integrity requirements and threats

2.3.1 The requirements in the GNSS SARPS is that the integrity risk is less than 2E-07 in any approach for operations with vertical guidance, i.e., LPV (APV-I in the SARPS).

2.3.2 For the SBAS, the integrity function is implemented by the concept of protection level. The protection level means the upper bound of user position error with the specified integrity risk. The SBAS-capable avionics has capability to compute horizontal and vertical protection levels based on integrity information broadcast from the SBAS.

2.3.3 The integrity risk means the probability that either (or both) horizontal or vertical position error exceeds the associated protection level.

2.3.4 The horizontal and vertical alert limits are defined with dependency upon each operation mode. For SBAS-capable avionics, the integrity is assured by monitoring both horizontal and vertical protection levels are within the associated alert limit. For example, horizontal and vertical alert limits are 40 meters and 50 meters, respectively, for LPV approach mode.

2.3.5 In general, the protection level consists of two essential components: formal and threat terms. The formal term represents the uncertainty of corrections due to measurement noise which can be derived by covariance matrix for estimation. This term also covers nominal errors involved in clock and orbit information in the ephemeris data. The threat term represents the uncertainty due to rare events in non-nominal conditions.
This term is regard to faulty and anomalous events perhaps not observed yet.

2.3.6 Among all GNSS error sources, a non-nominal condition of ionosphere likely makes the largest threat for aviation use. The range error due to fault of the onboard clock can be observed from all ground stations simultaneously and thus detected easily. For the satellite orbit error, non-nominal condition is not likely because GNSS satellites are orbiting under the law of physical dynamics. An exception is the maneuver for maintenance, but this can be predicted and detected by the network of the ground stations. In contrast, in the case of the ionosphere, the imperfection of the observability, because of limited density of the ground stations, causes the possibility of unpredicted variation of an ionospheric propagation delay due to small-scale spatial irregularities and temporal rapid changes of the status of ionosphere.

Chapter 3 Threat Mitigation Strategy Against Anomalous Ionospheric Conditions

3.1 High level principles

3.1.1 Improvement of availability and continuity of the system. The protection level means the upper bound of navigation system error, with the significance level of 1E-07, which reflects uncertainty of position information. The navigation system is available when both horizontal and vertical protection levels are less than the associated alert limits. This means that the reduction of protection levels is needed to improve the availability and continuity of the system.

3.1.2 The smaller the threat space, the better the performance. The protection levels are computed inside user receivers based on the parameters broadcast from the augmentation system. The broadcast integrity parameters provide information about uncertainty of corrections and are derived from two components: nominal uncertainty and margin for anomalous irregularity, i.e., the threat space. The former is associated with the Normal distribution and is not so large, while the latter is a countermeasure against very rare events and constitutes the dominant component of the protection levels. Large threat space (inside SBAS ground facility) yields large protection levels (inside user equipment), thus degrades availability and continuity of the system. As a result it is possible to improve performance of the system (availability and continuity) by employing a smaller threat space.

3.1.3 Usefulness in meeting integrity requirements is an essential characteristic of threat models. The Ionosphere Threat Model is used to meet SBAS integrity requirements. This means safety margin brought in to mitigate possibilities of ionospheric irregularities 'unobserved' (spatially and/or temporarily) from the ground stations. Each existing SBAS has its own ionosphere threat model to generate ionospheric correction information meeting integrity requirements. Each threat model should fit to its own service area. This document is concerned with the threat model for the Asia Pacific Region.

3.1.4 Schemes for ionosphere monitoring to protect airspace users. The behavior of the ionosphere is a natural phenomenon. Thus, the threat model once approved does not assure to overbound the anomalous ionospheric delays forever. This fact calls for an activity, ionosphere monitoring, to be conducted on a regular basis. The ionosphere monitoring shall be an activity similar with creation of the threat model to confirm that the threat space is actually overbounding real ionospheric anomalies.

3.1.5 Scintillation effects. It is known that active ionosphere often causes scintillation effects, which disturb the received power and phase of GNSS signals. Strong scintillation sometimes causes loss of lock on GNSS signals from multiple satellites simultaneously. SBAS is not a countermeasure against scintillation, and users should be aware that availability and continuity of navigation may be degraded due to scintillation effects. Further information is provided in “Guidance Material on Scintillation Measurements,” ISTF/3-WP/9 (Seoul, Korea, Oct. 2013).

3.2 Ionospheric correction by SBAS

3.2.1 SBAS broadcasts information on ionospheric delay for correction. Vertical ionospheric delays on L1 carrier frequency at IGPs are broadcast to users. They are accompanied by integrity parameters called GIVE representing uncertainty involved in the associated ionospheric correction. For each IGP, user receiver expects the vertical delay value on L1 and the associated GIVE index. The detail protocol of ionospheric correction and protection level computation is defined in the GNSS SARPS.

3.2.2 There are some methods for generation of ionospheric correction information inside SBAS. As an example, the algorithm of WAAS/MSAS, so-called ‘planar fit’, is explained in Appendix A.1.

3.2.3 The SBAS shall broadcast estimated ionospheric delay accompanied by the proper GIVE value regardless the ionospheric condition is nominal or non-nominal. This means that the GIVE value shall not be too small to ensure that both horizontal and vertical position errors never exceed the associated protection level, computed based on any combination of effective IC (and GIVE) information, for any users within the service area of the SBAS.

3.2.4 In other words, the GIVE parameter has to be computed with taking account of spatial and temporal threats, which are caused by local and/or short-term irregularities not sufficiently sampled by any ground station. SBAS must protect users against such irregularities.

3.2.5 Inside the SBAS system, in general, the GIVE value fundamentally involves the following terms:

- (i) The formal term due to the measurement noise of delay estimation;
- (ii) A term representing the threat of spatial variations; and
- (iii) A term representing the threat of temporal variations.

3.2.6 Term (i) is dependent upon the estimation methodology employed by the SBAS and the number of measurements made by the network of ground stations. A low-noise measurement environment contributes to the reduction of this term.

3.2.7 Term (iii) is derived from the largest rate of change of ionospheric delay. This term can be predicted well based on statistical analysis over the period of historical observations.

3.2.8 Among the three terms involved in the GIVE value, Term (ii) is the most difficult because the SBAS has to assume the existence of the largest ionospheric irregularities that might not be sampled by any ground station. Here the threat exists.

3.3 Necessity of the threat model

3.3.1 Overbounding uncertainty. The ionospheric vertical delay broadcast from the SBAS unfortunately contains some uncertainty because the estimation by the SBAS is not perfect and the thin shell ionosphere model cannot represent the real ionosphere completely. Thus the ionospheric vertical delay at each IGP is accompanied by the associated GIVE parameter representing uncertainty of estimation.

3.3.2 Even though the GIVE parameter is generated based on statistical processing along with the estimation of the associated vertical delay, there is some possibility, or risk, that the GIVE parameter does not overbound the actual error of the ionospheric vertical delay. This situation is called a ‘threat’.

3.3.3 Spatial and temporal threats. The ionosphere threat model is the actual function representing the associated threat space and is used to meet integrity requirements. This means adding safety margin to mitigate the possibility of the ionospheric irregularities being 'unobserved' (spatially and/or temporarily) by the ground stations, as illustrated in Figure 3-1.

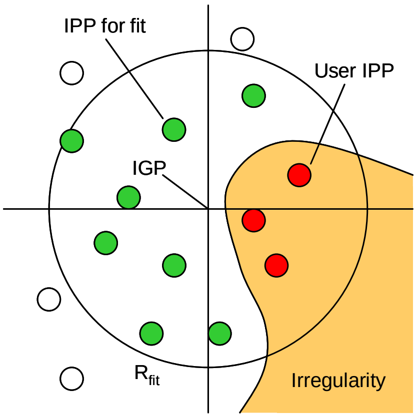


Figure 3-1: Schematic Diagram of Spatial Threat

3.3.4 Example of the spatial threat. In Figure 3-1, white and green plots represent ionospheric pierce points (IPPs) observed from ground stations of the SBAS, while Red plots represent IPPs observed from a user. Green IPPs inside the radius of R_{fit} centered at the IGP are used for the estimation of the status of the IGP. The problem is that the estimation does not reflect the irregularity coming from the right of the diagram, because no reference station observes the irregularity, while the user receiver shown in the figure does experience the irregularity. This situation may cause a large position error due to the irregularity observed by the user but unobserved by the ground stations.

3.3.5 An example of the spatial threat model is given in Appendix A.2. For generation of the spatial threat model, see Appendix A.3.

3.3.6 Operational Hazards related to the ionospheric threats. Operational Hazards or causes of operational hazards are identified as follows:

(1) Mainly, the problem is spatial threats. The threat means local ionospheric irregularities observed by some users, but NOT observed by ground stations. Temporal threats may also be a problem, but we should be able to mitigate this kind of threat with enough archived data.

(2) In general, ionospheric error roughly relates to vertical position error. In approach modes with vertical guidance, an incomplete ionospheric threat model may cause a safety hazard.

(3) Integrity events of operational systems: so far, no integrity events due to ionosphere have been reported by operational SBAS systems. One can check integrity, e.g., if GIVE always overbounds the actual ionospheric error everywhere, using 'Triangle Charts' constructed for this purpose. If integrity is not met, one can increase the magnitude of the threat model. A larger threat model provides more safety margin but results in less availability.

(4) A concern may be 'Plasma Bubble' because, for example, the ionosphere model for some SBAS systems does not explicitly include information about plasma bubbles. It can be interpreted that the effects of plasma bubble events are implicitly bounded by the safety margin embedded in the ionospheric threat model, which might not be the case.

3.3.7 Factors influencing the mitigation strategy. Factors influencing the mitigation strategy are identified as follows:

(1) Observability of ionosphere: The mitigation strategy is influenced (or constrained) by:
  - The number and distribution of ground stations
  - The number of signal sources and the number of core constellations in use
  - The spatially dense observation of the ionosphere, which reduces the spatial threat by improving ionospheric observability
  - The availability of additional ground stations for generation of the threat model since the threat model might be refined if a larger network is available.

(2) Relevance of the ionosphere model used for correction
  - An accurate ionosphere model (with enough observations) reduces the threat.
  - Geometry of the ionosphere model: Is the planar ionosphere model adequate for equatorial regions? What model could better represent equatorial anomalies?

(3) Archive data available for creation of threat model
  - Basically, the threat model is created from the residuals of corrections (meaning the difference between the projected ionospheric delay as corrected by SBAS and the actual ionospheric delay observed separately) with regard to given algorithms and parameters for generation of SBAS ionosphere messages. To compute the residual of corrections, a separate archive of ionospheric delay data for a certain period, ideally a whole solar cycle, is necessary.
  - The quality of the threat model depends upon the period and region of the archive data used. More data makes the threat model more accurate.
  - While a general rule is difficult to establish, following examples of criteria can be useful.
    - ➢ The archive data should be long enough to cover at least one solar maximum period (meaning the peak of the 11-year solar cycle and several years on either side of the peak).
    - ➢ In the USA, data were collected from all GPS satellites on a continuous basis from a network of stations similar to the WAAS reference network.
    - ➢ In Japan, the threat model was established based on observations at 6 MSAS ground stations for some years, including the solar maximum in 2001. The observations

contain storm days with a Kp index greater than 6 as well as nominal days.

- There are some options in the number and density of stations used to generate the threat model.
    - ➢ A network of stations same or similar to the SBAS ground stations.
    - ➢ A network of stations greater than the SBAS ground stations. Dense network is useful to make the threat model accurate and reduce margins.

(4) Implementation issues

- Some SBAS systems are already operational, while others are still in development.
- It should be considered if it is necessary to change the threat model with regard to its use in a specific region, even if the algorithm is the same. It should be noted always that the validity of the threat model is dependent upon the region to which it is applied.
- Also, the threat model is likely to be different for different SBAS ionospheric correction algorithms.

3.4 Creation of the threat model

3.4.1 The ionospheric threat model for the intended region might be created based on historical severe ionospheric storm data. The process should be:

(i) Prepare enough archive data for a certain period for the intended region with dual frequency observations;

(ii) Sort out periods of data that are expected to contain anomalous behavior based on indices of ionospheric and/or geomagnetic behavior, such as Kp and Dst. For example, data in which the worst daily values of Kp w□□□□□□□□ter than 6 and Dst were less than □200 were selected as potentially anomalous in analyzing CONUS data for development of the GBAS threat model [8]. Since SBAS is more sensitive to anomalous ionospheric conditions than is GBAS, somewhat lower thresholds (e.g., worst daily Kp □ 5 and Dst □ □100) might be used for SBAS;

(iii) Compute ionospheric delay measurements by removal of frequency-dependent biases;

(iv) Generate SBAS ionospheric correction and GIVE values, in the form of Message Type 26, based on the SBAS MCS algorithm and parameters;

(v) For the location of each ionospheric delay measurement, compute SBAS correction values based on the contents of Message Type 26 generated during this process;

(vi) The difference between measurement and SBAS correction shows the actual error observed (For example, see Figure 3-2); and

(vii) Accumulate the actual error and take the largest error as the threat - This accumulation might be performed with regard to the appropriate parameters used for generation of ionospheric corrections (Message Type 26), which means that the threat is modeled as a function of the parameters.

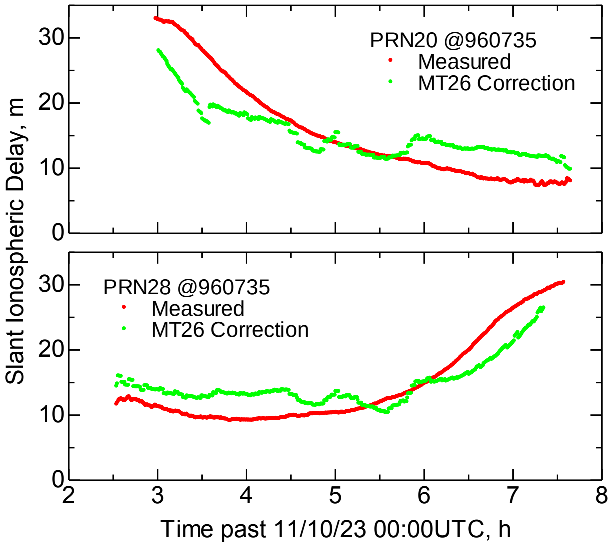


Figure 3-2: Example of Difference between Measurement and Correction

3.4.2 Necessity to archive data for a certain period: for how long? For this purpose, creation of threat model requires archive of GNSS data for a whole solar cycle (11 years), or at least during the latest peak of solar activity. A way to create the spatial threat model available for SBAS is 'data deprivation' (See Appendix A.3).

Chapter 4 Approval of SBAS

4.1 Approval: availability assessment

4.1.1 In general, the use of an augmentation system will involve a regulatory process of approval or safety assessment. This process is usually triggered by introduction of new PBN procedures. The process should be conducted for the intended airspace and operations and include:

(i) approval of SBAS system implemented by the State itself;
(ii) approval of an SBAS service provider operating from another State; or
(iii) assessment of GNSS SBAS vertical guidance availability.

4.1.2 The ANSP willing to enable the SBAS service within its FIR is responsible for construction of the safety case describing the system is safe for users against the certification by the regulator. The safety case should contain the explanation of the system architecture, conditions unsafe for users, the potential threats and mitigation including ionosphere.

4.1.3 Regional Dependence. In the case of approval of an SBAS service provider operating from another State, the regulator shall note that the behavior of ionosphere in the Asia-Pacific Region may be different from the assumptions of the SBAS service provider. For example, the Japanese MSAS, operating with the threat model developed for Japanese airspace, should not automatically be approved for use in airspaces of other States unless the assumptions and the threat model of MSAS are validated and approved for the intended region of the operation.

4.1.4 Intended operations. In the case of non-precision approaches (NPA), ionosphere threat model assessment might not be required where no vertical guidance is provided. The proper mitigation of ionosphere anomalous conditions by the SBAS system should be assessed in cases where it serves for approach operations with vertical guidance, such as LPV, or with more stringent requirements.

4.1.5 Safety index. A tool to measure how much the integrity requirements are met, or how much the safety margin is expected for the intended operation, is so-called ‘safety index’. The safety index is defined as the ratio of the actual user position error to the associated alert limit. As an example, with sufficient margin to establish the integrity level of 1E-07, roughly speaking, the safety index could be less than 5% in the nominal conditions while it could increase up to 10% or 20% even in the non-nominal conditions, both for the LPV operations.

4.1.6 Assessment of GNSS SBAS vertical guidance availability. With the safety case for the intended airspace including the validated and approved assumptions and threat model, the system performance can finally be assessed by availability of the system for the intended operations. Typically the availability of non-precision horizontal navigation is almost 100%, while it is recommended to assess carefully if the availability of vertical guidance operations is sufficient for the intended operations or not.

4.2 Evaluation of ionospheric conditions

4.2.1 Because the behavior of ionosphere depends upon the region, the ionospheric threat model implemented inside the SBAS shall be evaluated for the intended region when the appropriate authority intends to approve it.

4.2.2 For this approval, the appropriate authority shall evaluate:

- (i) if the design of the algorithm of ionospheric correction and the ionospheric threat model is appropriate for the intended region;
- (ii) the characteristics of the ionospheric threat model using the real data.

The latter activity would be similar with creation of the threat model to confirm the threat space is actually overbounding real ionospheric anomalies.

4.3 Post-adoption activities

4.3.1 As explained at Section 3.1.4, the threat model once evaluated and confirmed does not assure to overbound the anomalous ionospheric delays for the future. Therefore the ionosphere monitoring shall be performed on the regular basis after adoption of the SBAS.

4.3.2 The ionosphere monitoring shall be an activity similar with creation of the threat model to confirm the threat space is actually overbounding real ionospheric anomalies. If an irregularity which may cause the integrity problem was found, the threat model should be updated for the region as needed.

4.3.3 Even in case that it is difficult to perform the complete ionosphere monitoring, it is recommended at least to monitor the correlation between the safety index and solar activity. In case that the safety index often becomes larger than a certain threshold, for example 50%, during high solar activities, it is shown that the threat model employed in the SBAS may have some problem.

Appendix A Ionosphere Algorithms for WAAS/MSAS

A.1 Standard planar fit

A.1.1 The WAAS (IOC version) and MSAS employs a so-called planar fit algorithm to generate ionospheric correction information. This algorithm is implemented in the operational system and run in real time with measurements from ground stations. Here we review the planar fit procedure explained in [1], [2] and reviewed in [3].

A.1.2 Using the thin shell ionosphere model, the vertical ionospheric delay around an IGP is modeled as:

$$\hat{I}_v(\Delta\lambda, \Delta\phi) = \hat{a}_0 + \hat{a}_1\Delta\lambda + \hat{a}_2\Delta\phi \tag{A-1}$$

where $\Delta\lambda$ and $\Delta\phi$ are relative longitude and latitude from the location of the IGP, respectively.

A.1.3 Vertical ionospheric delay is estimated by the weighted least square method as:

$$\begin{bmatrix}\hat{a}_0 & \hat{a}_1 & \hat{a}_2\end{bmatrix}^{\mathrm{T}} = \left(G^{\mathrm{T}} \cdot W \cdot G\right)^{-1} \cdot G^{\mathrm{T}} \cdot W \cdot \mathbf{I_{v,IPP}} \tag{A-2}$$

where G is an $N \times 3$ design matrix which describes the geometry of IPPs, and W^{-1} is the covariance matrix of the observation set, $\mathbf{I_{v,IPP}}$. $\hat{I}_{v,IGP} = \hat{a}_0$ is the resulting estimation.

A.1.4 Integrity is the most important requirement for SBAS, so the bounding information of corrected pseudorange is broadcast to users. For ionospheric corrections, the SBAS broadcasts a GIVE value for this purpose. The current algorithm computes GIVE values based, in part, on the formal variance of the least square fit.

A.1.5 The formal variance of the least squares fit of Eqn. (A-2) is given by:

$$\sigma^2_{\hat{I}_v}(\Delta\lambda, \Delta\phi) = \begin{bmatrix} 1 \\ \Delta\lambda \\ \Delta\phi \end{bmatrix}^{\mathrm{T}} \cdot \left[\left(G^{\mathrm{T}} \cdot W \cdot G\right)^{-1}\right] \cdot \begin{bmatrix} 1 \\ \Delta\lambda \\ \Delta\phi \end{bmatrix}. \tag{A-3}$$

A.1.6 Then the formal variance to bound uncertainty around the IGP is given by:

$$\sigma^2_{IGP_k} = \max\begin{pmatrix} \sigma^2_{\hat{I}_v}(2.5, 2.5), & \sigma^2_{\hat{I}_v}(-2.5, 2.5) \\ \sigma^2_{\hat{I}_v}(2.5, -2.5), & \sigma^2_{\hat{I}_v}(-2.5, -2.5) \end{pmatrix}. \tag{A-4}$$

A.1.7 In case of SBAS, ionospheric information is broadcast on the grid points located every 5 degrees latitude and longitude, so each IGP takes care of threat region of 5 degrees square centered at itself.

A.1.8 The confidence bound with consideration of undersampled and temporal threat models is finally computed as [4]:

$$\begin{aligned}\sigma_{GIVE}^2 = R_{irreg}^2\sigma_{IGP_k}^2 + \max\left(R_{irreg}^2\sigma_{decorr}^2, \sigma_{undersampled}^2\right) \\ + \sigma_{rate-of-change}^2\end{aligned} \tag{A-5}$$

where $\sigma_{undersampled}^2$ denotes the undersampled threat, or spatial threat model, which is a function of geometry of IPPs relative to the corresponding IGP.

A.1.9 The term σ_{decor} denotes inherent uncertainty of the fit plane, and R_{irreg} is the so-called inflation factor as a function of the degree of freedom which is given by:

$$R_{irreg} = \sqrt{\frac{\chi_{1-P_{FA}}^2(n-3)}{\chi_{P_{MD}}^2(n-3)}}. \tag{A-6}$$

This factor is computed based on the chi-square statistics as a function of the degrees of freedom (the number of observations minus the number of unknowns).

A.2 Ionosphere Estimation Algorithm Based on Kriging

A.2.1 In WAAS Follow-On Release 3, the estimation of ionospheric delays is performed by an established, geo-statistical technique known as kriging. In addition to the standard planar fit algorithm, we also review the kriging based algorithm explained in [8][9].

A.2.2 The vertical ionospheric delay around an IGP is modeled in the same way as the standard planar fit, shown in Eqn. (A-1).

A.2.3 Vertical ionospheric delay is determined from a linear combination of known ionospheric delay measurements at IPPs near the IGP as

$$\hat{I}_{v,IGP} = \mathbf{w}^T\mathbf{I}_{v,IPP} \tag{A-7}$$

where **w** is the vector whose components include weight coefficients applied to the ionospheric delay measurements. $\hat{I}_{v,IGP}$ is the resulting estimation at the

IGP. The weight vector **w** is determined as

$$\mathbf{w} = [\mathbf{W} - \mathbf{W}\mathbf{G}(\mathbf{G}^T\mathbf{W}\mathbf{G})^{-1}\mathbf{G}^T\mathbf{W}]\mathbf{c} + \mathbf{W}\mathbf{G}(\mathbf{G}^T\mathbf{W}\mathbf{G})^{-1}\mathbf{s} \qquad \text{(A-8)}$$

$$\mathbf{s} = [1 \;\; \Delta\lambda \;\; \Delta\phi] \qquad \text{(A-9)}$$

where G is an $N \times 3$ design matrix which describes the geometry of IPPs, and W^{-1} is the covariance matrix of the observation set, $\mathbf{I}_{v,\mathbf{IPP}}$. $\Delta\lambda$ and $\Delta\phi$ are relative longitude and latitude from the location of the IGP, respectively.

A.2.4 The formal error variance of the kriging estimate of Eqn. (A-7) is given by:

$$\sigma(\mathbf{w}) = R_{irreg}^2[\mathbf{w}^{\mathrm{T}}\mathbf{C}\mathbf{w} - 2\mathbf{w}^{\mathrm{T}}\mathbf{c} + c_0] + \mathbf{w}^{\mathrm{T}}\mathbf{M}\mathbf{w} \qquad \text{(A- 10)}$$

where R_{irreg} is the same inflation factor shown in Eqn. (A-6). **w** is the weight vector in Eqn. (A-7). **C** is the matrix describing the covariance between the ionospheric residuals from the planar trend and c_0 is the variance of the ionospheric residuals from the planar trend. **M** is the covariance of measurement noise between measurement locations. Note that Kriging effectively weights the contributions of vertical delays at IPPs near the IGP more heavily in the estimation than does the planar fit model by modeling the ionospheric covariance, C, more accurately than the planar fit model.

A.2.5 The integrity bound, σ_{GIVE}^2, is expressed formally as [8]:

$$\sigma_{GIVE}^2 \equiv \sigma_{IGP}^2 + \sigma_{undersampled}^2 \qquad \text{(A-11)}$$

where the term σ_{IGP}^2 is the formal error variance shown in Eqn. A-10, and $\sigma_{undersampled}^2$ is the same term as used in standard planar fit (Eqn. (A-5)).

A.3 Spatial threat model

A.3.1 One of the major concerns for SBAS is the potential error due to ionospheric irregularities which are not sampled by IPPs measured by the ground station network. The SBAS generates and broadcasts corrections and integrity information based on measurements of its own ground station network; However, some users might experience large error caused by unsampled ionospheric irregularities. This problem is called undersampling.

A.3.2 Figure A-1 explains such a condition. The planar fit estimates the vertical delay based on measurement IPPs within the radius of R_{fit} from the IGP, indicated by green circles. In this condition, the irregularity region is not sampled by monitor stations. However, some users have IPPs indicated by red circles in an irregularity region and would be exposed to a large error in the position solution. This is an undersampled threat condition.

A.3.3 In order to account this type of threat, WAAS and MSAS employ the ionospheric spatial threat model. The term $\sigma^2_{undersampled}$ in Eqn. (A-5) is determined by the threat model so that it ensures the actual ionospheric error is always overbounded by the threat model for any users in the service volume.

A.3.4 For the MSAS (and IOC WAAS), the ionospheric spatial threat is characterized as a function of two metrics, i.e., the fit radius, R_{fit}, and the relative centroid metric, RCM computed as follows [5]:

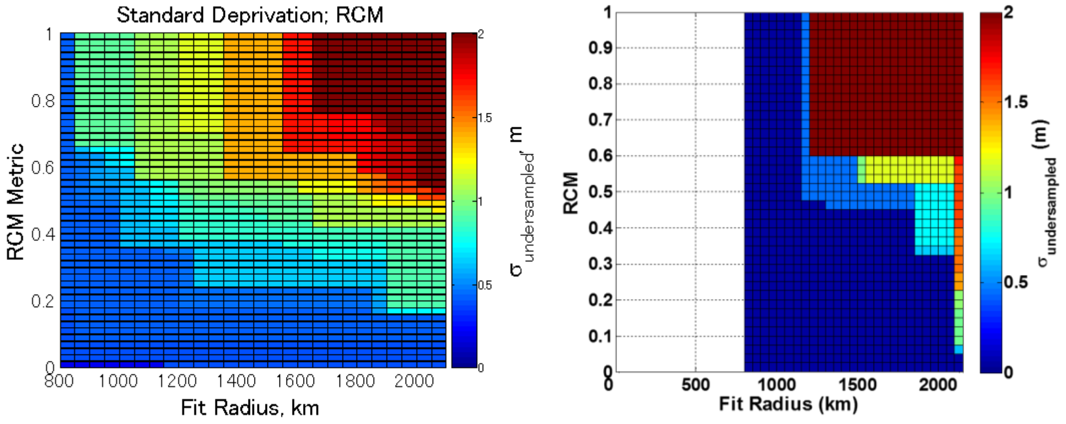
$$\left\lfloor \begin{matrix} 1 \\ d_{cent,x} \\ d_{cent,y} \end{matrix} \right\rfloor = \frac{G^{\mathrm{T}} \cdot W \cdot \mathbf{1}}{\mathbf{1}^{\mathrm{T}} \cdot W \cdot \mathbf{1}} \qquad \text{(A-7)}$$

$$RCM = \sqrt{d_{cent,x}^2 + d_{cent,y}^2} \Big/ R_{fit}$$

where i-th row of matrix G represents the geometric relationship between i-th IPP and the IGP.

$$G_i = \lfloor 1 \quad \mathbf{d}_{IPPi} \cdot \mathbf{e}_E \quad \mathbf{d}_{IPPi} \cdot \mathbf{e}_N \rfloor, \qquad \text{(A-8)}$$

where $\mathbf{d}_{IPP}$ is a vector to i-th IPP from the IGP, and $\mathbf{e}_E$ and $\mathbf{e}_N$ are unit vectors directing east and north from the IGP, respectively. The matrix W in Eqn. (A-7) is weighting matrix same to Eqn. (A-2). $\mathbf{d}_{cent} = \lfloor d_{cent,x} \quad d_{cent,y} \rceil^{\mathrm{T}}$ is the weighted centroid of IPPs for fit.



(a) Spatial Threat Model for MSAS (b) Spatial Threat Model for KASS

Figure A-1: Example of Spatial Threat Model

A.3.5 Figure A-1(a) shows an example of the ionosphere spatial threat model for MSAS using the observation dataset taken in Japan [6]. This example is similar with the operational version for MSAS.

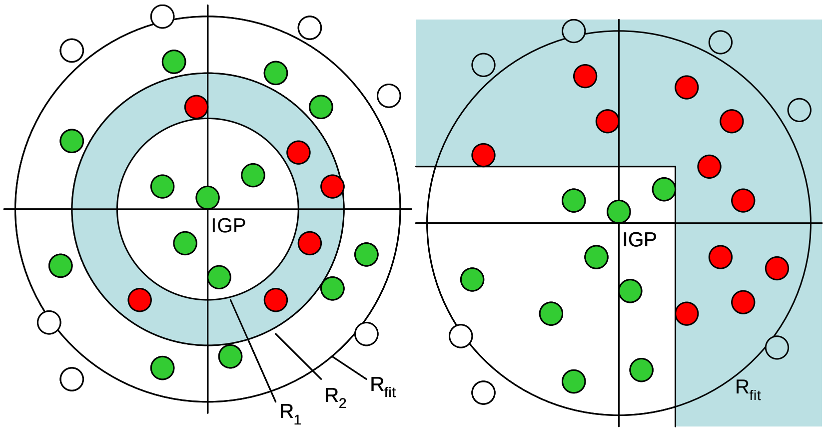
A.3.6 An example of the ionospheric irregularity threat model for Korea Augmentation Satellite System (KASS) is shown in Figure A-1 (b). This model is an example which is developed using ionospheric storm data collected from reference stations in South Korea [11].

A.4 Generation of spatial threat model

A.4.1 The current threat model for MSAS was created by the data deprivation scheme [4]. In this scheme, the set of IPPs observed at an epoch is divided into two sets, the set of measurements used for the fit and the set of virtual users. The planar fit algorithm is performed on the first set of measurements, and ionospheric delays at IPPs of the virtual user set are estimated from the second. Each residual between the planar fit estimate and a virtual user measurement provides a sample of possible error to which users are exposed.

A.4.2 The residuals are tabulated with respect to the threat model metrics, R_{fit} and RCM, and the largest residual contributes to the resulting threat model. The virtual user IPPs are defined within the threat region which is a 5 by 5 degrees square centered at an IGP, because in case of an SBAS, ionospheric information is broadcast on the grid points located every 5 degrees latitude and longitude.

A.4.3 Two schemes are used to create the threat model which covers the worst case undersampling condition. First, as shown in Figure A-2 (a), the annular deprivation scheme separates out data in successive annuli. In each iteration, measurements on an annulus (red plots) are not used for the fit and serve as virtual user measurements. The width of each annulus is set to 200 km and the inner radius of annuli changes from 0 to 2000 km. This scheme takes care of local irregularities and troughs of the ionosphere.



(a) Annular Deprivation (b) Three-Quadrant Deprivation

Figure A-2: Data Deprivation Schemes for the Threat Model

A.4.4 The second scheme is the three-quadrant deprivation illustrated in Figure A-2 (b). In this scheme, measurements in three quadrants are used as virtual user measurements and the planar fit algorithm is performed with IPPs in the remaining quadrant. The cutoffs are done at every 100 km within a 500 km range in four directions, so 44 iterations are performed for each IGP.

A.4.5 In addition to these two deprivation schemes, here called ‘standard deprivation,’ used to create the current MSAS threat model, the malicious deprivation scheme has been developed [7]. This scheme provides the worst case undersampling condition with a lesser number of IPP removals. If the storm detector trips, the IPP with the largest residual from the plane is removed and set to be used as a virtual measurement, then planar fit is performed again. If storm detector trips again, the same process is repeated. The number of removed IPPs removed by this method is limited to no more than two for our study.

A.4.6 The last scheme of data deprivation is missing station deprivation [5]. In this scheme, measurements related to either a monitor station or a satellite are removed from the fit and used as virtual user measurements. This scheme provides conditions of loss of a station and decommissioning or outage of a satellite. Both are realistic for the actual operating system.

A.4.7 For the construction of the preliminary KASS ionospheric threat model shown in Figure A-1 (b), the missing station deprivation and the malicious deprivation are used. In addition to the missing station deprivation and the malicious deprivation scheme, the oversampling method developed for MSAS threat model [6] is applied to construct the ionospheric threat model. In the oversampling method, additional measurements observed from more than 60 GPS reference stations in South Korea are used to identify ionospheric irregularities that are not sampled by the KASS monitor stations [11].

A.4.8 Note that data deprivation provides two functions for creation of a threat model. At first, it derives possible conditions missing some IPPs for safety and conservativeness. Second, it provides IPP samples as virtual users to compute residuals and tabulate as a threat model.

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