International Civil Aviation Organization

Twenty Seventh Meeting of the Communications/ Navigation and Surveillance Sub-group (CNS SG/27) of APANPIRG

Bangkok, Thailand, 28 August – 01 September 2023

Agenda Item 6: Navigation

6.2 Review Report of the Fifth Meeting of GBAS/SBAS Implementation Task Force (GBAS/SBAS ITF/5)

REVIEW REPORT OF THE FIFTH MEETING OF GBAS/SBAS IMPLEMENTATION TASK FORCE (GBAS/SBAS ITF/5)

(Presented by the Secretariat)

SUMMARY

This paper provides information on the outcomes of the GBAS/SBAS ITF/5 held in Tokyo, Japan from 21-23 June 2023 for the review by the meeting.

1. INTRODUCTION

1.1 The fifth Meeting of the ICAO Asia/Pacific GBAS/SBAS Implementation Task Force (GBAS/SBAS ITF/5) was held in Tokyo, Japan on 21-23 June 2023. A total of 85 participants from States, Administrations, IATA, IFALPA and ICAO were registered for the GBAS/SBAS ITF/5. A total of nine (9) Information Papers (IPs) and five (5) Working Papers (WPs) were presented in the meeting. The relevant presentations and documents are available at following link: https://www.icao.int/APAC/Meetings/Pages/2023-GBAS-SBAS-ITF-5.aspx.

2. DISCUSSION

2.1 The meeting deliberated on the following main Agenda Items:

Agenda Item 2: Progress on the work of Expert Groups constituted to:

- Review and revise the GBAS and SBAS safety assessment guidance document related to anomalous ionospheric conditions.
- Draft a Guidance Document on Implementation Process for GBAS/SBAS.

Agenda Item 3: Updates on GBAS/SBAS and States' Implementation status

Agenda Item 4: Visit to GBAS-SBAS Facilities

Agenda Item 5: Review of Action Item List

2.2 Progress on the work of Expert Groups

2.2.1 **Expert group 3-1 – GBAS safety assessment guidance document related to anomalous ionospheric conditions -** Mr. Susumu Saito, Co-Chair of the task force, presented the draft of the revised GBAS safety assessment guidance document related to anomalous ionospheric conditions (Appendix A to GBAS/SBAS ITF/5 WP01). Major updates to the GBAS iono guidance document are inclusion of latest GAST D SARPs along with existing materials on GAST D, materials about the protection levels and a summary of how to develop the GBAS ionospheric threat model based on the experience and input by Thailand. The meeting agreed that the revised draft GBAS safety assessment guidance document related to anomalous ionospheric conditions was ready to be put up to CNS-SG/27 for recommendation to APANPIRG/34 to adopt the document.

<table>
<tr><td colspan="2">Draft Conclusion CNS SG/27 /XX – Draft revised GBAS safety assessment guidance document related to anomalous ionospheric conditions</td></tr>
<tr><td>What: That, the revised GBAS safety assessment guidance document related to anomalous ionospheric conditions (Edition 2.0) provided in Appendix A be adopted.</td><td>Expected impact:
☐Political / Global
☐ Inter-regional
☐ Economic
☐Environmental
■ Ops/Technical</td></tr>
<tr><td>Why: Major updates to reflect the development of GAST D SARPs and progress of GBAS development and implementation in the region.</td><td>Follow-up: ☐ Required from States</td></tr>
<tr><td>When: 30-Aug-23</td><td>Status: Draft to be adopted by PIRG</td></tr>
<tr><td colspan="2">Who: ■CNS Sub group ☐APAC States ■ICAO APAC RO ☐ICAO HQ ☐Other:</td></tr>
</table>

2.2.2 **Expert group 3-1 – SBAS safety assessment guidance document related to anomalous ionospheric conditions -** Mr. Susumu Saito, Co-Chair of the task force, also presented the draft of the revised SBAS safety assessment guidance document related to anomalous ionospheric conditions (Appendix A to GBAS/SBAS ITF/5 WP02). Main updates to the SBAS iono guidance document are inclusion of information on new SBAS services under development/deployment, such as SDCM, BDSBAS, KASS, South-PAN, and A-SBAS, distinction between the disturbed and quiet ionospheric conditions for SBAS, GAGAN ionospheric threat model based on MLDF (Multi-Layer Data Fusion), interface control documents (ICD) of BDSBAS, differences of DFMC from L1 SBAS from ionospheric effects perspective and new guidance material on post-adoption activities of SBAS for ionospheric monitoring.

<table>
<tr><td colspan="3">Draft Conclusion CNS SG 27/XX – Draft revised SBAS safety assessment guidance document related to anomalous ionospheric conditions</td></tr>
<tr><td colspan="2">What: That, the revised SBAS safety assessment guidance document related to anomalous ionospheric conditions (Edition 2.0) provided in Appendix B be adopted.</td><td>Expected impact:
☐Political / Global
☐ Inter-regional
☐ Economic
☐Environmental
■ Ops/Technical</td></tr>
<tr><td>Why: Major updates to enrich the contents and reflect the progress of SBAS development and implementation in the region and DFMC SBAS SARPs development.</td><td colspan="2">Follow-up: ☐Required from States</td></tr>
<tr><td>When: 30-Aug-23</td><td colspan="2">Status: Draft to be adopted by PIRG</td></tr>
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2.2.3 **Expert group 3-2 – Guidance Document on Implementation Process for GBAS/SBAS - Co-chair**

Mr. George Wong, Co-Chair of the task force, presented progress of Expert Group 3-2 in developing the guidance document for the implementation of GBAS/SBAS. Taking into consideration the current readiness and completeness of draft materials for prepared guidance on GBAS and SBAS implementation, it was considered more justified in splitting the GBAS/SBAS implementation guidance document into two separate volumes (i.e. one book for GBAS implementation and the other one for SBAS implementation).

The draft guidance documents for GBAS and SBAS Implementation were placed as **Attachment A and B** of GBAS/SBAS ITF/5 WP03 respectively. The majority of the draft GBAS implementation guidance document was considered completed in principle and ready for States' review. However, further fine tuning on some details was required and it was anticipated to be wholly completed and ready for promulgation in 2024 after consolidating another round of comments from States on this revision of draft guidance document for GBAS.

To enhance the draft guidance document for SBAS Implementation, further review and consolidation of States' inputs was considered necessary. As per the assessment of Leads/Co-Leads of Expert Group, it was anticipated the draft guidance document to be ready for final review in 2024/2025, subject to the progress in further enriching the draft guidance document for SBAS Implementation with another round of consolidation.

Since the Asia/Pacific GBAS/SBAS Implementation Task Force was initially planned for a period of 3 years with the last meeting in 2023. In view of the status of the draft guidance documents for GBAS and SBAS Implementation and the need for spending more time to finish these two guidance documents, the Expert Group considered the need and necessity to extend the period of Asia/Pacific GBAS/SBAS Implementation Task Force for another three (3) years for inputs/comments to be collected from States.

2.3 Updates on GBAS/SBAS and States' Implementation status

2.3.1 **Revised Navigation Strategy for Asia Pacific Region (Secretariat)**

The Secretariat presented the Navigation Strategy for Asia/Pacific Region, which was revised in 2016 by CNS SG/20 and adopted via Conclusion APANPIRG/27/37. In view of the latest developments in GNSS navigation, there was a need to review the navigation strategy for the region. A draft navigation strategy as agreed by PBNICG/10 meeting and reviewed by the NSP secretary was placed for review by the ITF on GBAS and SBAS elements. After members' deliberation on the final draft navigation, the meeting agreed to GBAS and SBAS elements of the draft revised navigation strategy presented in the meeting.

2.3.2 **Update on DFMC (Secretariat)**

The Secretariat provided an update on DFMC (Dual Frequency Multi Constellation) that ICAO Council adopted ICAO SARPs for DFMC GNSS in March 2023 and the DFMC GNSS SARPs would introduce the next generation of GNSS for aviation as follows:

- two entirely new GNSS constellations, Galileo (Europe) and BeiDou (China), were being standardized by ICAO for the first time.
- the existing SARPs for the GPS (USA) and GLONASS (Russia) constellations were being enhanced to introduce a second frequency and modernized technology.
- the existing satellite-based augmentation system (SBAS) SARPs were being enhanced to introduce a second frequency and the ability to augment the new constellations.

2.3.3 **Australia's GBAS Implementation Experience (Australia)**

Australia provided an update of Australia's experience with implementing GBAS and the number of GLS capable aircraft operating into Australian airports that were GBAS equipped. The biggest impact to system availability had been a result of lightning damage in highly susceptible sites such as Sydney airport**.** The use of fibre optic cables to connect to the reference antennas was currently being investigated as a possible solution. Australia actively monitored changes to the GPS satellite constellation configuration and would remove the GBAS from service (through a NOTAM) during periods where the Vertical Dilution of Precision (VDOP) is inflated. To enhance availability during high VDOP periods, Australia was exploring the option of implementing a region-specific Ionosphere Threat Model. To facilitate a precision approach capability to the displaced threshold, Australia developed, implemented and validated a temporary GLS approach to the displaced threshold in Melbourne Airport demonstrating the capability of the technology. In 2022, 36% of Sydney arrivals and 45% of Melbourne arrivals had GLS capability. There was demand from industry to utilize the GBAS beyond existing capabilities offered by the GAST-C system to support operations below Category I.

2.3.4 **SouthPAN in Australia and New Zealand (Australia)**

Australia presented a brief summary of the SouthPAN program, which would provide a SBAS aeronautical radio navigation service to Australia and New Zealand by 2028. SouthPAN commenced service delivery on 26 September 2022 and had provided a number of Early Open Services:

a) L1 SBAS Open Service (on the L1 navigation signal), augmenting the L1 C/A GPS signal.

b) DFMC SBAS Open Service (on the L5 navigation signal), augmenting the L1 C/A and L5 GPS signals, and the E1 and E5a Galileo signals; and

c) Precise Point Positioning (PPP) Via SouthPAN (PVS) (on the L5 navigation signal), augmenting the L1 C/A and L5 GPS signals, and the E1 and E5a Galileo signals.

Further information about SouthPAN's services can be found in the Service Definition Document available on Geoscience Australia's website: https://www.ga.gov.au/southpan-sdd-os.

2.3.5 **Update from Philippines (Philippines)**

Philippines presented activities in relation to GBAS/SBAS implementation in their State. In cooperation with JRANSA (Japan Radio Air Navigation Systems Association) and the Country of Japan, the Civil Aviation Authority of the Philippines hosted GIPTA (GNSS Implementation Plan Training for ASEAN) at Civil Aviation Training Center (CATC) in November 2022.

2.3.6 **Update on GBAS Proof-of-Concept Project** (**Thailand**)

Thailand presented updates on the GBAS Proof-of-Concept (PoC) Project between Japan and Thailand. It focused on the development of the ionospheric threat model, flight demonstration results, and future actions to be carried out for the GBAS implementation at Suvarnabhumi International Airport in Bangkok, Thailand. Aeronautical Radio of Thailand (AEROTHAI) conducted several GBAS flight demonstrations using their Beechcraft Super King Air 350 aircraft equipped with the GBAS Flight Inspection System (FIS). Several parameters were evaluated during these demonstrations, including the coverage of the VHF Data Broadcast (VDB), deviation errors between GLS and ILS approaches, and radio signal interferences. The overall results of the demonstration indicated that the GBAS system successfully met all performance requirements. Additionally, the GBAS system demonstrated its ability to improve runway throughput and capacity by eliminating the need for critical or sensitive areas of the ILS during runway operations.

2.3.7 **GBAS Status Update in Japan (Japan)**

Japan presented the status of GBAS implementation in Japan. Japan Civil Aviation Bureau (JCAB) installed the first GBAS at Tokyo international airport (HND) and had been conducting CAT-I trial operation since 2020. Pilot feedback indicated GLS provided a more stable approach compared to ILS. Electronic Navigation Research Institute (ENRI) had carried out research and development activities related to GBAS which included DFMC GBAS concept development, GAST-D performance enhancement for the low latitude region and advanced operations by GBAS.

2.3.8 **MSAS Program Update (Japan)**

Japan informed the meeting that the MSAS was declared operational in 2007 up to NPA due to ionospheric effect. Commercial flight-based trial operations of RNP approach procedures with LPV250 minima was ongoing within limited time at fourteen airports in Japan. The Research and development activities on Dual Frequency Multi constellation MSAS (DFMC MSAS) including message authentication using L5 QPSK signals were undergoing at the Electronic Navigation Research Institute (ENRI).

2.3.9 **GNSS RFI monitoring service by JCAB in Japan (Japan)**

Japan Civil Aviation Bureau (JCAB) established the Network Performance Assessment Center (NPAC) in 2020 for the mission of centrally monitoring, analyzing, and assessing service levels of CNS as the core of CNS performance management. This paper introduced the performance monitoring of GNSS conducted by NPAC. NPAC collected GNSS signals by GPM system and provided the following three services to users.

a) GNSS Performance Prediction Service providing availability forecasts for ABAS and SBAS
b) GNSS Performance Monitoring Service providing information on the impact on operations utilizing GNSS.
c) GNSS Performance Analysis and Evaluation Service conducting analysis and evaluation of GNSS performance for safe and continuous utilization of GNSS.

2.3.10 **SBAS Development Status (Pakistan)**

Pakistan informed the meeting that the Pak-SBAS program was initiated in 2019. It was owned by the Government of Pakistan and was being implemented and would be operated by SUPARCO (www.suparco.gov.pk) – the National Space Agency of Pakistan. PCAA was cooperating with SUPARCO in the implementation of Pak-SBAS and planned to utilize its services for Performance Based Navigation (PBN) in the aviation sector in Pakistan.

2.3.11 **Korean SBAS (KASS) development and implementation status (Republic of Korea)**

The Republic of Korea (ROK) presented the implementation status of its SBAS, called KASS (Korea Augmentation Satellite System) and updated that KASS Sol Service will be started in Dec 2023. On a query from ICAO, ROK informed the meeting that they were planning to publish APV-1 procedures first in Incheon.

2.4 Visit to GBAS-SBAS Facilities

2.4.1 **GBAS Facility**

The participants visited Tokyo International Airport (Haneda) where the GBAS under operational trial was installed. JCAB and NEC Corp. explained about functions and implementation of the GBAS system. The participants also visited the GBAS reference stations in the airfield.

2.4.2 **MSAS Facility**

The participants visited the Technical Management Center (TMC) of JCAB. It was collocated with the Tokyo Area Control Center. JCAB introduced the backup system of MSAS and the GNSS performance monitoring system.

2.5 Review of the Action list

The Action List of the task force is a collection of technical matters identified during the first meeting of the task force. It provides description, relevance, ownership and priority to be assessed in each meeting. A review of the current status of tasks in the Action List was conducted in the meeting and the follow-up actions, as well as revised target dates, of outstanding tasks were discussed and deliberated in the meeting. Some of the action items had been closed as those actions had been completed and new target dates have been assigned for the remaining ones per the discussion among members in the meeting. The updated Action list as concluded in the meeting has been attached as Appendix C to the GBAS-SBAS ITF/5 report.

2.5.2 With reference to the latest status in the updated Action List, the following tasks in high priority are still outstanding:

(a) Organize a workshop with airspace users of APAC Region
(b) Organize a specific meeting with APAC regulators interested in GBAS/SBAS
(c) GBAS and SBAS Safety Assessment
(d) GBAS/SBAS Performance Demonstration
(e) Develop High Level Guide on Implementation Process for GBAS and SBAS (i.e. GBAS and SBAS Implementation Guidance Documents)

As per members' deliberation in the meeting, these remaining tasks were considered essential for fulfilling the objectives stated in the Terms of Reference (TORs) of the Asia/Pacific GBAS/SBAS Implementation Task Force (APAC GBAS/SBAS ITF). Taking into consideration the remaining tasks listed above, especially for the need in getting more time to finish up the GBAS and SBAS implementation guidance documents, the meeting concluded and agreed that the task force should be extended by another three-year term to complete these outstanding tasks.

Draft Conclusion CNS SG/27/XX - Extension of the Asia/Pacific GBAS/SBAS Implementation Task Force to complete tasks as per TORs of GBAS/SBAS ITF	
What: To extend the period of Asia/Pacific GBAS/SBAS Implementation Task Force for another 3 years (i.e. up to 2026) for completing the following remaining tasks with high priority in the Action List and considered essential for fulfilling the objectives stated in the Terms of Reference (TORs) of the APAC GBAS/SBAS ITF: - GBAS and SBAS implementation guidance documents; - Workshop/meeting for APAC airspace users and regulators; and - Discussion and deliberation on technical issues in relation to GBAS/SBAS Safety Assessment and Performance Demonstration.	Expected impact: ☐Political / Global ☐ Inter-regional ☐ Economic ☐Environmental ■ Ops/Technical
Why: To complete tasks, such as guidance reference for GBAS/SBAS Implementation, under the TORs of Asia/Pacific GBAS/SBAS Implementation Task Force	Follow-up: ■Required from States
When: June 2023	Status: Draft to be adopted by CNS SG
Who: ■CNS Sub groups ■APAC States ■ICAO APAC RO ☐ICAO HQ ☐Other:	

3. ACTION BY THE MEETING

3.1 The meeting is invited to:

a) Review the Summary Report on the outcome of the GBAS/SBAS ITF/5 Meeting;

b) Adopt draft conclusions stated in Para. 2.2.1, 2.2.2 and 2.5.2; and

c) Discuss any relevant matters as appropriate.

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INTERNATIONAL CIVIL AVIATION ORGANIZATION

ASIA AND PACIFIC OFFICE

GBAS safety assessment guidance related to anomalous ionospheric conditions

Edition 2.0 – June 2023
Adopted by APANPIRG/XX

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Records of amendments

Amendment Number	Date	Amended by	Comments

TABLE OF CONTENTS FOR GUIDANCE ON GBAS THREAT MODEL

Preface

The scope of this guidance is to provide high level principles and necessary activities to implement Ground-Based Augmentation System (GBAS) by mitigating threats associated with ionospheric anomalies. Technical details such as necessary observation setup, detailed analysis techniques, or interpretation of analysis results are out of the scope of this document. Such details may be included in the GBAS Manual which is being considered by the ICAO Navigation Systems Panel.

1. 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 have been effective since 2001, and ones for CAT-III (GAST D; GBAS Service Type D) have been effective and applicable since 2018. These are based on the single-frequency GPS and/or GLONASS signals at the L1 band. SARPs for GBAS with dual-frequency (L1 and L5 bands) and multi-constellation (all the four standardized constellations including GPS, GLONASS, Galileo and Beidou) GNSS signals are under development. 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 an important fact 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.

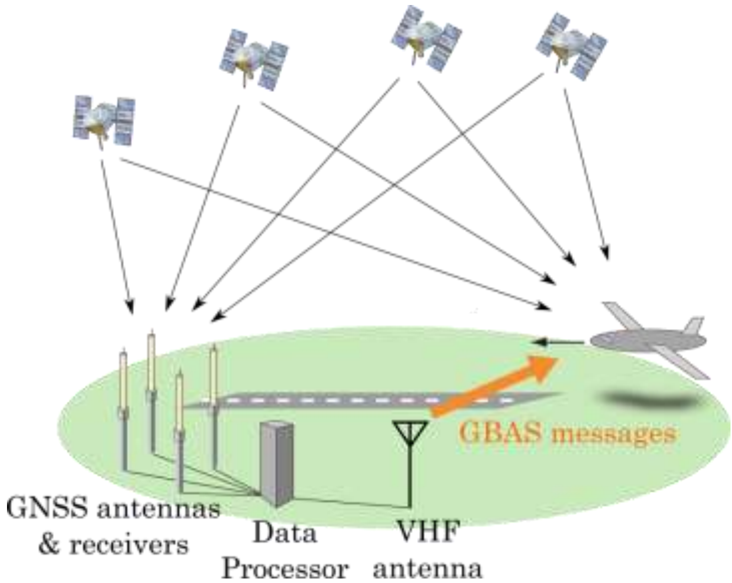

Figure 1. GBAS outline

Because it is necessary for an operational GBAS ground subsystem to meet the stringent safety requirements defined by the SARPs in Annex 10, its validation only by monitoring continuous run behavior is not enough for operational approval of the ground subsystem. A service provider has to prove its system is able to meet the safety requirements specified by its state's aviation safety authority, and each country or regional's regulator has to judge whether it satisfies them or not.

1.2. Scope: GBAS ionospheric 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 above. Namely, effects of GBAS correction for ionospheric delay are worse at far points from GBAS ground station than near ones. Therefore, GBAS takes its effects into account as evaluation parameters, which are broadcasted from ground subsystem to airborne, for calculation reliability of user's final positioning solution. In other words, GBAS protects users from the spatial decorrelation effects of ionospheric delay under "nominal" condition within a certain range that is covered by the evaluation parameters. However, 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 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 include not only integrity but also continuity, required performances of an integrity monitor shall 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 adequate for safe system design [2]. Because the required integrity level is different between GAST C and GAST D, the threat model parameters may be different in principle. However, as it is difficult to obtain enough amount of data to distinguish between them, it is common to use the same threat model developed conservatively for both GAST C and GAST D.

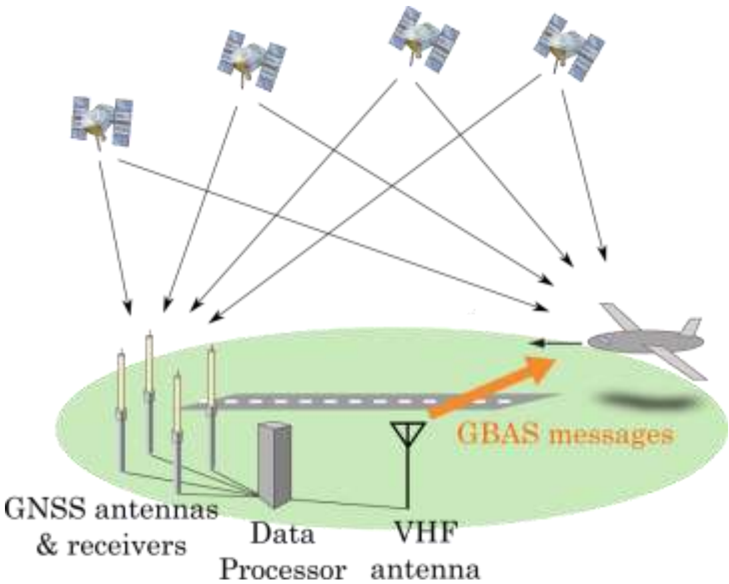

Figure 2. An example scenario of ionospheric delay anomaly for GBAS.

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 [3]. This process increases ionospheric range error because the ionosphere delays code pseudo range, 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 [2].

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 [4].

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) and used to compute the vertical and lateral protection levels as defined in the ICAO Annex 10 Volume I [1] and RTCA LAAS MOPS, DO-253D Change 1 [5]. The protection level bounds the errors in the position solutions of the aircraft at the level of the integrity required for the corresponding operations. Therefore, anomalous ionosphere conditions are required to be accounted for in GBAS ground subsystem safety design. Anomalous conditions are those that spatial gradients generated are 6 times larger than 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-253D Change 1 [5]). 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 [6][7]. 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 [8]. These effects should be covered by the parameter σ_{vig} broadcast by GBAS, although the details depend on the system safety design approaches. In general, σ_{vig} should be determined to bound a large population of observed data [9][10][11][12]. 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 in low latitude regions [13].

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 [14][15][16]. It frequently occurs after sunset in high solar activity periods around the magnetic equator and further develops toward higher latitudes. In the Asia Pacific (APAC) region, its frequency of occurrence is highest during equinox seasons from March to April and from September to October. It is known that characteristics of plasma bubbles are different along longitudes. For example, plasma bubble activities in terms of the occurrence rate and the steepness of the slope are known to be high in South America [17]. However, they can be considered similar in longitude within the APAC region.

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

An ionospheric threat model that includes all possible ionospheric anomaly conditions is required for a safe system design. An ideal threat model should mitigate most 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 [18]. 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 front 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 [19]. Definition 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 define 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 these requirements, it is required 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 threats. However, it is notable that false alarm in the mitigation degrades continuity performance. Because integrity and continuity risks are 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 errors are different among various scenarios 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 [6]. The simulation analysis should be conducted by different ways for GAST C [6][7] or D [20].

2.5.2. Positioning errors in the final implementation

Regarding CAT-I GBAS or GAST C, 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 [19][21][22]. 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 [23]. For GAST D, this process is not necessary for the ground subsystem, because potential positioning errors are evaluated by the airborne subsystem by using the potential range error provided by the ground subsystem in the GBAS message dedicated for GAST D.

2.6. Other important descriptions

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 possible 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., typically 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) [9]. 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 [18][24]. 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 [24]. The LTIAM tool has been developed and used for the analysis [25]. The tool enables 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 [26]. 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 [9].

3.1.3 Summary of how to develop the ionospheric threat model

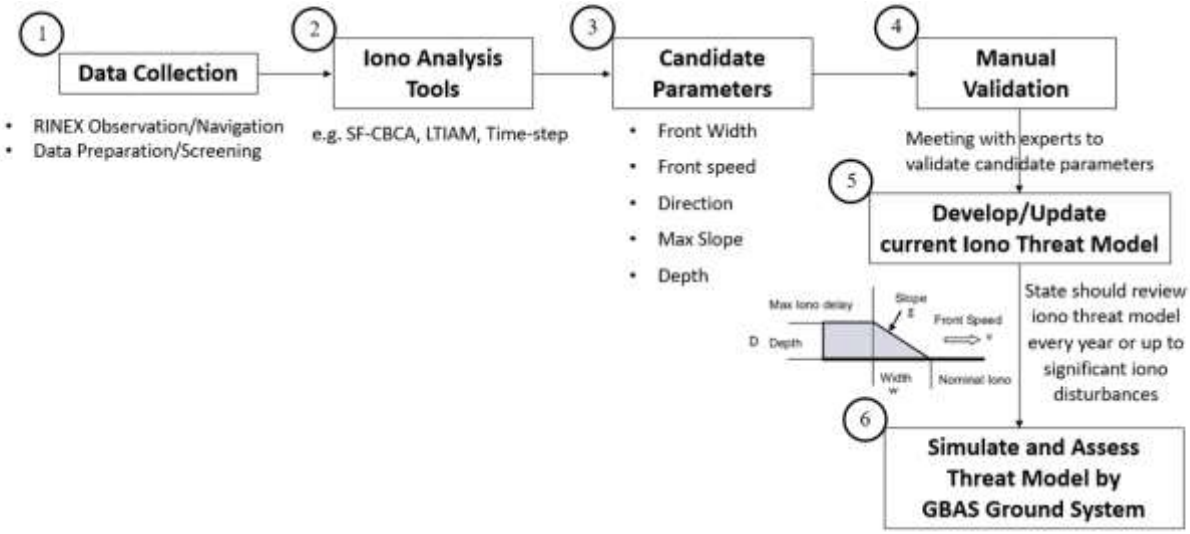

Figure 3. Steps for developing the ionospheric threat model.

Steps for evaluating ionospheric variability and developing the ionospheric threat model are summarized in Figure 3. Beginning with the step-1, the ionospheric threat model is developed with information from collected GNSS data in the area planned for implementation. To make data sharing and exchange easier, the GNSS data collected are recommended to be translated to RINEX (Receiver Independent Exchange Format) format, which is composed of both observation (*.**o) and navigation file (*.**n). The file name is recommended to follow the convention of RINEX which indicated the station identification and date of observation. For example, VTBS001.22o and VTBS001.22n are the observation and navigation file observed on 1 January 2022 at VTBS station. If timing of data collection is limited, focus of GNSS data should be given during equinox months, e.g., March, April, September and October during sunset and nighttime period since most ionospheric activity and plasma bubble mostly occur during these periods. Close attention should be given in the collection process since data is needed from all the receivers concerned, so faulty electric supply can cause missing data leading to inadequate information on a given day, or physical changes of the position of receivers can lead to incorrect judgement of gradient analysis. Moreover, if diverse types of receivers are used, make sure the data used for validation is of the same type and quality.

After adequate data is collected, there are various tools that could be used for the analysis in the step-2, e.g., LTIAM, SF-CBCA, and Time-Step method, which could be used to derive candidate parameters for the model, e.g., Front Width, Front Speed, Direction, Max Slope and Depth. For efficiency, since most parameters are derived from events with extreme ionospheric activity, collected data could be deduced first by techniques such as ROTI (Rate of TEC Change Index) to isolate events of which data is to be analyzed. Once candidate parameters have been chosen, there is still the need to validate the chosen parameters by looking at the events that caused such values again in the step-4. It is satisfactory to use parameters resulting from such analysis tools, but to improve the model to match actual behavior, manual validation of individual events that may cause a worst-case scenario should be further analyzed. Since candidate parameters that result from ionosphere analysis tools sometimes come from an event of data jumping due to cycle-slip in a carrier phase measurement when the receiver loss of signal tracking, a meeting with the ionosphere experts and engineers is therefore conducted to confirm these candidate parameters. Once the ionosphere threat model has been developed, the model should then be used in an actual GBAS ground station to assess the operational limitations and availability as well as the integrity risk of the system. Since ionospheric activities mainly cause by a solar activity of each solar cycle, it is vital to monitor ionospheric activities continuously and regularly updated at least on an annual basis.

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 [27], simulation analysis concerning plasma bubble [28].

3.3. Validation

Threat model should cover observational and simulation results of the ionospheric delay gradient with appropriate safety margin.

3.4. GBAS ionospheric threat model for APAC region

The Ionospheric Studies Task Force (ISTF), which was established under the APANPIRG CNS Subgroup in 2012 and disbanded in 2016, collected ionospheric delay gradient data in the APAC region and established the GBAS ionospheric threat model for APAC region [29][30]. It defines an conservative upper limit of the ionospheric delay gradient as 600 mm/km. This model can be used in the APAC region, though validation is necessary before actually used for individual GBAS implementation. The ICAO APAC GBAS ionospheric threat model defines only about the spatial gradient. Other parameters such as the front moving speed, width and drop are not defined in it, for which some studies have been made [31].

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 neighboring area, i.e. such an event list gives candidate dates for the neighboring area.

4.2. Maintenance of threat model

There are two viewpoints. The first is to search new events which are not covered by the current threat model. The second is reconsideration of safety margin.

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6. Annexes

6.1. CONUS model

CONUS model is described in [2].

6.2. Safety analysis for GBAS prototyping in Osaka

The ionospheric threat model is described in [32].

6.3. Other

Ionospheric threat model analysis is performed in such as [33].

INTERNATIONAL CIVIL AVIATION ORGANIZATION
ASIA AND PACIFIC OFFICE

SBAS safety assessment guidance

related to anomalous ionospheric conditions

Edition 2.0 – June 2023
Adopted by APANPIRG/XX

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Records of amendments

Amendment Number	Date	Amended by	Comments

Table of Contents

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. The system 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 currently deployed single-frequency(L1) SBAS as a part of integrity assessment. Differences from L1 SBAS from ionospheric effects perspective only have been incorporated. 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. Europe and China are developing systems (Galileo and the BeiDou Navigation Satellite System (BDS)) that will be interoperable with upgraded GPS and GLONASS.

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 of them are the single-frequency SBAS. All SBAS systems are continuously broadcasting augmentation information via GEO (geostationary satellite). Apart from them, presently, there are five SBAS systems under various stages of planning/development/deployment. These are – the System of Differential Correction and Monitoring

(SDCM) (Russia), the BeiDou SBAS (BDSBAS) (China), the Korea Augmentation Satellite System (KASS) (Republic of Korea), the SBAS for Africa and Indian Ocean (A-SBAS) which is renamed as Augmented Navigation for Africa (ANGA) (ASECNA) and the Southern Positioning Augmentation Network (SouthPAN) (Australia and New Zealand). BDSBAS has already published an interface control document (ICD) (http://en.beidou.gov.cn/SYSTEMS/ICD/).

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 broadcasts 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. However, some current SBAS GEOs broadcast additionally on 1176.45 MHz (L5) also which can be used as additional ranging source.

2.2.4 DFMC SBAS can improve robustness and navigation performance. The use of dual frequencies will help mitigate vulnerabilities in respect of ionospheric delay and delay variation caused by space weather and of radio frequency interference affecting a single frequency. While DFMC SBAS cannot correct for scintillation effects, the availability of multiple constellations will help to alleviate the risk of insufficient satellites which may be experienced with a single constellation. Aircraft equipped with DFMC GNSS receivers would be able to continue the intended operation during ionosphere events like plasma bubbles and ionospheric storms.

2.2.5 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.

2.2.6 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.

2.2.7 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.

2.2.8 The usage of IC (and GIVE) is mandatory 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 systems are 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 regarding 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 a 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 Ionospheric Characteristics

3.1.1 The Ionosphere is primarily dependent on Solar radiation i.e. the electron density will increase/decrease as solar activity increases/decreases. However, the distribution of electron density around Earth is controlled by various factors- Earth's Magnetic field and Electric field, Neutral winds and their density etc. Accordingly, the regions of ionospheric electron density distribution are divided or characterised, based on the location with respect to geomagnetic equator over Earth. In general, there are 3 ionospheric regions-

(i) Equatorial and Low Latitude region ($0^o \pm 30^o$ Geomagnetic Latitude)

(ii) Mid Latitude region ($30^o \pm 60^o$ Geomagnetic Latitude)

(iii) High or Polar Latitude region ($60^o \pm 90^o$ Geomagnetic Latitude)

3.1.2 The Equatorial and Low latitude region is the most complex and dynamic of all ionospheric regions due to several phenomena operating over magnetic equator like Equatorial Ionization Anomaly (EIA) and Scintillations. Most of the Asia Pacific region lies in this ionospheric region and hence vulnerable to the ionospheric disturbances very often. The geomagnetic equator is approximately 8-9 degree offset in North to the geographic equator in Asia Pacific region and is not fixed.

3.2 Definition of Nominal and Anomalous ionosphere

3.2.1 Usually, the nominal and anomalous ionosphere is defined or identified by geomagnetic parameters – Kp and Dst index. These geomagnetic indices define the intensity of geomagnetic storms over the globe. The ionospheric response to the geomagnetic disturbances is well correlated over Mid and High Latitudes as they can induce the ionospheric disturbances like Storm Enhanced Density (SED).

3.2.2 The equatorial and low latitude ionosphere is, in general, anomalous in nature due to inherent characteristics of EIA. Moreover, the equatorial ionospheric response to magnetic storms can be positive or negative i.e. enhancement or reduction in electron density. In other words, during positive ionospheric storm, it can lead to enhanced EIA i.e. enhancement in electron density and/or shifting of Crest latitude farther away from equator. During negative ionospheric storm, the EIA can be weak, i.e. reduced electron density and/or shifting of Crest latitude towards equator; and even the complete absence of EIA i.e. crest formation at equator. Hence it is not realistic to correlate the anomalous ionospheric condition with global geomagnetic parameters (Kp, Dst) over Equatorial and low latitude region.

3.2.3 Since equatorial and low latitude ionosphere is mostly governed by local/regional phenomena, the anomalous ionospheric conditions can be represented by localised ionospheric irregularity indicators like ROTI (Rate of change of TEC Index) and AATR (Along Arc TEC Rate). These are calculated using the GPS derived TEC measurements for the particular receiver. The Rate Of change of the TEC Index (ROTI) is one of the most widely used ionospheric indicators to characterize the ionospheric fluctuations [13]. It is considered as a proxy parameter of scintillation index - S4 and is useful in identifying the scintillation occurrence in absence of Scintillation monitoring receiver.

Rate of TEC: $ROT = \frac{\Delta TEC}{\Delta t}$

Rate of TEC Index: $ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}$

where brackets (⟨ ⟩) mean the ensemble average.

3.2.4 Similarly, AATR (Along Arc TEC Rate) was introduced and developed for EGNOS [14]. It was chosen as the metric to define the ionospheric operational conditions for the EGNOS. It was also adopted by ICAO APAC, ISTF for identifying the disturbed ionospheric conditions [ISTF/5, WP/06].

$$AATR_i = \frac{\Delta STEC_i}{(M(\varepsilon))^2 \Delta T}$$

Where, *i* indicate the observation epoch; $\Delta STEC_i$ correspond to the difference of $STEC_s$ between two consecutive observations in the same satellite-receiver arc; ΔT is the elapsed time between these consecutive observations (typically 30 or 60 seconds); and M (ε) is the mapping function or obliquity factor to convert slant TEC to vertical TEC.

3.3 High level principles

3.3.1 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.

3.3.2 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.

3.3.3 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.

3.3.4 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 over bound 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 to the creation of the threat model to confirm that the threat space is actually overbounding real ionospheric anomalies.

3.3.5 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). It should be noted that the scintillation effects would also affect the DFMC SBAS performance.

3.4 Ionospheric correction by SBAS

3.4.1 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.

3.4.2 There are some methods for generation of ionospheric correction information inside SBAS.

As an example, the algorithm of WAAS/MSAS, so-called ‘planar fit’ and ‘MLDF’ (Multi Layer Data Fusion) model used in GAGAN , is explained in Appendix A.1 and A.5, respectively.

3.4.3 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.

3.4.4 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.

3.4.5 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.

3.4.6 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.

3.4.7 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.

3.4.8 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.

3.5 Necessity of the threat model

3.5.1 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.

3.5.2 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’.

3.5.3 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.

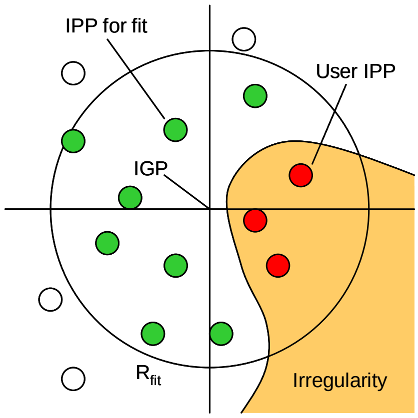


Figure 3-1: Schematic Diagram of Spatial Threat

3.5.4 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.

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

3.5.6 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' with the horizontal axis of ionospheric correction residual error divided by the obliquity factor and the vertical axis of 5.33 times σ_{GIVE}. Figure 3-2 shows an example of the triangle chart of ionospheric correction residual. If integrity is not met, i.e. there are any misleading information (MI), 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.

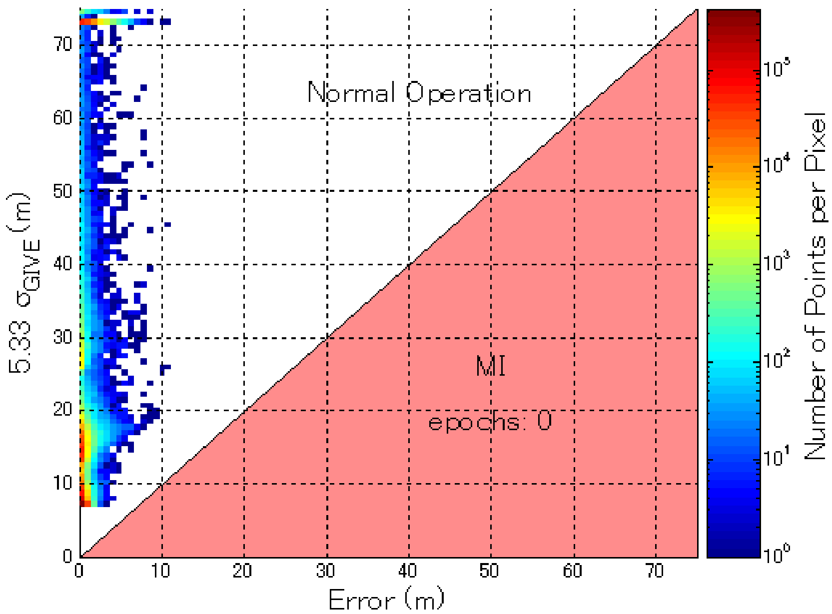


Figure 3-2: Example of Triangle Chart of Ionospheric Correction Residual.

3.5.7 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.
  - ➢ In India, data from a network of 25 GAGAN-TEC stations, 15 GAGAN reference stations, and 2 IGS stations was selected to establish the threat model. The selected data includes stormy and nominal days over the period of 2004-2011.

- 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.

3.6 Creation of the threat model

3.6.1 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 AATR, ROTI and/or Kp and Dst. For example, data in which the worst daily values of Kp greater than 6 and Dst were less than -200nT 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.

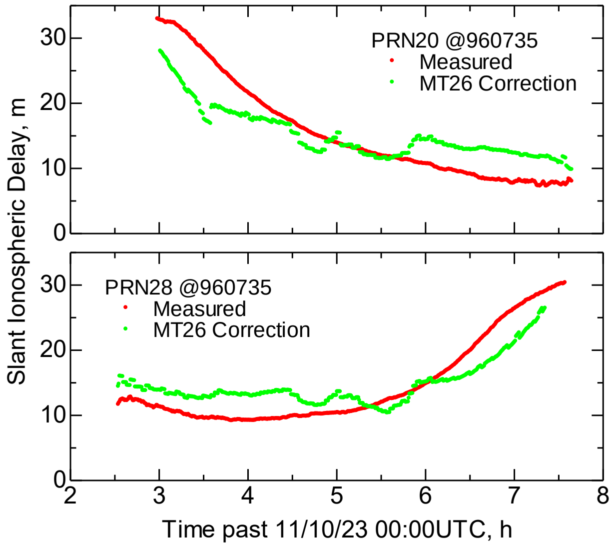


Figure 3-3: Example of Difference between Measurement and Correction

3.6.2 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 the 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. Operational issues such as the generation of NOTAMs and briefing material, and the training of controllers and technical personnel should also be addressed.

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 10^{-7}, roughly speaking, the safety index for the LPV operations could be less than 5% in the nominal conditions while it could increase up to 10% or 20% in the non-nominal conditions.

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 over bounding real ionospheric anomalies.

4.3 Post-adoption activities

4.3.1 As explained at Section 3.3.4, the threat model once evaluated and confirmed does not assure to over bound 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 to the 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 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.

4.3.4 Independent data sources for ionospheric monitoring: The ionospheric monitoring can be performed using data from either ground Reference station which is an integral part of SBAS system or from the independent stations having high-quality dual-frequency GNSS receiver. The data source from the independent stations provide an added advantage of capturing 'unseen' ionospheric activities by ground reference station, thus enabling the opportunity to monitor localized events like plasma bubbles or depletions. The examples of independent data sources are USA's CORS network; JAPAN's GEONET ; India's GAGAN-TEC Network etc.

4.3.5 Depletion monitoring: The undetected Depletions or plasma bubbles are potential threat to any GNSS augmentation system and SBAS is no exception to that. During deep depletions, there is a potential risk that residual ionospheric delay is not bounded by the threat model. Hence, it is pertinent to monitor the depletion events using independent data sources which are spatially separated from ground reference stations. For SBAS perspective, the depth of the depletions or plasma bubbles is important parameter to monitor and note. The threat assessment shall be carried out during deep depletion events and in case of non-conformity of threat space, necessary update to threat model shall be done.

Appendix A Ionosphere Algorithms for WAAS/MSAS/GAGAN

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 $(\hat{I}_v)$ 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:

$$[\hat{a}_0 \quad \hat{a}_1 \quad \hat{a}_2]^{\mathrm{T}} = (G^{\mathrm{T}} \cdot W \cdot G)^{-1} \cdot G^{\mathrm{T}} \cdot W \cdot \mathbf{I}_{\mathbf{v,IPP}} \tag{A-2}$$

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, $\mathbf{I}_{\mathbf{v,IPP}}$. $\hat{I}_{v,IGP} = \hat{a}_0$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:

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

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

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

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]:

$$\sigma_{GIVE}^2 = R_{irreg}^2 \sigma_{IGP_k}^2 + max\left(R_{irreg}^2 \sigma_{decorr}^2, \sigma_{undersampled}^2\right) + \sigma_{rate-of-chnge}^2 \quad \text{(A-5)}$$

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_{decorr}^2 denotes inherent uncertainty of the fit plane, and σ_{decorr}^2 is the so-called inflation factor as a function of the degree of freedom which is given by:

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

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

$$\hat{I}_{v,IGP} = \mathbf{w}^{\mathrm{T}} \mathbf{I}_{\mathrm{v,IPP}} \quad \text{(A-7)}$$

where $\mathbf{w}$ 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 $\mathbf{w}$ is determined as

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

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

where $\mathbf{G}$ is an $N \times 3$ design matrix which describes the geometry of IPPs, and $\mathbf{W}^{-1}$

is the covariance matrix of the observation set, $\mathbf{I_{v,IPP}}$. $\Delta\lambda$ 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). $\mathbf{w}$ is the weight vector in Eqn. (A-7). $\mathbf{C}$ 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. $\mathbf{M}$ 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, $\mathbf{C}$, 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 irregularrities 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 $\sigma_{undersampled}^2$ 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]:

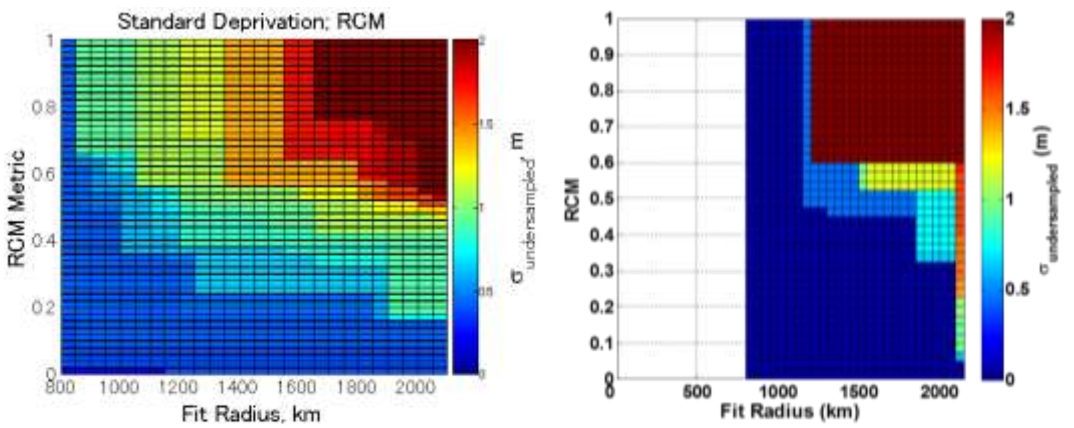
$$\begin{bmatrix} 1 \\ d_{cent,x} \\ d_{cent,y} \end{bmatrix} = \frac{G^{\mathrm{T}} \cdot W \cdot \mathbf{1}}{\mathbf{1}^{\mathrm{T}} \cdot W \cdot \mathbf{1}}$$

$$RCM = \sqrt{d_{cent,x}^2 + d_{cent,y}^2} / R_{fit} \qquad \text{(A-12)}$$

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

$$G_i = [1 \quad \mathbf{d}_{IPPi} \cdot \boldsymbol{e}_E \quad \mathbf{d}_{IPPi} \cdot \boldsymbol{e}_N] \qquad \text{(A-13)}$$

where $\mathbf{d}_{IPPi}$ is a vector to i-th IPP from the IGP, and $\boldsymbol{e}_E$ and $\boldsymbol{e}_N$ are unit vectors directing east and north from the IGP, respectively. The matrix W in Eqn. (A-12) is weighting matrix same to Eqn. (A-2). $\mathbf{d}_{cent} = [d_{cent,x} \quad d_{cent,y}]^{\mathrm{T}}$ 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.

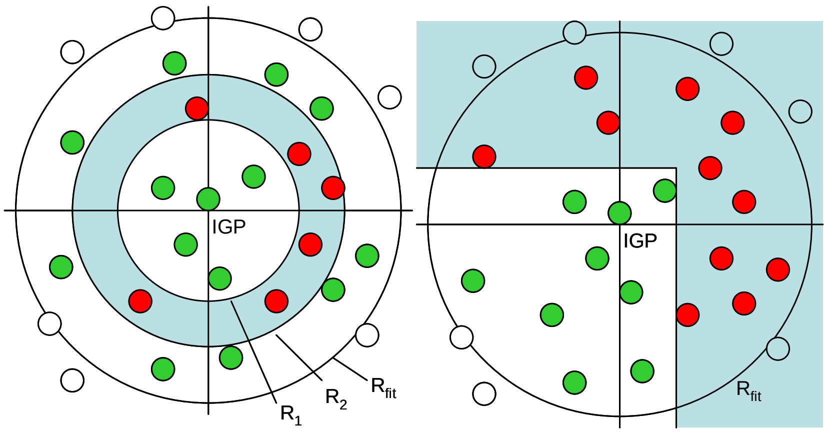
A.3.6 An example of the ionospheric irregularity threat model for Korea Augmentation Satellite System (KASS) is shown in Figure A-1 (b). This model is an example which is developed using ionospheric storm data collected from reference stations in South Korea [11].

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 under sampling 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.

A.5 GAGAN MLDF Model

A.5.1 Overview

A.5.1.1 The GAGAN employs a different approach to model the ionospheric delay, Multi Layer Data Fusion (MLDF) Model, in order to account for the vertical movement of ionosphere which is characteristic to the equatorial and low latitude region.

A.5.1.2 The MLDF Model is designed to capture the ionosphere variability at 2 different shell heights and provide a calculated value for the user at a 350 km shell height. The ionospheric delay and an error bound at 350 km is provided through "data fusion" technique in message type 26 [12].

A.5.1.3 The Threat model is required to ensure that the broadcast GIVEs have a sufficiently high level of integrity such that the User Ionosphere Vertical Errors (UIVEs) computed by user receivers will bound their vertical ionosphere errors.

A.5.2 Assumptions

A.5.2.1 Ionosphere is assumed to be concentrated at two layers rather than one layer (due to typical equatorial ionosphere characteristics).

A.5.2.2 The distribution of the input noise and ionospheric delay residuals in the GIVE monitor are assumed to have near zero mean, symmetry, uni-modal and Cumulative Distribution Function (CDF) over bounding.

A.5.3 Features

A.5.3.1 The algorithm is designed on the new concept of computing Grid Ionospheric Vertical Delay (GIVD) at two different layers instead of a single thin shell so as to capture the large scale feature of the ionosphere.

A.5.3.2 Since the delays and confidences are finally transformed and fused to provide the GIVD, GIVE at 350km, this algorithm does not require any changes in the message structure (MOPS). The existing ionosphere messages in SBAS, i.e., message type 18 and 26, can be retained for ionosphere corrections.

A.5.3.3 The algorithm uses two different data sets for the kriging fit at individual layers. This ensures data independence while fusing the individual layer outputs.

A.5.4 Algorithm Description

A.5.4.1 The Grid Ionosphere Vertical Error (GIVE), consists of the fit error bound and threat models (Spatial, Temporal, Undersampled, Depletion and Storm detector inflation parameter). The GIVD at 350 km shell height is obtained by fusing the delays from two shell heights using data fusion. In the same manner, the fit error bound at 350 km is obtained by fusing the fit error bound from two shell heights using data fusion. The associated threat models are also computed at 350 km and the GIVE at 350 km is derived. Data fusion is performed only if required values are available for both lower and upper shell height. The fits at each shell height are performed using kriging estimation with geodetic latitude and longitude coordinate based variograms and ionospheric decorrelation models.

A.5.4.2 The steps involved in the MLDF algorithm are broadly described below:

(i). Computation of pierce points at individual shell heights

(ii). GIVD and fit Error bound at individual shell heights

a. Ionosphere pierce point search algorithm

b. Computation of delay (GIVD) and fit error bound using a kriging fit

c. Goodness of fit (χ^2) and computation of inflation factor (R^2_{irreg})

d. Computation of under sampling metrics from the fit

e. Computation of antenna bias error bound from the fit

(iii). Data Fusion at 350 km

(iv). Computation of threat model at 350 km

(v). Computation of GIVE at 350 km

A.5.4.3 The schematic block diagram of MLDF algorithm is shown in Figure A.1

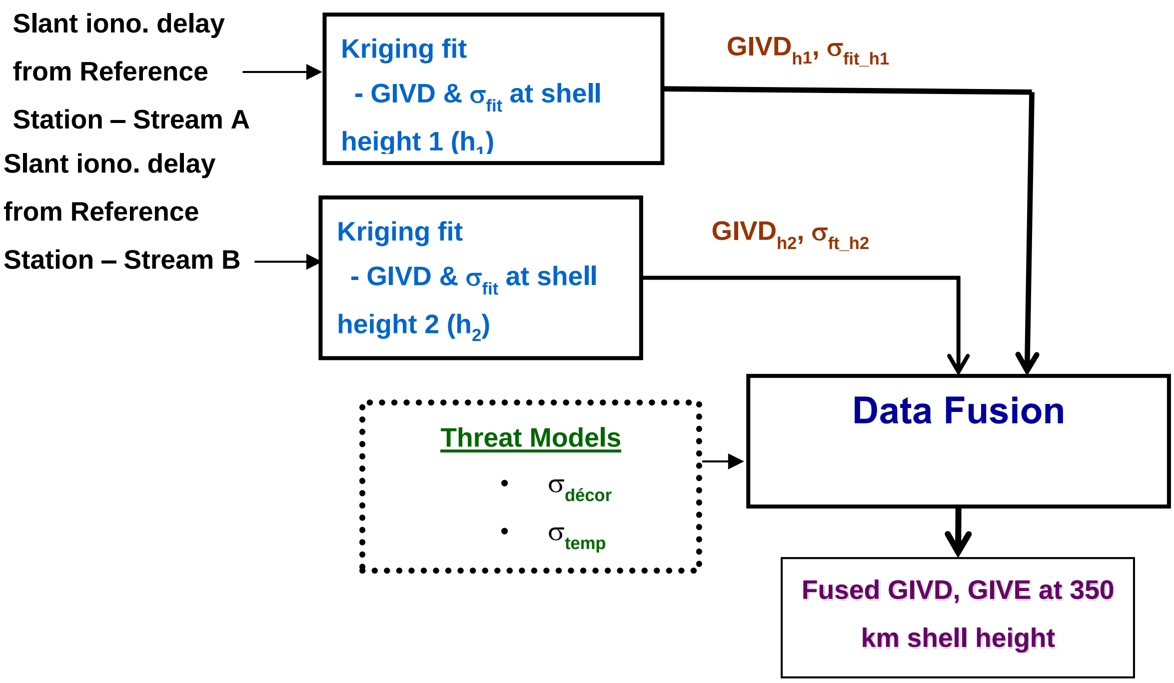


Figure A.3 : MLDF Algorithm – Block Diagram

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