[EN-I-076] Assessment of CAT-I GBAS under the ionospheric conditions in Thailand using APAC ionospheric threat model

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Abstract: The non-uniform ionospheric characteristics called "ionospheric delay gradient" is an important parameter in the GBAS (Ground-Based Augmentation System) safety assessment. Since the characteristics of the ionosphere are different for each region, the ICAO (International Civil Aviation Organization) has established the ISTF (Ionospheric Studies Task Force) in order to collect and analyze the ionospheric data in the APAC (Asia Pacific) region. Recently, the 27th meeting of APANPIRG (Asia/Pacific Air Navigation Planning and Implementation Regional Group) made the conclusion to adopt the GBAS ionospheric threat model (GITM) for APAC region. This model is set the ionospheric delay gradient to 600 mm/km irrespective of satellite elevation angle. In order to assess its impacts on CAT-I GBAS operation, the simulation approach is used to estimate the worst-case position error of the aircraft. This paper presents the simulation results of CAT-I GBAS under the ionospheric condition in Thailand, which is influenced by the equatorial plasma bubble (EPB). The major characteristics of EPB are utilized to simulate the worst-case aircraft position errors. In addition, the appropriate inflation factors are computed to inflate the broadcast parameters. The simulation results show that only inflation of σ_{vig} is not enough to protect the CAT-I GBAS integrity requirements during the worst-case EPB occurrences scenario. The inflated σ_{pr_gnd} is therefore occasionally needed in order to protect the integrity of GBAS users.

Keywords: GBAS, Ionosphere, Equatorial Plasma Bubble, Ionospheric Threat Model

1. INTRODUCTION

The GNSS (Global Navigation Satellite System) is a key enabler for enhancing efficiency, safety, accessibility and predictability of the current air transportation system. However, the standalone GNSS avionics is not enough to support all phases of flight, especially the approach and landing phases, which require strict navigation performances (e.g. accuracy, integrity, continuity and availability). In order to enhance the GNSS-based PBN (Performance-Based Navigation) procedures, the augmentation systems based on the differential global positioning system (DGPS) technique such as SBAS (Satellite-Based Augmentation System) and GBAS (Ground-Based Augmentation System) were developed and standardized by the ICAO (International Civil Aviation Organization) for supporting regional and local operational area [1]. Since the current SBAS and GBAS standards are based on single-frequency (1.57542 GHz for GPS SPS and 1.6 GHz for GLONASS CSA), the reference stations are required to calculated the atmospheric delays due to the Earth's atmosphere (e.g. ionosphere and troposphere). The differential corrections and integrity information are broadcasted to the users for improving the navigation performances. These augmentation systems are in a module of the ICAO ASBU (Aviation System Block Upgrade) framework for optimizing the airport accessibility [2]. Note that the current standard is now available for only CAT-I operation. The CAT-II/III standard is under the development and will be effective in 2018. Although the SBAS and GBAS are already implemented in many States, the large spatial and temporal ionospheric variations are still major challenge for the other States located in the equatorial and low-latitude regions. For the current SBAS, it is therefore not practical to provide APV (Approach Procedure with Vertical Guidance) services in these regions. For the current GBAS, the ionospheric anomaly called "EPB (Equatorial Plasma Bubble)" can cause a large spatial change in the ionospheric delay and could pose an integrity risk, if it is undetected. Hence, the ISTF (Ionospheric Studies Task Force) was established in 2011 by the ICAO APAC (Asia/Pacific) regional office in order to collect and analyze the GNSS data for developing the

GBAS ionospheric threat model (GITM) of APAC region [3]. The GNSS data were collected from several countries (India, Thailand, Indonesia, Japan, and Singapore) and analyzed by Electronic Navigation Research Institute (ENRI), Japan. Recently, the ISTF deliver the GITM and also the guidance materials for safety assessment. The threat model is set the upper bound to 600 mm/km of any satellite elevation angle in order to bound the largest ionospheric delay gradient (518 mm/km) observed in Ishigaki, Japan. After that, the 27th meeting of APANPIRG (Asia/Pacific Air Navigation Planning and Implementation Regional Group) made the conclusion to adopt this threat model for the APAC region [4].

The GNSS-based navigation for aeronautical application was officially initiated in Thailand since 2007 when the Thailand's National Working Group for PBN and GNSS Implementation was established. After that, the Thailand PBN implementation plan was developed and approved in 2009. This plan corresponded to the APAC regional PBN implementation plan developed by the ICAO APAC regional office. Consequently, the instrument flight procedures (e.g. En-Route, Terminal and Approach) were officially published. In January 2017, the Thailand PBN implementation plan was revised to be line with the current Regional APAC Seamless ATM Plan. In this plan, the GBAS is planned to be installed at Suvarnabhumi International Airport to support GLS (GBAS Landing System) operations at four runway ends. The target date for GLS implementation at Suvarnabhumi International Airport is 2020, by which time the third runway, currently being built, is expected to be operational. Since Thailand located in the equatorial region which affected by the EPB occurrences, the assessment of its impact is necessary information for approving GBAS operational in Thailand.

This paper presents the assessment of EPB impacts on CAT-I GBAS operation in Thailand. The estimation of worst-case aircraft positioning error is based on the simulation approach. The major characteristics of EPB and the APAC ionospheric threat model are used in the simulation. In order to protect the unsafe situations, the geometry screening method is applied to screen the potential unsafe satellite geometry by increasing the broadcast parameters (e.g. σ_{vig} and σ_{pr_gnd}).

2. METHODOLOGY

The EPB is an area of low electron density, which is usually originated at the bottom and penetrated to the topside of the ionosphere. In practical, the EPB has a complex shape and structure aligning with the geomagnetic field, showing the depletion region elongates in the North-South alignment. It is a common phenomenon in the equatorial and low-latitude regions, which generally occurs after sunset and moves along the geomagnetic equator in the eastward direction due to the atmospheric neutral wind. To simulate the impact of EPB on GBAS users, the PDGS (Position Domain Geometry Screening) technique is used for determining the worst-case aircraft positioning error and adjusting the broadcast parameters (e.g. σ_{vig} and σ_{pr_gnd}) by inflation factors [5]. Although the anomalous ionospheric spatial gradient can be detected by the CCD (Code Carrier Divergence) monitor in the GBAS ground station, the detection capability relies on the relative velocity between the IPP (Ionospheric Piece Points) motion and the ionospheric spatial gradient movement. Table 1 shows the close-form differential correction error in range domain due to the CCD monitor miss detection,

Table 1. Differential correction error in range domain

Relative Velocity (Δv) (m/s)	Error in range domain (ε_k) (m)
$\Delta v \le 40$	$\varepsilon_k = \min\left(\frac{50}{w}, g\right) \times \left(x_{air} + 2\tau v_{air}\right)$
$40 < \Delta v \le 110$	$\varepsilon_k = 4$
$110 < \Delta v$	$\varepsilon_k = 2.5$

where Δv is the relative velocity (m/s), it can be divided into slow relative velocity $(\Delta v \le 40)$, moderate relative velocity $(40 < \Delta v \le 110)$, and fast relative velocity $(110 < \Delta v)$, ε_k is the differential correction error in range domain (m), g is the ionospheric delay gradient (m/km), which is set to be the same as GITM (600 mm/km or 0.6 m/km), w is the width of the ionospheric gradient, x_{air} is the separation distance between the GBAS ground station and the aircraft (km), τ is the time constant of carrier-smoothing filter (100 s for CAT-I GBAS), and v_{air} is the ground speed of the aircraft (assume to be 70 m/s).

To compute the ionosphere-induced error in vertical position error (IEV), the worst pair of possible satellites is assumed to be the worst-case scenarios. It can be obtained from Eq. (1),

$$IEV_{k1,k2} = \left|S_{vert,k1}\varepsilon_{k1}\right| + \left|S_{vert,k2}\varepsilon_{k2}\right| \quad (1)$$

where $S_{vert,i}$ is the vertical position component of the weight-least squares projection matrix (refer to the Appendix B in [1]), ε_{k1} and ε_{k2} are the error in range domain of the satellite $k1$ and $k2$, respectively. Since the PDGS technique in [5] was designed based on the characteristics of the ionospheric storm enhance density events observed in CONUS (Conterminous United States), the worst-case impact scenarios are much different than the characteristics of EPB (e.g. moving direction, number of ionospheric front, time of occurrence, and loss of satellite signal due to scintillation). Therefore, we use the method developed by [6], which designed for the worst-case impact scenarios based on the characteristics of EPB.

2.1 Worst-case EPB impact scenarios

2.1.1 Single-satellite impact scenario

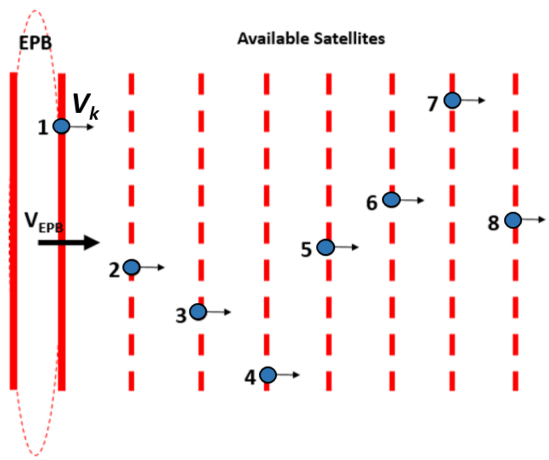

Figure 1. Single-satellite impact scenario

Fig. 1 shows the top view of the single-satellite impact scenario in 2-D when it is affected by the EPB. The blue dots indicate the IPPs of each available satellite (there are 8 available satellites in this example). Since the EPBs usually move along the geomagnetic equator in the eastward direction, the eastward velocity of each IPP (V_k) are calculated in order to estimate the differential correction error in range domain. To create the worst-case scenario, the velocity of EPB (V_{EPB}) is deliberately set to give the relative velocity as low as possible, implying that giving the maximum error in range domain. If we assume that the threat space of V_{EPB} is between $V_{EPB,min}$ and $V_{EPB,max}$ ($V_{EPB,\min} \leq V_{EPB} \leq V_{EPB,max}$), the worst-case scenarios can be divided in 3 cases depending on V_k,

a) $V_{EPB,\min} \leq V_k \leq V_{EPB,max} \quad \rightarrow V_{EPB} = V_k$

b) $V_k < V_{EPB,min} \quad \rightarrow V_{EPB} = V_{EPB,min}$

c) $V_k > V_{EPB,max} \quad \rightarrow V_{EPB} = V_{EPB,max}$.

After calculating the differential correction error in range domain (ε_k) corresponding with the relative velocity ($\Delta v = |V_{EPB} - V_k|$) in the Table 1, the IEV can be obtained from Eq. (1) in a similar manner, but only single satellite. Then, this process is repeated for all possible satellite of a particular subset satellite geometry. After calculating all possible IEVs, the maximum IEV (MIEV) is selected for a particular subset satellite geometry, i.e.,

$$MIEV_{1sat} = \max(IEV_k). \tag{2}$$

2.1.2 Double-satellite impact scenario with same EPB

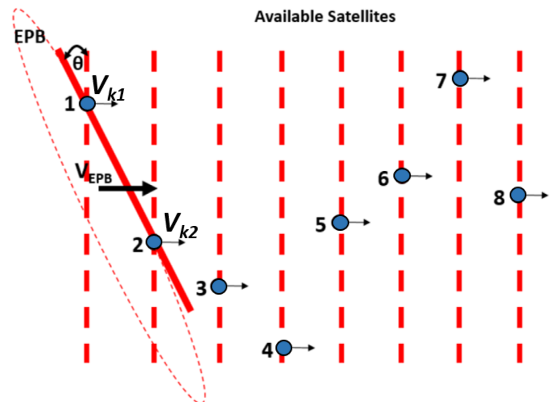

Figure 2. Double-satellite impact scenario by the same EPB

Fig. 2 shows the possible impact scenario when the EPB affected double satellites at the same time. This scenario is created in a similar manner to the worst-case scenario for ionospheric storm enhance density events observed in CONUS. However, the selection of satellite pair is limited to the tilt angle of EPB (e.g. ±35° from the geomagnetic north). The worst-case scenarios can be divided in 4 cases,

a) $V_{EPB,\min} \leq V_{k1} \leq V_{EPB,max} \rightarrow V_{EPB} = V_{k1}$

b) $V_{EPB,\min} \leq V_{k2} \leq V_{EPB,max} \rightarrow V_{EPB} = V_{k2}$

c) $V_{EPB} = V_{EPB,min}$

d) $V_{EPB} = V_{EPB,max}$.

Then, the process is repeated in a similar maner as described in the single-satellite impact scenario. The MIEV for a particular subset satellite geometry can be express as,

$$MIEV_{2sat,EPB} = \max(IEV_{k1k2}). \tag{3}$$

2.1.3 Double-satellite impact scenario with different EPB

Since the multiple EPBs were often observed at the same time, Fig. 3 shows the possible worst-case impact scenario. Two satellites are assumed to be simultaneously affected by multiple EPBs (e.g. EPB1 and EPB2). To resemble the EPB phenomenon, the minimum horizontal separation (W) of consecutive EPBs is defined.

The IPP pairs with horizontal distance more than the defined minimum horizontal separation are only used to calculate the IEVs. In this work, the velocity of each EPB is assumed to be independent (e.g. V_{EPB1} and V_{EPB2} are independent). The IEVs are therefore calculated in a similar way with the single-satellite impact scenario. Then, the MIEV of this scenario can be express as,

$$MIEV_{2sat,Multi-EPB} = \max(IEV_{k1k3}). \quad (4)$$

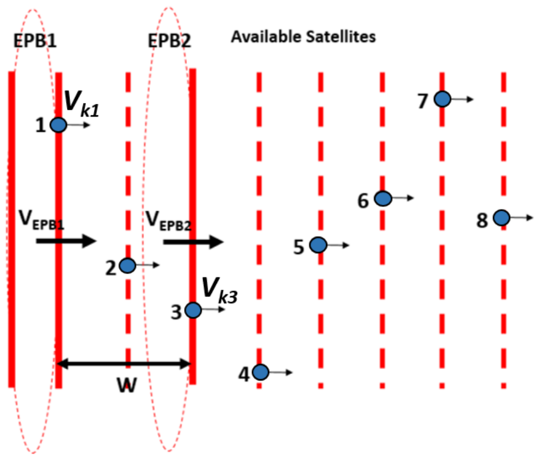

Figure 3. Double-satellite impact scenario by different EPB

After calculating MIEVs for all scenarios, the highest MIEV is considered to be a potential worst-case vertical position error of the aircraft during EPB occurrence, i.e.,

$$MIEV_{EPB} = \max([MIEV_{1sat}\; MIEV_{2sat,EPB}\; MIEV_{2sat,Multi-EPB}]). \quad (5)$$

The subset satellite geometries with $MIEV_{EPB}$ over the TEL (Tolerable Error Limit) derived from the obstacle clearance surface (28.8 meters for CAT-I GBAS [7]), will be screened out by inflating the broadcast parameters (σ_{vig} and σ_{pr_gnd}) until the VPLs (Vertical Protection Level) exceed the VAL (Vertical Alert Limit). The σ_{vig} and σ_{pr_gnd} are the standard deviation of a normal distribution associated with the residual ionospheric uncertainty due to spatial decorrelation, and the signal-in-space contribution of the pseudo-range error at the GBAS reference point, respectively. The calculation of VPLs can be obtained from,

$$VPL_{H0} = K_{ffmd}\sqrt{\sum_{i=1}^{N} S_{vert,i}^2 \sigma_i^2} \quad (6)$$

$$VPL_{eph,k} = \left|S_{vert,k}\right| x_{air} P_k + K_{mde}\sqrt{\sum_{i=1}^{N} S_{vert,i}^2 \sigma_i^2} \quad (7)$$

where VPL_{H0} is the protection level in vertical under the normal condition (no GBAS reference station faults), K_{ffmd} is the multiplier derived from the probability of fault-free missed detection, $VPL_{eph,k}$ is the protection level in vertical under the single-satellite (satellite k) ephemeris error, P_k is the broadcast ephemeris decorrelation parameter for the satellite k ranging source, K_{mde} is the broadcast ephemeris missed detection multiplier for the satellite k ranging source, σ_i is the standard deviation of a normal distribution of the residual error after correction for each satellite under the fault-free hypothesis, which can be obtained from (see Appendix B in [1]),

$$\sigma_i^2 = \sigma_{pr\_gnd,i}^2 + \sigma_{tropo,i}^2 + \sigma_{iono,i}^2 + \sigma_{air,i}^2. \quad (8)$$

2.2 Simulation Parameters

Table 2. Simulation Parameters

GBAS Parameters
$M = 3$
$x_{air} = 6$ km
$v_{air} = 70$ m/s
$K_{ffmd} = 5.81$
$K_{mde} = 3.8$
$P_k = 0.00018$
$\sigma_{vig} = 15$ mm/km
Location = 13.6945°N, 100.7608°E
Time = 18:00 – 06:00 (night time)
Almanac = 31 current GPS satellites

EPB Threat Space
g = 600 mm/km (APAC GITM)
V_{EPB} = 50-250 m/s
W = 500 km
EPB tilt angle = ±35°
Loss of satellite = 3

Table 2 shows the simulation parameters that used in this work. The GPS satellites observed at Suvarnabhumi International Airport, Thailand, during only night time are used to simulate the worst-case EPB impact scenarios. Most of GBAS parameters are defined same as in [6]. Since the APAC GITM only defined the ionospheric delay gradient (g), the other EPB threat parameters are defined based on the observation in Brazil [8]. In addition, some of all-in-view satellites are assumed to be loss of tracking due to the ionospheric scintillation effects (up to 3 satellites). Thus, the $MIEV_{EPB}$ for all possible subset satellite geometry will be simulated to identify the integrity risk. The $MIEV_{EPB}$ exceeding the TEL, but the maximum VPLs below the VAL (10 meters for CAT-I precision approach), are considered to be potentially hazardous to the GBAS users. The σ_{vig} is initially increased by the inflation factor in order to provide timely alerts for the onboard avionics. If there are still the potential unsafe subset satellite geometries, the σ_{pr_gnd} is additionally increased for all remaining potential unsafe subset satellite geometries.

3. RESULTS AND DISCUSSIONS

Since the error in range domain related to the IPP velocity, Fig. 4 shows the histogram of all possible IPP velocities in the eastward direction obseved at Suvarnabhumi International Airport, Thailand. The possible eastward IPP velocities are about 0-400 m/s, which mainly is about 20 m/s. Hence, the velocity of EPB is deliberately set with the lower bound ($V_{EPB,min}$) to create the maximum error in range domain. However, the vertical position error still depends on the vertical position component of the weight-least squares projection matrix of subset satellite geometry. Then, the $MIEV_{EPB}$ and VPLs of all possible subset satellite geometries are evaluated to identify the potential unsafe subset satellite geometry.

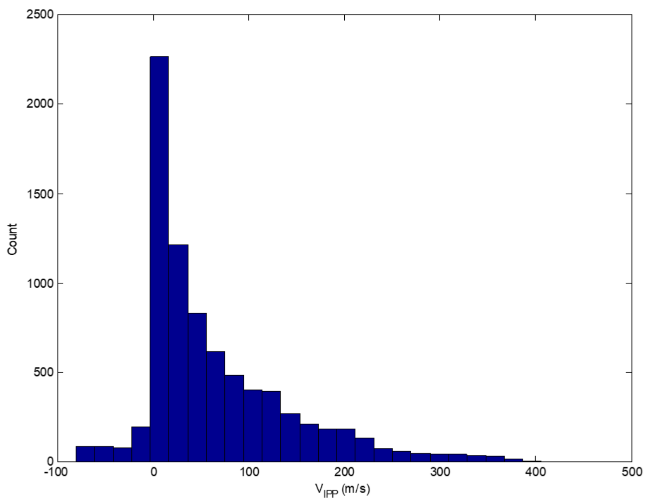

Figure 4. Histogram of all possible IPP velocities in eastward direction

To screen out the potential unsafe subset satellite geometries from the onboard avionics, the σ_{vig} is inflated by the inflation factors. Fig. 5 (top) shows the inflation factors for the σ_{vig} when assuming that some of all-in-view satellites cannot track due to the ionospheric scintillation (1 2 and 3 loss of tracking satellites, respectively). Since the maximum broadcast value of σ_{vig} is 25.5 mm/km [1], the available inflation factor is therefore less than 1.7 (the starting σ_{vig} is 15 mm/km in this simulation). The inflation factors are more frequently needed when increasing the number of loss of tracking satellite. In addition, the inflation factors occasionally reach the limit, implying that only σ_{vig} is not sufficient to completely screen out the potential unsafe subset satellite geometries. Hence, the inflations for another broadcast parameter is applied to screen out the remaining potential unsafe subset satellite geometries. To reduce the complexity of simulation, the $\sigma_{pr\_gnd,i}$ of available satellites are multiplied by the common inflation factors. Fig. 5 (bottom) shows the additional inflation factors for the $\sigma_{pr\_gnd,i}$. The additional inflation factor is generally less than 2 while the maximum broadcast value of $\sigma_{pr\_gnd,i}$ is 5.08 m [1], which can be applied the inflation factor up to ~20. Although all potential unsafe subset satellite geometries can be protected by applying both inflated broadcast σ_{vig} and $\sigma_{pr\_gnd,i}$, some of safe subset satellite geometries could be loss, which leads to reducing the system availability.

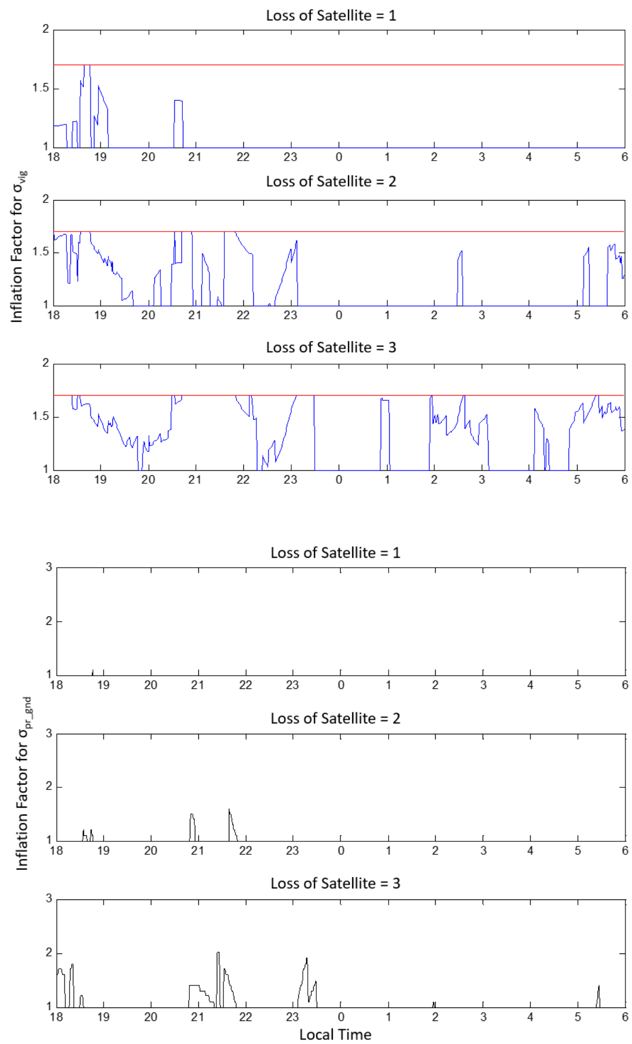

Figure 5. Inflation factor for σ_{vig} (top) and σ_{pr_gnd} (bottom)

4. CONCLUSIONS

In this work, we assess the impacts of EPB on CAT-I GBAS. The worst-case EPB impact scenarios associated with the APAC ionospheric threat model are used to simulate the worst-case position error of GBAS users. The simulation results show that both σ_{vig} and σ_{pr_gnd} are required to protect the potential unsafe subset satellite geometries. However, the system availability could be affected due to losing some of safe subset satellite geometries. The background loss of lock statistics of particular satellite could be useful for improving the system availability during the EPB occurrence.

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