OPERATIONAL MITIGATION PRACTICE TO ENABLE THE USE OF GBAS ON AREAS INFLUENCED BY HARSH IONOSPHERE PHENOMENA

Glaucia Costa Balvedi, MSc
Boeing Research & Technology Brazil
Estrada Dr. Altino Bondesan 500, Parque Tecnológico, São José dos Campos, SP, Brazil,
+55 12 3908 5463, glaucia.c.balvedi@boeing.com

Matt Harris, MSc
Boeing Commercial Aircraft Seattle
matt.harris@boeing.com

William Peterson, MBA
Boeing Commercial Aircraft Seattle
william.j.peterson2@boeing.com

José Alexandre Guerreiro Fregnani, MSc
Boeing Research & Technology Brazil
Estrada Dr. Altino Bondesan 500, Parque Tecnológico, São José dos Campos, SP, Brazil,
+55 12 3908 5464, jose.a.fregnani@boeing.com

Osamu Saotome, PhD
ITA - Instituto Tecnológico de Aeronáutica, Electronic Engineering Division
Pça. Mal. Eduardo Gomes, 50, Vila das Acácias, São José dos Campos, SP, Brazil,
+55 12 3947 5818, osaotome@gmail.com

ABSTRACT

The Ground Based Augmentation System (GBAS) is a differential augmentation system designed to correct pseudo range errors on Global Positioning System (GPS) signals in a vicinity of airports enabling the execution approach procedures based on the Performance Based Navigation (PBN) concept. In the current GBAS configurations ground stations send correction messages to the GLS-capable aircrafts, which in turn employ this information to calculate accurately its position, enabling precision approaches under CAT I and II minima.

However the current certified GBAS cannot meet the necessary ICAO Annex 10 performance requirements for CAT I approaches in some regions of the world (for instance over the Brazilian territory and South Atlantic) mainly influenced by the harsh ionosphere phenomena. These anomalies may disrupt the GPS signals in a way that the system cannot meet the necessary accuracy, availability, integrity and continuity required for reliable operations. Research efforts have been done around the world in order to find alternate possibilities in order to mitigate the ionosphere perturbations influence, including operational procedures and near future design features

(such as multiconstellation capability). In this paper, a potential implementation is proposed in order to leverage the use of GBAS in Brazil.

Keywords: GPS, GBAS, Ionosphere, PBN, Multiconstellation, Approach Procedures.

1. INTRODUCTION

Ground Based Augmentation System (GBAS) is a key enabler for current and future precision approach operations. It meets the stringent operational needs of aviation, is more economical than conventional ILS (Instrument Landing System), and has low installation, maintenance and lifecycle costs. However, GBAS is not implemented in Brazil due to harsh ionospheric effects, which affects Global Positioning System (GPS) signals in a manner that impede the system to be safely used in the Brazilian territory.

This paper presents a brief explanation of GPS and augmentation systems (Section 2), followed by a further explanation of the GBAS concept (Section 3). The reason that prevents GBAS from being used in Brazil is clarified in Section 4.

Section 5 presents potential implementation to leverage the use of GBAS in Brazil.

2. GPS AND AUGMENTATION SYSTEMS

GPS is a satellite-based radio navigation system, part of the Global Navigation Satellite System (GNSS) core constellations, that provides position and time information to a user with an appropriate receiver. It comprises at least 24 satellites at a distance of nearly 20200 km from Earth surface, distributed into six almost circular orbital planes. The period of each GPS satellite is around 12 hours. This configuration allows any user at Earth's surface to receive at least signals from four different satellites.

The satellites continually transmit range signals and navigation messages at 1575.42 MHz (L1, the civilian frequency) and 1227.6 MHz (L2, the encrypted frequency). The navigation message includes information regarding time of transmission, satellite ephemerides, and clock and propagation delay corrections.

The receiver requires signals from at least four different satellites to calculate its position and time: three for triangulation and one for clock synchronization. GPS triangulation works by determining the time it takes to receive a signal from orbiting GPS satellites. The slight time differences between each of the signals determines a location on Earth.

According to (ICAO Annex 10) the GPS position accuracy, at 95% of the time, varies according to the values indicated at Table 1. As can be noticed, vertical positioning presents more

severe errors than horizontal positioning. GPS positioning errors have many sources, including: multipath, receiver noise, hardware errors, broadcasted ephemerides errors, troposphere and ionosphere propagation errors (Parkinson B. , 1996).

Table 1: GPS position accuracy for civilian use (ICAO Annex 10)

	Global Average (95% of the time)	Worst Site (95% of the time)
Horizontal Position Error	13m (43 ft)	36m (118 ft)
Vertical Position Error	22m (72 ft)	77m (253 ft)

Navigation and Approach Aids (NAVAIDs) must meet specified requirements of accuracy, continuity, availability and integrity to each phase of flight. Signal-in-space performance requirements were establish by International Civil Aviation Organization (ICAO), also published in (ICAO Annex 10). As can be observed from Table 2, only en-route, terminal and non-precision approach operations can be safely supported by GPS ranging signals alone. Precision approach operations require stringent requirements, demanding GPS augmentation systems that can restrain navigation errors to accepted levels.

Table 2: Signal-in-space performance requirements (ICAO Annex 10)

Typical Operation Phase of Flight	**Accuracy Horizontal (95%)**	**Accuracy Vertical (95%)**	**Integrity**	**Time-to-alert**	**Continuity**	**Availability**
En-route	3.7 km (2 NM)	N/A	$1\text{-}1x10^{-7}$/h	5 min	$1\text{-}1x10^{-4}$/h to $1\text{-}1x10^{-8}$/h	0.99 to 0.99999
En-route Terminal	0.74 km (0.4 NM)	N/A	$1\text{-}1x10^{-7}$/h	15 s	$1\text{-}1x10^{-4}$/h to $1\text{-}1x10^{-8}$/h	0.99 to 0.99999
Initial approach Intermediate approach Non-precision approach (NPA) Departure	220m (720 ft)	N/A	$1\text{-}1x10^{-7}$/h	10 s	$1\text{-}1x10^{-4}$/h to $1\text{-}1x10^{-8}$/h	0.99 to 0.99999
Approach operations with vertical guidance (APV-I)	16m (52 ft)	20m (66 ft)	$1\text{-}2x10^{-7}$/h in any approach	10 s	$1\text{-}8x10^{-6}$ per 15 s	0.99 to 0.99999
Approach operations with vertical guidance (APV-II)	16m (52 ft)	8 m (26 ft)	$1\text{-}2x10^{-7}$/h in any approach	6 s	$1\text{-}8x10^{-6}$ per 15 s	0.99 to 0.99999
CAT I precision approach	16m (52 ft)	6m to 4m (20 ft to 13 ft)	$1\text{-}2x10^{-7}$/h in any approach	6 s	$1\text{-}8x10^{-6}$ per 15 s	0.99 to 0.99999

Aircraft-Based Augmentation System (ABAS), Ground-Based Augmentation System (GBAS) and Satellite-Based Augmentation System (SBAS) are examples of augmentation systems (Blanch, Walter, & Per Enge, 2012), (Murphy & Imrich, 2008). Except for ABAS, all other systems uses the concept of differential correction. In Section 3, further details about GBAS is provided.

3. GROUND BASED AUGMENTATION SYSTEM – GBAS

Ground-Based Augmentation System (GBAS) is an augmentation system that provides ranging errors corrections and integrity monitoring of Global Positioning System (GPS) signals. Developed to attend civil aviation landing procedures and substitute ILS, GBAS broadcasts its differential correction to provide required accuracy, availability, and integrity necessary for all-weather approaches (CAT I, CAT II and CAT III)[1]. Current GBAS systems approved by the Federal Aviation Administration (FAA) only monitor and augment the GPS L1 signals.

GBAS consists essentially of the space segment (GPS satellites), airborne segment (avionics) and ground segment (GPS reference receivers and central processing facility). The GPS reference receivers are installed at surveyed locations so as its latitude, longitude and height are precisely defined.

The difference between the calculated position and the surveyed position provides indication on the amount of propagation errors induced by troposphere and ionosphere, for each reference receiver. The processing facility then computes pseudorange corrections for each satellite signal sensed by the reference receivers, and broadcasts differential corrections and integrity information to the aircraft over Very High Frequency (VHF) data link from a ground transmitter. The airborne system applies the correction information in navigation solution, in order to obtain protection levels smaller than the alert limits corresponding to the current phase of flight (Lee, 2005). The corrections broadcast by GBAS improve the accuracy of GPS from 4m to better than 0.5 m. GBAS error bounds are updated every 0.5s, and thus have the potential to meet the time-to-alert requirements for all categories of precision approaches (Blanch, Walter, & Per Enge, 2012). Figure 1 depicts a typical GBAS system (Murphy & Imrich, 2008).

Today, many commercial transport aircraft are equipped with the GNSS Landing System (GLS). GLS consists of three elements: navigation satellites (GPS), onboard airplane avionics, and GBAS. Flying GLS approaches enables operational efficiency by allowing flexible operations to increase capacity, enhance safety, and reduce delays and environmental impacts. GLS offers capabilities beyond today's instrument landing system, such as added approach procedure

[1] Weather categories, CAT I, CAT II and CAT III, are used to define the decision height, runway visual range and minimum visibility for precision approaches.

flexibility, elimination of ILS critical areas to reduce delays, cost savings for airport infrastructure, and potential all weather operations.

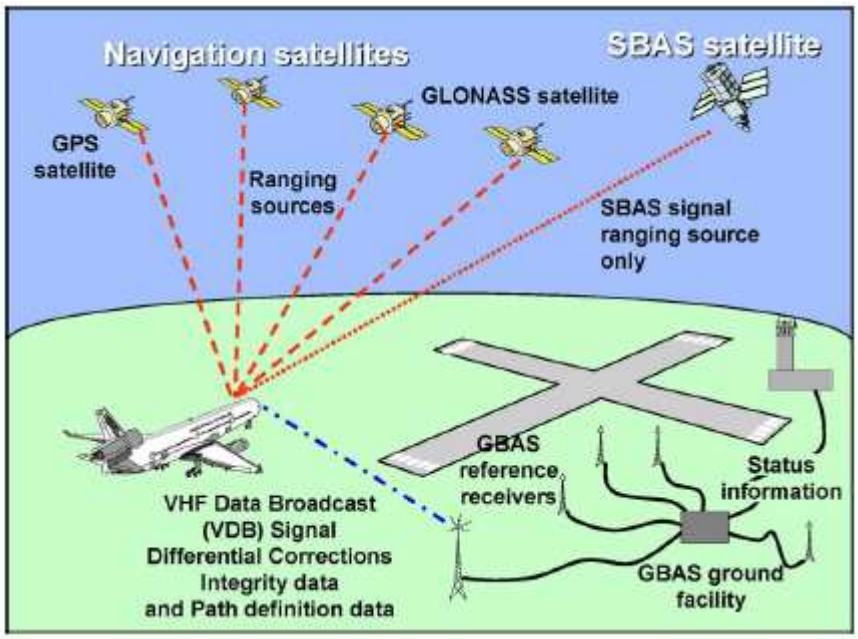


Figure 1: Ground Based Augmentation System (GBAS): space segment (satellites), airborne segment and ground segment.

4. IONOSPHERIC EFFECTS ON GPS AND GBAS

With regard to signal propagation behavior, the atmosphere can be divided in two main layers: troposphere (from Earth surface to about 50 km) and ionosphere (from 50 km to about 1000 km height). These propagation media influences radio signals, causing the tropospheric and ionospheric propagation errors, respectively. Under nominal or “quiet” atmosphere, the propagation errors can be modeled and the correction parameters, broadcasted in GPS navigation messages (Klobuchar, 1987), are sufficient to mitigate these propagation errors.

However, Brazil is located under the geomagnetic equator, which implies that Brazilian territory is under harsh disturbances in the ionosphere, such as Equatorial Anomaly (Figure 2), plasma bubbles (Figure 4), South Atlantic Magnetic Anomaly (Figure 3) (Kinter & Ledvina, 2004), (Kinter, Ledvina, de Paula, & Kantor, 2004), (de Paula, et al., 2015). The amount of error introduced by these anomalies (commonly referred to as “threats”) can be much greater than the

correction broadcasted in GPS navigation message, which increases the urgency for assessing the impact of these errors in any satellite-based aeronautical navigation system.

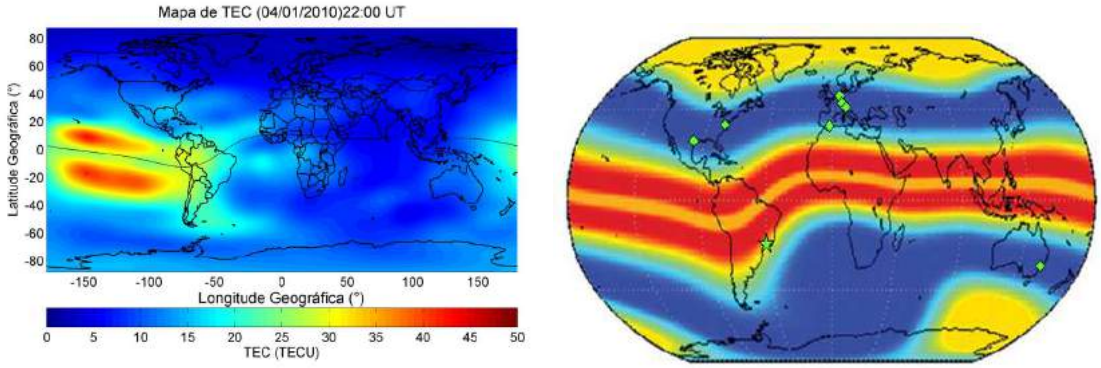


Figure 2: Equatorial Anomaly. On the left, the anomaly close to Brazilian territory. On the right, footprint of the anomaly over the globe.

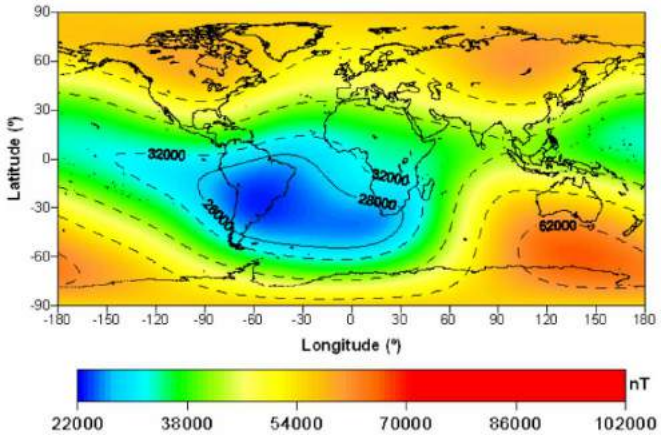


Figure 3: South Atlantic Magnetic Anomaly: region with low intensity magnetic field, enabling the penetration of cosmic radiation.

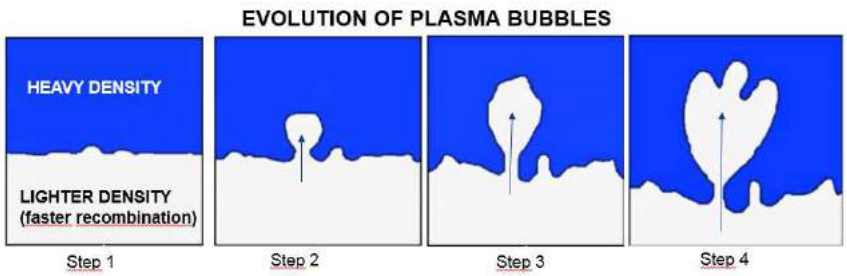


Figure 4: Evolution of plasma bubbles: lighter density plasma moves upwards heavy density plasma.

Anomalous (or disturbed) ionosphere introduces two main effects on GPS signal propagation: substantial ranging errors and scintillations. The range from the satellite from the receiver (the pseudorange) is calculated by multiplying the speed of light and time of signal propagation. However, radio signals slow down when passing through a high density, high Total Electronic Content (TEC) plasma. The optical path becomes considerable higher than the line-of-sight (LOS) path, leading to large errors on pseudorange calculation. This effect can be corrected installing reference receivers on ground, at surveyed locations, and estimate the ranging error for each GPS channel. However, if horizontal gradient scale lengths are shorter than reference receiver spacing, the corrections will be inaccurate.

Plasma depletions (plasma bubbles) of different scales sizes, varying from cm to km, scatter GPS radio signals, so that they reach a receiver through multiple paths, leading to both increase and decrease in signal amplitude (scintillations). The reduced signal amplitude can affect the receiver ability to track the GPS signals, resulting in navigation failures, as it influences directly the availability of satellite signals. This effect can last for about a minute, consequently jeopardizing the use of GPS on approaching procedures. Depending on satellite geometries, plasma bubbles can affect multiple satellites simultaneously (Harris, Murphy, & Saito, 2010). Figure 5 illustrates ranging errors and scintillations effects, and Figure 6 shows an example of scintillations affecting a GPS channel for more than one minute, impacting critically the use of GPS on precision approaches operations (de Paula, et al., 2015):

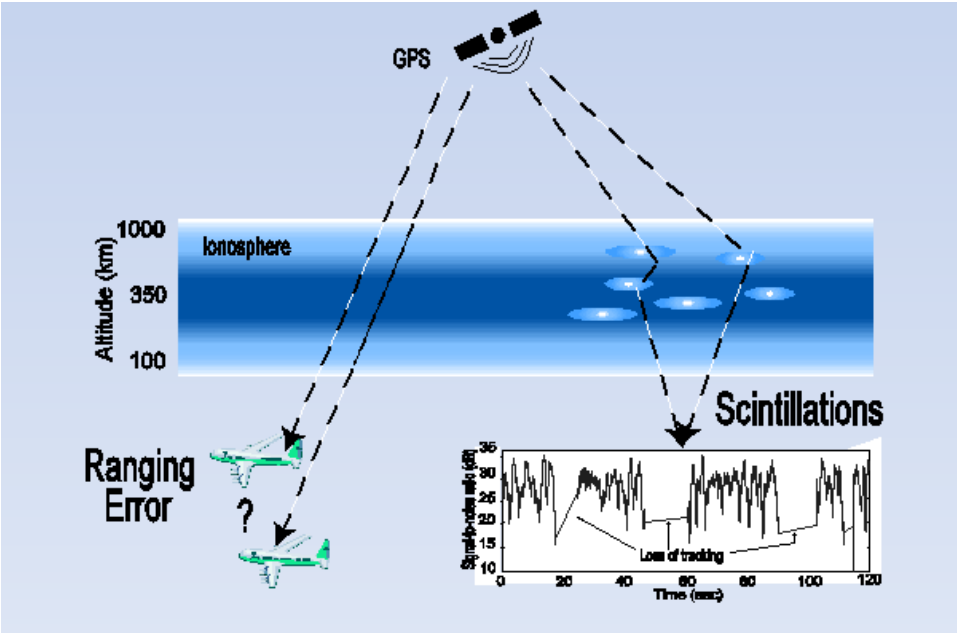


Figure 5: GPS signals can be affected by anomalous ionosphere predominantly by two ways: ranging errors and scintillation.

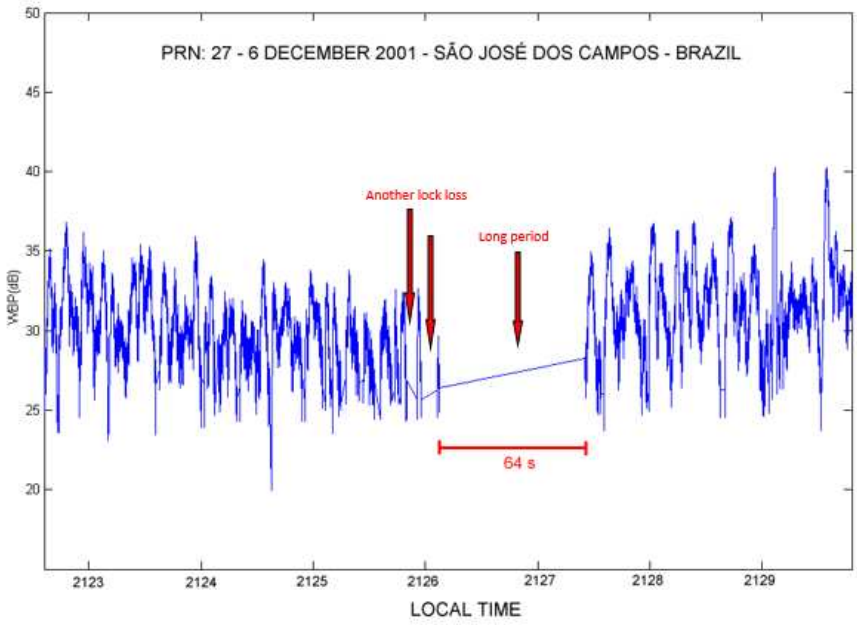


Figure 6: Example of scintillations affecting GPS channel for more than one minute.

For GBAS, the worst condition occurs when the reference receivers and the airborne equipment does not have a common error source, i.e, the ionosphere disturbances affect differently airborne and ground facility (Figure 7). This spatial decorrelation must be over-bounded and kept as small as possible, in order to reach the required levels defined in Table 2 (Mayer, Belabbas, Jakowski, Meurer, & Dunkel, 2009).

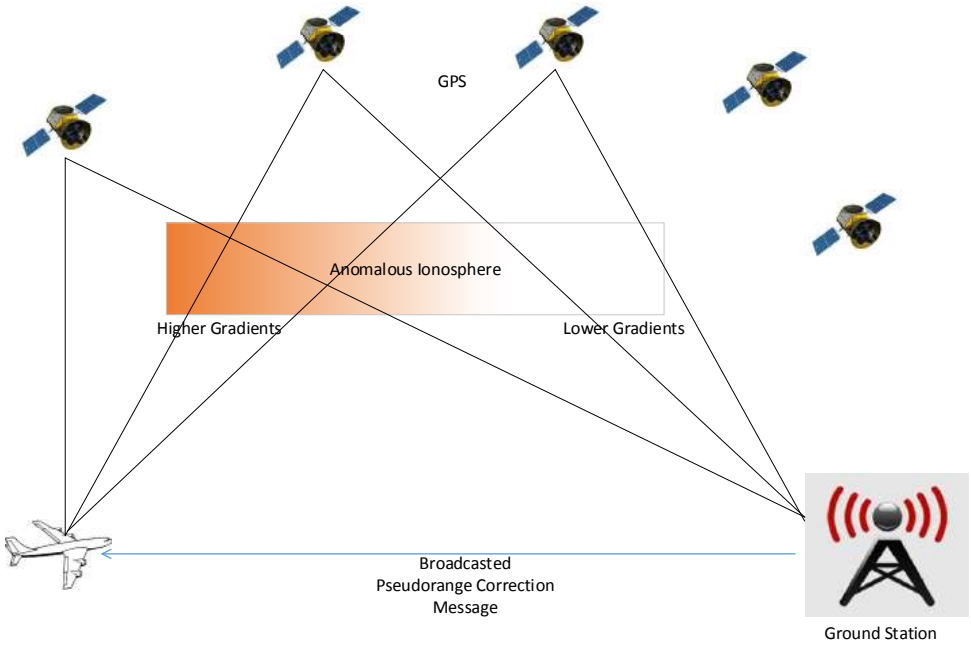


Figure 7: Worst scenario for GBAS: ionospheric disturbances affect differently reference receivers and airborne equipment.

The GBAS architecture cannot mitigate the spatially decorrelated data only by monitoring. In order to deal with the decorralated data, ionospheric threat models are applied to GBAS solution. Threat models are developed considering a set of monitored ionospheric gradients versus satellite elevation angle over a territory, in order to define the threat space: slope, velocity and width of ionospheric fronts. At each epoch (specific GPS instant time), the worst threat is assumed to occur in 100% of the time, preventing the aircraft from using unsafe combinations of GNSS satellites (Mayer, Belabbas, Jakowski, Meurer, & Dunkel, 2009).

The current GBAS ionospheric threat model (used in US GBAS stations) was assembled based on observed ionospheric data collected in CONUS (Continental United States). The CONUS ionospheric threat model has a maximum spatial gradient of 425 mm/km (Yoon, Kim, Lee, Rungraengwajiake, & Pullen, 2016).

CONUS data is not universally applicable due to the unique aspects of the ionospheric threats occurring in low latitudes, associated with the geomagnetic equator. The largest observed gradient in Brazilian territory (860 mm/km) is two times the upper bound for the CONUS. Due to this fact, there is a need for an ionospheric threat model for GBAS in Brazil, which will allow DECEA to proceed with the certification process to support GBAS installations in Brazil. The GBAS station installed at Galeao International Airport (GIG), Rio de Janeiro, Brazil, is configured with the ionospheric threat model developed to CONUS, what makes impractical its use when severe ionospheric events are occurring.

Efforts have been made by federal aviation agencies and research institutes to mitigate the ionospheric threats, in order to certify the use of GBAS as a landing method in all regions of the world including Brazil (Yoon, Kim, Lee, Rungraengwajiake, & Pullen, 2016).

5. PROPOSED GBAS OPERATIONS IN BRAZIL

The existing ionospheric threat model (CONUS) does not accurately represent the conditions found over the magnetic equator and over most part of the Brazilian territory, preventing current GBAS operations thereby compromising airspace efficiency and capacity in the terminal areas. The only currently certified GBAS station uses an ionosphere threat model initially developed for mid-latitude locations and is insufficient for Brazil, not meeting ICAO Annex 10 requirements.

Over the Brazilian territory, the ionosphere scintillation adverse effects on GPS signals are pronounced after sunset, between 1800 and 0500 local time (Yoon, Kim, Lee, Rungraengwajiake, & Pullen, 2016), and the phenomena is enhanced during summer months, from September to March (Aguiar, 2010).

Therefore, a suitable operational mitigation practice could be developed in order to allow the use of GBAS stations in Brazil out of this high activities period until the complete development of

the Brazilian ionosphere threat model, which could permit a wider availability of the GBAS stations. The authors initially suggest setting the times of GBAS operations from 0600 to 1700 local time at Southern, Southeast, Central and Northeast Brazilian Airports. Airlines trials could be performed, within those time limitations, using a higher Decision Altitude (DA) than CAT I (for example 500 ft) and obtain control baseline operational data. A conservative solution would be to use similar operational approval methodologies adopted by the Brazilian local authorities in similar contexts. For example, using operational approval standards applied to Required Navigation Performance Authorization Required (RNP-AR) approach procedures certification at Santos Dumont Airport (SBRJ). In this example, in the sake of proof of concept, during a tryout period all approaches were performed under Visual Meteorological Conditions (VMC) by the applicant airline. Afterwards, higher decision altitudes were applied until a solid safety case was built. This safety case could be used to assist the determination of operational constraints (via Notice to Airman - NOTAM), restricting the period of operations of GBAS approaches.

From September to March, the GBAS operations are suggested to be carefully monitored in order to determine the suitable operational time periods. Other operationally mitigation practices requires further multidisciplinary research efforts to be determined and implemented.

6. CONCLUSIONS

GBAS, a key component for precision approach operations, is not used in Brazil due to a lack of a suitable ionospheric threat model that represents the ionospheric conditions found over Brazilian territory. Until the development of such model, the use of the system can be leveraged by using the system during nominal ionospheric periods of the day.

GBAS has been under considerable spotlight due to its advantages over ILS. It is also target to support CAT II and III operations (Harris, Murphy, & Saito, 2010), (Harris & Murphy, 2009). Future architecture implementations such as multifrequency and multiconstellation GBAS are also being envisaged (Circiu, et al., 2015), (Alcantarilla, et al., 2006), (Konno, Pullen, Rife, & Per Enge, 2006).

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