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WORKING PAPER

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Agenda Item 3: Global and Regional Developments
3.3 CAR/SAM Air Navigation Services (ANS) Implementation Level

EVOLUTION OF THE GNSS AT LOW-LATITUDE REGIONS

(Presented by Brazil)

EXECUTIVE SUMMARY	
This document addresses issues related to the Global Navigation Satellite System (GNSS), more specifically its augmentation systems, and presents the analyses carried out to evaluate the feasibility of using these technologies in Brazil. This paper also shows the actions that have been undertaken to implement a GNSS backup system.	
Action:	As indicated in Section 5
Strategic objectives:	• Air navigation capacity and efficiency • Safety
References:	• ICAO (2002). Second Coordination Meeting on GNSS Augmentation Trials. Montreal: ICAO, 2002. (RLA/00/009 Project Document). Available at: https://www.icao.int/SAM/Documents/2002/GNSSA2/GNSSAII_WP04.pdf. Accessed on: 4 Oct. 2021. • ICAO (2006). GNSS augmentation tests. Montreal: ICAO, 2006. (RLA/00/009 Project Final Report). Available at: https://www.icao.int/SAM/eDocuments/RLA00009_ProjectFinalReport.pdf. Accessed on: 4 Oct. 2021. • Marini-Pereira, L., Pullen, S., Moraes, A. de O., & Sousassantos, J. (2021b). GBAS operation in low latitudes - PART 1: Challenges, Mitigations, and Future Prospects. Journal of Airspace Technology and Management, 13(e4621), 1–24. https://doi.org/10.1590/jatm.v13.1236

1. Introduction

1.1 The navigation requirements established in Brazil are RNAV 5 for routes and RNAV 1 for Terminal procedures. This condition allows aircraft to evolve through all phases of flight, up to the minimum decision altitude for the RNAV approach procedure, slightly higher than the minimum for a precision approach.

1.2 Therefore, aiming to optimize the services provided by GNSS, studies were carried out to apply the SBAS and GBAS augmentation systems in the country, with a view to improving the integrity, availability and continuity of the service, as well as reducing the minimum requirements to provide the use of CAT I precision approach.

1.3 During the analyses, a strong impact of ionospheric effects on signals from satellites at low-latitude regions was observed. Currently, the Dual Frequency Multi-Constellation (DFMC) concept brings with it the expectation of a solution for the implementation of augmentation systems in this portion of the globe. Another factor considered in the discussion was the cost-benefit of using these services and the implementation of a backup system, providing greater safety and fluidity to air traffic, against interference in signal reception and unavailability of the service provided by GNSS.

1.4 Therefore, considering the impact caused by the ionosphere in low-latitude regions, spurious interference in the GNSS and solutions to improve the service, this is an opportune moment for the engagement of participants with a view to analyzing technological solutions for the CARSAM environment.

2 SBAS at Low-Latitude Regions

2.1 System Assessment

2.1.1 The Brazilian Department of Airspace Control (DECEA) has been assessing, over two decades, the possibilities of implementing GNSS augmentation systems in Brazil. Around 2002, with the support of the United States Federal Aviation Agency (FAA), a Satellite-Based Augmentation System (SBAS) test bed was installed and evaluated in the country, using the infrastructure shown in Figure 1. This assessment concluded that it would not be possible to use SBAS for precision approaches in Brazil, due to the strong influence of the ionosphere. The results of this test bed are detailed in ICAO (2002; 2006), which concludes that “as a result of the first flight trials carried out in 2002 in Brazil, and later in Argentina, Bolivia, Chile and Peru, it was proven that the ionosphere effect over the GPS signal did not guarantee non-precision approaches (NPA) with vertical precision requirements.”

Figure 1 – Master and Reference Stations used in the SBAS test bed in 2002.

2.1.2 In addition to the trial mentioned above, other studies were conducted, in the academic context, to evaluate the feasibility of a SBAS in Brazilian territory, using data from the Brazilian Network for Continuous Monitoring of GNSS Systems (*Rede Brasileira de Monitoramento Contínuo* - RBMC).

2.1.3 The work carried out by Komjathy et al. (2003) compared the performance of planar and quadratic adjustments to estimate the ionospheric delay based on observations from 10 reference stations in Brazil. Furthermore, Rajagopal et al. (2004) analyzed the correlation structure of the ionosphere, using 2-D histograms, and Blanch et al. (2004) evaluated the performance of an extension of a kriging algorithm for estimating ionospheric delay. The performance of SBAS in Brazil was also evaluated by Lejeune et al. (2003), who focused on ionospheric error limits based primarily on small variations of WAAS algorithms. The studies highlighted the poor performance of the system in the Brazilian region, based on detailed analysis of various results.

2.1.4 In relation to the performance of SBAS in Brazil, the assessment by Trilles et al. (2015) showed better availability results, using 29 reference stations in Brazil and standard EGNOS algorithms, with a version developed to improve performance for what the authors called “severe ionospheric conditions.” Despite the improvements in the technique developed, the results presented by Trilles et al. (2015) are considered optimistic, as data was collected and processed out of the plasma bubble season. The cited papers focused on defining specific parameters related to the calculation of error limits in estimating ionospheric delay, while Lejeune et al. (2003) showed performance results for this parameter in Brazil. These works were limited by the restricted amount of data available.

2.1.5 More recently, the work of Marini-Pereira et al. (2021a) showed the low level of availability obtained with a single-frequency Satellite-Based Augmentation System (SBAS), using WAAS (Wide Area Augmentation System – used in the United States) algorithms with small variations. The best availability result achieved between the combinations of methodology and parameters is shown in Figure 2, for days with and without significant ionospheric activity. It is important to highlight that the analysis by Trilles et al (2015) did not consider the period of strong activity in the ionosphere.

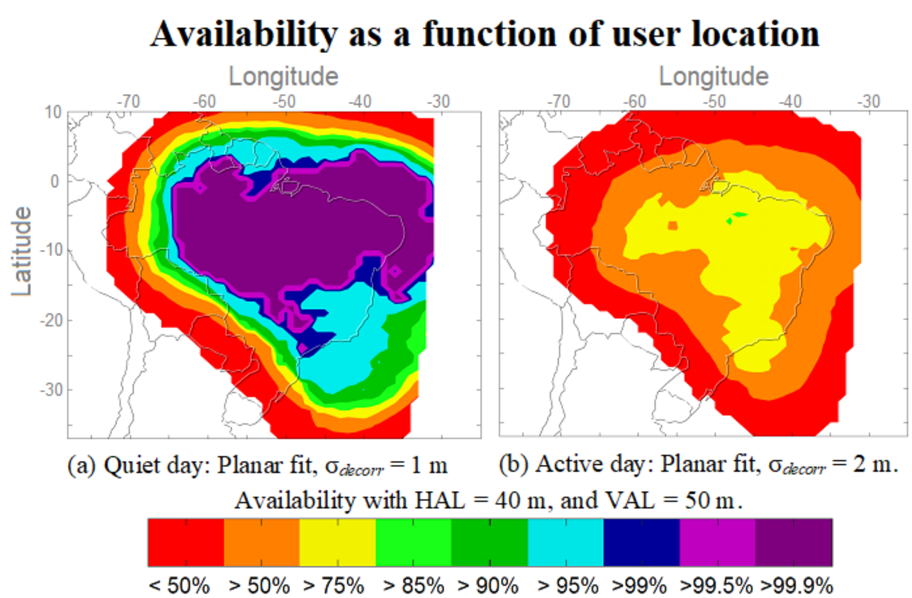

Figure 2 – Availability graphs obtained for days with high and low activity, using different parameters with planar fit interpolation, as presented in Marini-Pereira et al. (2021a).

2.1.6 Accordingly, it is possible to note that the challenges imposed by the ionosphere for the implementation of SBAS in low-latitude regions have not yet been overcome by currently available technologies.

2.2 COST-BENEFIT analysis for Brazil

2.2.1 In addition to technical limitations, it is important to analyze the operational scenario in Brazilian airspace, to verify whether the investment in implementing such a system is justified. Firstly, it is worth highlighting that 99% of the upper airways and 79% of the lower airways are RNAV 5 and that the IFR procedures in the Brazilian TMA have RNAV 1 requirements. Therefore, it is noted that the service provided by GNSS, without the augmentation systems, meets the navigation criteria stipulated for the country.

2.2.2 Figure 3 shows the result of an analysis of all Brazilian runways at all aerodromes that have RNAV/RNP (Non-Precision Approach) procedures. In the graph presented, it can be seen that approximately 45% of runways have OCH below 350 feet and this percentage rises to 65% for runways with OCH below 400 feet.

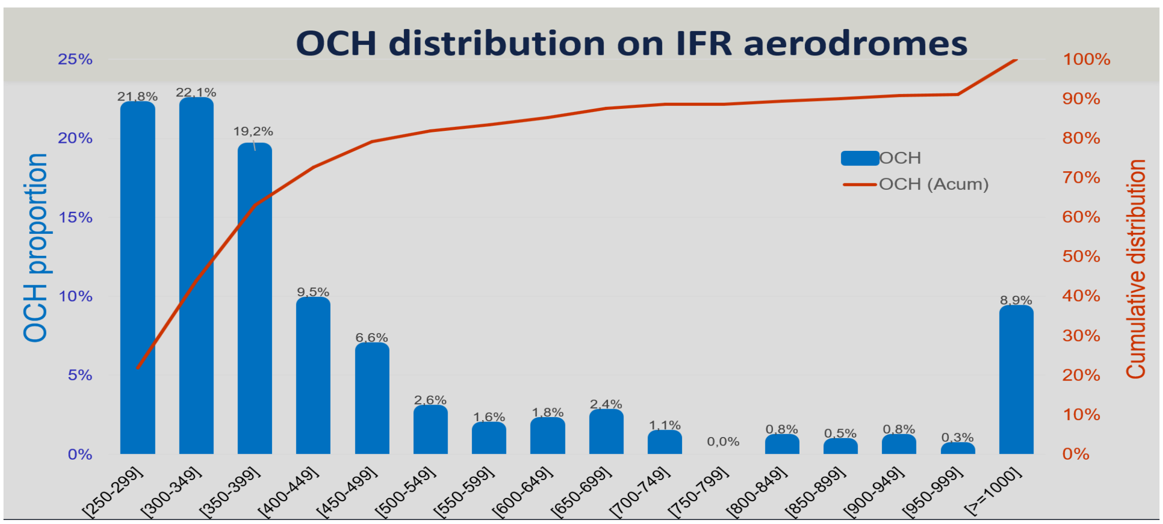

Figure 3 – OCH distribution of IFR procedures in Brazil.

2.2.3 It is worth noting that, for aerodromes that operate with CAT I precision approach, in general the OCH of RNAV procedures are 50 to 100 FT higher than those of ILS procedures. Therefore, considering the ground infrastructure necessary for the operation of an SBAS, which requires resources for its installation and maintenance (Figure 4), and considering the negative results of the trials and studies carried out, DECEA understands that this solution does not present an advantageous cost-benefit ratio for the country, in the model in which it currently operates.

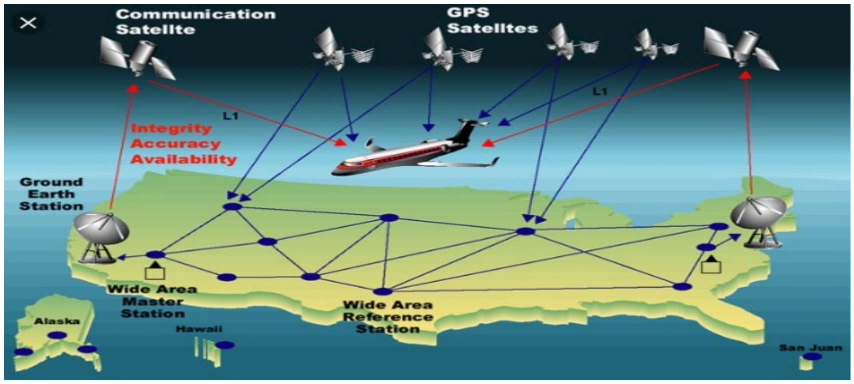

Figure 4 – Configuration of an SBAS service operation

2.2.4 Recently, DECEA began research investigating the possibility of reducing the Minimum Decision Altitude (MDA) of RNAV/RNP procedures, based on the availability of the GPS L5 frequency. The aim is to evaluate whether the use of the two GPS frequencies will make it possible to reduce the minima of the aforementioned procedures, without making use of the SBAS ground infrastructure. The expectation is that this project will be completed in 2027, taking advantage of the increase in the solar cycle predicted for 2024 and 2025.

3 GBAS at Low-Latitude Regions

3.1 System Assessment

3.1.1 In light of the conclusions regarding the suitability of an SBAS in the Brazilian region, particularly those described in the ICAO reports (2002; 2006), DECEA redirected its focus to the potential adoption of the GBAS (Ground-Based Augmentation System). A concise overview of the fundamental principles and a brief historical account of Brazil's efforts to implement GBAS technology can be found in the work of Marini-Pereira et al. (2021b) and are summarized in this document.

3.1.2 In 2011, after the FAA certified the Honeywell SLS-4000 GBAS station for use in the Continental United States (CONUS), DECEA acquired and installed a station at Rio de Janeiro International Airport (Galeão), to carry out tests and evaluate the feasibility of its use in Brazil. GBAS installation was completed when the solar activity cycle (11 years) was reaching its peak, along with the scintillation season.

3.1.3 As it was not designed for this type of environment, the station suffered unexpected alerts and shutdowns due to the occurrence of plasma bubbles in the ionosphere. For example, one of the GBAS monitors was programmed to exclude satellites with inconsistent measurements for 48 h, based on the assumption of a satellite fault. In the low-latitude environment, this monitor interpreted the scintillation effect as out-of-tolerance parameters and thus all satellites impacted by scintillation were excluded for 48 hours. As the signals from several satellites were affected by ionospheric effects, the GBAS monitor excluded a significant number of transmitting sources, significantly reducing the number of satellites considered, leading to the shutdown of the System.

3.1.4 In 2012, Honeywell started the development of a new software version of the SLS-4000 to perform better at low latitudes. Among the new features, it was possible to configure a custom ionospheric threat model (as opposed to the fixed CONUS threat model originally included). A low-latitude ionospheric threat model (focused on Brazil) was developed by a multidisciplinary team from several organizations in Brazil, the US and South Korea. The results are described in Mirus Technology (2015) and discussed in

Lee et al. (2015) and Yoon et al. (2017). They show anomalous ionospheric gradients much larger than those in the CONUS threat model, affecting the availability and integrity of a GBAS in Brazil (Figure 5).

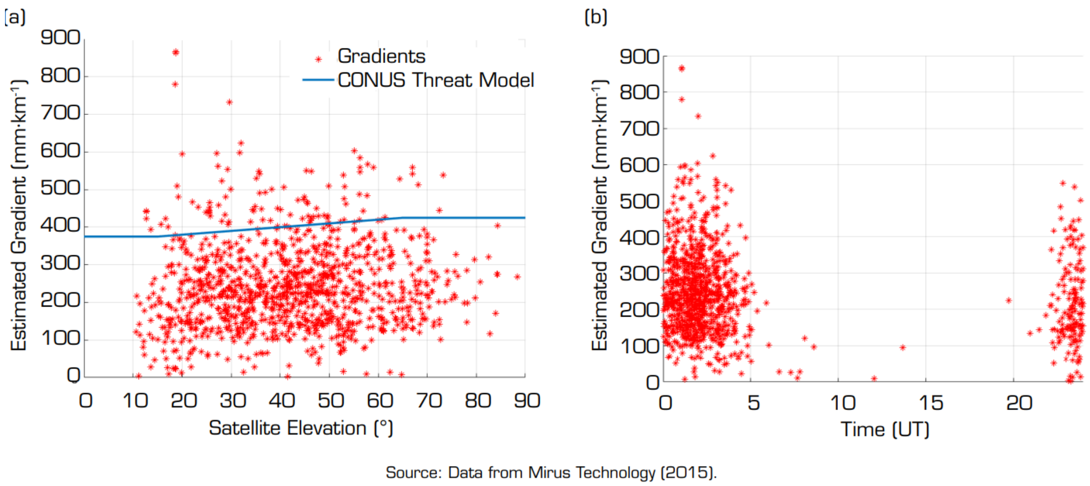

Figure 5 – Ionospheric gradients observed in Brazil. (a) Distribution based on the satellite elevation angle, CONUS threat model as reference; (b) Distribution based on UTC time

3.1.5 This multidisciplinary team also examined the station's operational conditions and identified that GBAS operation would only be safe at specific times of the day (Figure 5), when the CONUS ionospheric threat model can be used (Chang et al. 2019; 2021). Due to this restriction, Brazilian authorities decided not to certify the system for operations in Brazil.

3.1.6 With the advent of the Dual Frequency Multi-Constellation (DFMC) concept, expectations for the application of GBAS in Brazil have been renewed and are being monitored by the DECEA team.

3.2 Perspectives for DFMC GBAS

3.2.1 The United States and Europe have been investing resources in the analysis of GBAS GAST-C (GBAS Service Type C) and GAST-D. These models provide the service of increasing positioning from a single frequency constellation, viable for use in mid-latitude regions. Other nations, such as Japan, have focused on analyzing and developing a system that uses the DFMC concept to solve ionospheric problems (GAST-F and GAST-X) at low latitudes.

3.2.2 The expectation is that the availability of GPS L5 and Galileo E5 signals has the potential to mitigate ionospheric effects in real time and, thus, guarantee the integrity necessary for air navigation. However, scintillation at low-latitude regions affects the L5 signal more prominently, which raises concerns for the use of this frequency. It can be seen, based on the work of Salles et al. (2021a), that scintillation events have a greater impact on the L5 frequency than on L1. It was also noticed that the fading of the L5 signal reaches values close to twice the values of the L1 signal. These results corroborate the statistical analysis presented by Moraes et al. (2018), in which evidence of more severe fading occurrences was found in the L5 frequency.

3.2.3 One of the solutions considered for this problem consists of using dual frequency only for monitoring the ionosphere, with positioning carried out only with the L1 frequency. The work produced by Felux et al. (2017a) suggests using an “ionosphere-free” model for monitoring the ionospheric gradient, while position calculation is performed by the single-frequency approach, if possible, using two constellations.

3.2.4 DECEA is restructuring the ionosphere monitoring network to receive new constellations and frequencies, with a view to evaluating the impact of ionospheric effects on the DFMC concept, for the application of augmentation systems, especially GBAS, for future use of this technology in the country. The forecast is that, by 2028, Brazil will have robust data to evolve in proposing a solution that allows the application of precision procedures based on satellite signals, starting in the 2030s.

4 Implementation of DME/DME Navigation as GNSS backup

4.1 As previously mentioned, a considerable number of Routes RNAV 5 and RNAV 1 are already in operation in Brazilian airspace. Performance-Based Navigation (PBN), supported exclusively by GNSS data, presents the inconvenience of the air navigation service provider not having control of the satellite environment, in addition to possible interference to which the system is subject. To mitigate these potential risks, ICAO, through the Global Air Navigation Plan (GANP), defined the objective of adopting measures that guarantee the necessary resilience for air navigation services.

4.2 To comply with ICAO guidelines, States began installing DME to support DME/DME and/or DME/DME/INS navigation, as a contingency to GNSS. In Brazil, the implementation of new DME systems aimed to improve the safety and efficiency of performance-based navigation, when used in conjunction with other available means, in a broader GNSS/DME/INS context.

4.3 During the design phase of the new System, it was defined that DME/DME navigation should serve the main upper airways, above FL 250 inclusive, and the main Terminal Areas (TMA) in the country. The implementations began in 2016 and will be completed in 2025, totaling 52 isolated pieces of equipment. The DME associated with the DVOR were also used to analyze DME/DME coverage. The DME associated with the ILS are not considered, due to the adjustment to indicate the distance from the runway threshold and not the actual position of the equipment.

4.4 Due to the extension of the Brazilian territory, DME/DME/INS navigation was chosen for the en-route, arrival (STAR) and departure (SID) flight phases. The airways that connect the busiest airports in the country were also prioritized, as shown in Figure 6.

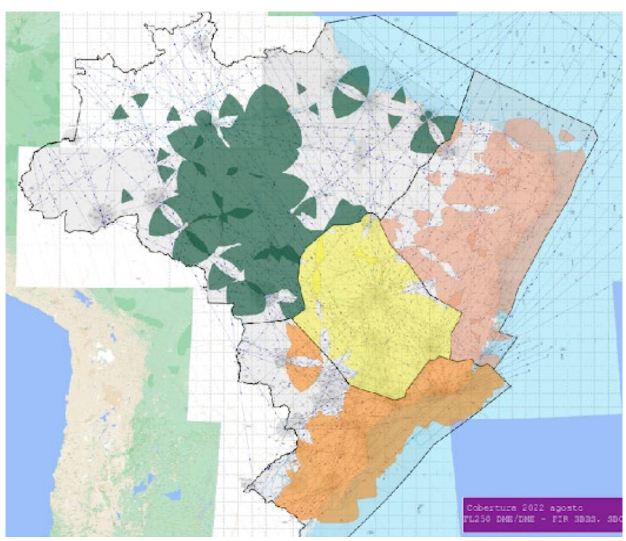

Figure 6 – DME/DME coverage map of upper airways (FL 250)

4.5 When analyzing the number of regular flights operating in Brazilian airspace, it was identified that approximately 85% of traffic has the capacity to carry out DME/DME or DME/DME/INS navigation (Figure 7). This fact indicates that, in the event of failure or interference in the GNSS, the DME system will significantly reduce the impact of the lack of GNSS, maintaining the fluidity of air traffic.

PERÍODO: 01/12/2020 - 13/01/2021									
EMPRESA	TOTAL	B1C1D1	B3D3	B5D1	B3D1	B5D4	PERCENTUAL ROTA DME/DME/INS	PERCENTUAL PROC. DME/DME/INS	PERCENTUAL DME/DME
GOL	22.973	21.485		1.475			99,94%	99,94%	0,00%
TAM	17.494	17.463					99,82%	99,82%	0,00%
AZUL	28.406	17.778	6.310	2.508			71,41%	71,41%	22,21%
PASSAREDO	1.755						0,00%	0,00%	0,00%
TAP	228	228					100,00%	100,00%	0,00%
AAL	229	229					100,00%	100,00%	0,00%
EMIRATES	105	105					100,00%	100,00%	0,00%
UAL	232	231					99,57%	99,57%	0,00%
SIDERAL	1211		1	10		1.157	96,37%	96,37%	0,08%
TOTAL	331						0,00%	0,00%	0,00%
ABSA	268	1			267		0,37%	100,00%	99,63%
FEDERAL EXPRESS	36	36					100,00%	100,00%	0,00%
LUFTHANSA CARGO	73	73					100,00%	100,00%	0,00%
QATAR	94	94					100,00%	100,00%	0,00%
CARGOLUX	62	62					100,00%	100,00%	0,00%
TOTAL	73.497	57.785	6.311	3.993	267	1.157	85,63%	85,99%	8,95%
NACIONAIS	70.628	56.726	6.310	3.983	0	0	85,96%	85,96%	8,93%
INTERNACIONAIS	887	888	0	0	0	0	100,00%	100,00%	0,00%
CARGAS	1.981	172	1	10	267	1.157	67,59%	81,07%	13,48%
TODOS FLP/RPL	169.311	60.624	8.618	4.379	267	1.372			
	B2D2	41.814							

Figure 7 – Distribution of navigation criteria for traffic operating in Brazil

4.6 Finally, to evaluate the characteristics of the service, to be made available to users of the Brazilian Airspace Control System in 2024, the following documentation was used to define the navigation, flight inspection and ground testing criteria:

- Annex 10, Volume 1;
- Doc 9613;
- Doc 8168;
- Doc 8071;
- EUROCONTROL-GUID-0114; and
- AC 90-100A.

5 SUGGESTED ACTIONS

5.1 The Meeting is invited to:

a) Take note of the information contained in this working paper and provide comments and opinions;

b) Contribute with additional analyses; and

c) Formulate other actions deemed necessary by the group for the CARSAM environment.

— END —