DEMAND FOR INSTRUMENT LANDING IN BRAZIL BASED ON HISTORICAL WEATHER ASSESSMENT

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ABSTRACT

Ground-Based Augmentation System (GBAS) is being discussed as an opportunity for safer and cost efficient approaches. Thus, it is important to quantify the impact of diversions due to meteorological conditions. We proposed a methodology to assess demand for instrument landing related to meteorological conditions in Brazil based on the Meteorological Aerodrome Report (METAR) data. The top quartile aerodromes in Brazil were used to test and validate the proposed methodology. Our analyses showed that Visual Meteorological Condition (VMC) and Non-Precision Approach (NPA) together represent 97% of the conditions to which the aerodromes investigated operate under over the last eight years. Instrument landings were demanded, on average, 1.5% of the time in Category I; whereas Categories II and III represented 0.9 and 0.6% of operations, respectively. The analysis of the Brazilian top quartile aerodromes weather data shows that the implementation of GBAS CAT I/II and III operations may represent approximately 150 Million USD potential savings for the industry, related to avoided diversions and cancelled flights.

Keywords: Ground-Based Augmentation System (GBAS), Meteorological Aerodrome Report (METAR), landing procedure, Instrument Landing System (ILS), diversion, Ionosphere scintillation.

1. INTRODUCTION

Ground-Based Augmentation System (GBAS) is a system that provides differential corrections and integrity monitoring of Global Navigation Satellite Systems (GNSS). GBAS provides navigation and precision approach service in the vicinity of the host airport (approximately a 23 nautical mile (Nm) radius), broadcasting its differential correction message via a very high frequency (VHF) radio data link from a ground-based transmitter. GBAS yields the extremely high accuracy, availability, and integrity necessary for Category I (CAT I), and eventually Category II (CAT II) and Category III (CAT III) precision approaches, as detailed by the Federal Aviation Administration (FAA, 2016). GBAS demonstrated accuracy is less than one meter in both the horizontal and vertical axis. Indeed, the corrections broadcast by GBAS improve the accuracy of Global Positioning System (GPS) from 4 m to better than 0.5 m. In the past, FAA referred to GBAS as the Local Area Augmentation System (LAAS). The FAA GBAS program is currently conducting research and development (R&D) in many countries prototyping effort to reduce the technical risk and validate new requirements associated with meeting the GBAS Approach Service Type D (GAST-D), which will be capable of supporting approaches to CAT III minima. The requirements validation effort supports the acceptance of national and international standards for GAST-D. This effort will support approval of the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) and Radio Technical Commission for Aeronautics (RTCA) Minimum Operational Performance Standards (MOPS).

GBAS is not implemented in Brazil yet due to harsh ionospheric effects (Pereira and Camargo, 2017), which affects GPS signals in a manner that the requirements of accuracy, availability, integrity and continuity are not guaranteed to be achieved by the system to safely be used over the Brazilian territory. 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 (2010) requirements. This results in an inefficient use of airspace capacity around those areas where airlines and other aircraft operators are impacted not only with higher costs and delays, but also with significant decrease in airport's capacities and multiple diversions in some regions. Ionospheric effects cause signal scintillation, which occurs more intensely in areas around the magnetic Equator (i.e., low-latitude locations). In addition, recent researches pointed out that the phenomena over the Brazilian territory tend to be more severe around the spring and summer (September to March in the South hemisphere) (Aguiar, 2010) and also between 6PM and 5AM local time (Yoon et. al., 2016). Therefore solutions tailored for other regions (such as the Continental United States (CONUS)) are not certifiable along a wide area of the Brazilian territory and South Atlantic.

Brazilian Department of Airspace Control (DECEA), Mirus Technology, FAA, Boston College, Honeywell and Boeing Research & Technology - Brazil (BR&T-Brazil) are working towards GBAS in Brazil and interoperability by sharing technical expertise, operational experience and approval processes via the GBAS Safety Case Working Group. The initial proposal from DECEA is to develop a safety case to Rio de Janeiro region, permitting GBAS CAT I operations to be certified at Galeão International Airport (SBGL) with assessment of the period the system would be allowed to be used (i.e., not necessarily 24/7). In addition, there are further opportunities in other key airports in the Southern region of the Brazilian territory where GBAS could be implemented in complement to Required Navigation Performance – Authorization Required (RNP-AR) and area navigation (RNAV) approaches. These locations are frequently affected by impending meteorological conditions during winter season (June to September) and may vide a solid business case for GBAS implementation in such airports. In this case, minimums could be lowered from Non-Precision Approaches (NPAs) to CAT I at least.

The aim of this investigation is to propose a methodology to estimate percentages of approaches according to historical reported meteorological conditions and assess the impact (with a business case) of having eventually GBAS CAT I, II or III operations implemented. Top quartile

aerodromes in Brazil, in terms of number of operations, were selected to test and validate the proposed methodology as well as to provide a flavor of the business case associated to landing operations with severe weather conditions in Brazil.

2. MATERIAL AND METHODS

For this study, we considered the top quartile aerodromes in Brazil based on number of operations (sum of landing, take off, crossing and go-around) in 2016 as reported by DECEA (2016). Aerodromes SBMT (Campo de Marte, in São Paulo city) and SBJR (Jacarepaguá, in Rio de Janeiro city) are ranked 8th and 12th (with 84,317 and 72,475 operations in 2016), respectively, but were not included because they do not operate for commercial aviation. Table 1 lists all the 23 ranked aerodromes considered with detailed location, as shown in Figure 1.

Table 2: Ranked top quartile aerodromes in Brazil based on number of operations (DECEA, 2016).

Rank[1]	ICAO[2] Code	IATA[3] Code	Airport Name (Nickname)	City, State	Latitude	Longitude	Altitude ft (m)[4]	Runway (s)
1	SBGR	GRU	Gov. André Franco Montoro (Cumbica)	Guarulhos, SP	23°26'08"S	46°28'23"W	2461 (750)	09L/R; 27L/R
2	SBSP	CGH	Congonhas	São Paulo, SP	23°37'34"S	46°39'23"W	2631 (802)	17L/R; 35L/R
3	SBBR	BSB	Pres. Juscelino Kubitschek	Brasília, DF	15°52'16"S	47°55'07"W	3497 (1066)	11L/R; 29L/R
4	SBGL	GIG	Antonio Carlos Jobim (Galeão)	Rio de Janeiro, RJ	22°48'36"S	43°15'02"W	28 (9)	10; 28; 15; 33
5	SBRJ	SDU	Santos Dumont	Rio de Janeiro, RJ	22°54'36"S	43°09'45"W	10 (3)	02L/R; 20L/R
6	SBKP	VCP	Viracopos	Campinas, SP	23°00'25"S	47°08'04"W	2156 (657)	15; 33
7	SBCF	CNF	Tancredo Neves (Confins)	Belo Horizonte, MG	19°37'28"S	43°58'19"W	2713 (827)	16; 34
9	SBSV	SSA	Deputado Luis Eduardo Magalhães	Salvador, BA	12°54'31"S	38°19'21"W	66 (20)	10; 28
10	SBPA	POA	Salgado Filho	Porto Alegre, RS	29°59'38"S	51°10'16"W	10 (3)	11; 29
11	SBRF	REC	Gilberto Freire (Guararapes)	Recife, PB	08°07'35"S	34°55'22"W	33 (10)	18; 36
13	SBCT	CWB	Afonso Pena	Curitiba, PR	25°31'54"S	49°10'34"W	2989 (911)	15; 33; 11; 29
14	SBGO	GYN	Santa Genoveva	Goiânia, GO	16°37'47"S	49°13'36"W	2451 (747)	14; 32
15	SBFZ	FOR	Pinto Martins	Fortaleza, CE	03°46'33"S	38°31'56"W	82 (25)	13; 31
16	SBFL	FLN	Hercílio Luz	Florianópolis, SC	27°40'13"S	48°33'09"W	16 (5)	14; 32
17	SBVT	VIX	Eurico de Aguiar Salles	Vitória, ES	20°15'29"S	40°17'11"W	10 (3)	05; 23
18	SBBH	PLU	Carlos Drummond de Andrade (Pampulha)	Belo Horizonte, MG	19°51'07"S	43°57'02"W	2589 (789)	13; 31
19	SBBE	BEL	Julio Cezar Ribeiro (Val de Cans)	Belém, PA	01°23'05"S	48°28'44"W	56 (17)	06; 24; 02; 20
20	SBRP	RAO	Leite Lopes	Ribeirão Preto, SP	21°08'11"S	47°46'36"W	1804 (550)	18; 36
21	SBEG	MAO	Eduardo Gomes	Manaus, AM	03°02'20"S	60°02'46"W	262 (80)	11; 29
22	SBLO	LDB	Governador Jose Richa	Londrina, PR	23°19'49"S	51°08'12"W	1867 (569)	13; 31
23	SBNF	NVT	Ministro Victor Konder	Navegantes, SC	26°52'43"S	48°39'03"W	16 (5)	07; 25
24	SBCG	CGR	(Campo Grande)	Campo Grande, MS	20°28'10"S	54°40'13"W	1834 (559)	06; 24
25	SBUL	UDI	Ten-Cel Av César Bombonato	Uberlândia, MG	18°53'01"S	48°13'31"W	3094 (943)	04; 22

[1]Ranked aerodromes in Brazil based on number of operations (landing, take off, crossing and go-around) in 2016 according to DECEA (2016). Although SBMT (Campo de Marte, in São Paulo) and SBJR (Jacarepaguá, in Rio de Janeiro) are ranked 8th and 12th (with 84,317 and 72,475 operations in 2016), respectively, they do not operate for commercial aviation (but military and general ones); [2]ICAO is the International Civil Aviation Organization; [3]IATA is the International Air Transport Association; [4]Altitude reported in feet (ft) and, inside parenthesis, the same altitude reported in meters (m).

Table 2: Number of METAR observations downloaded from INPE (2017), with detailed information per aerodrome (total of 23 as listed in Table 1) per year (2009 to 2016).

ICAO[1] Code	Total	2009	2010	2011	2012	2013	2014	2015	2016
SBGR	**67,683**	9,494	8,767	8,764	8,687	8,718	5,802	8,707	8,744
SBSP	**66,839**	8,760	8,758	8,747	8,673	8,723	5,808	8,669	8,701
SBBR	**67,687**	9,496	8,759	8,752	8,698	8,730	5,808	8,717	8,727
SBGL	**67,679**	9,502	8,764	8,760	8,687	8,720	5,803	8,706	8,737
SBRJ	**56,225**	9,317	6,570	6,573	6,491	6,569	4,361	7,623	8,721
SBKP	**66,925**	8,758	8,763	8,750	8,684	8,716	5,801	8,711	8,742
SBCF	**67,608**	9,496	8,758	8,748	8,660	8,718	5,798	8,706	8,724
SBSV	**67,753**	9,512	8,776	8,783	8,694	8,725	5,804	8,716	8,743
SBPA	**66,973**	8,759	8,758	8,777	8,686	8,722	5,814	8,714	8,743
SBRF	**67,690**	9,493	8,757	8,775	8,682	8,722	5,810	8,714	8,737
SBCT	**67,687**	9,498	8,757	8,783	8,682	8,728	5,816	8,710	8,713
SBGO	**67,529**	9,449	8,760	8,747	8,640	8,715	5,803	8,703	8,712
SBFZ	**67,652**	9,495	8,750	8,745	8,686	8,718	5,806	8,714	8,738
SBFL	**67,707**	9,497	8,760	8,761	8,687	8,722	5,812	8,717	8,751
SBVT	**67,485**	9,423	8,757	8,742	8,642	8,717	5,792	8,695	8,717
SBBH	**62,934**	8,690	8,742	8,693	7,751	8,481	5,764	8,149	6,664
SBBE	**67,681**	9,505	8,767	8,759	8,666	8,718	5,822	8,708	8,736
SBRP	**68,341**	10,244	8,763	8,744	8,643	8,718	5,801	8,704	8,724
SBEG	**66,831**	8,727	8,733	8,688	8,684	8,724	5,818	8,714	8,743
SBLO	**67,620**	9,504	8,759	8,747	8,683	8,721	5,801	8,704	8,701
SBNF	**52,614**	7,044	6,862	6,959	6,831	6,695	4,624	6,897	6,702
SBCG	**67,731**	9,499	8,760	8,753	8,688	8,729	5,838	8,715	8,749
SBUL	**64,533**	10,174	8,737	8,694	7,717	8,487	5,538	7,602	7,584
TOTAL	**1,519,407**	**213,336**	**197,337**	**197,244**	**193,642**	**195,936**	**130,644**	**195,715**	**195,553**

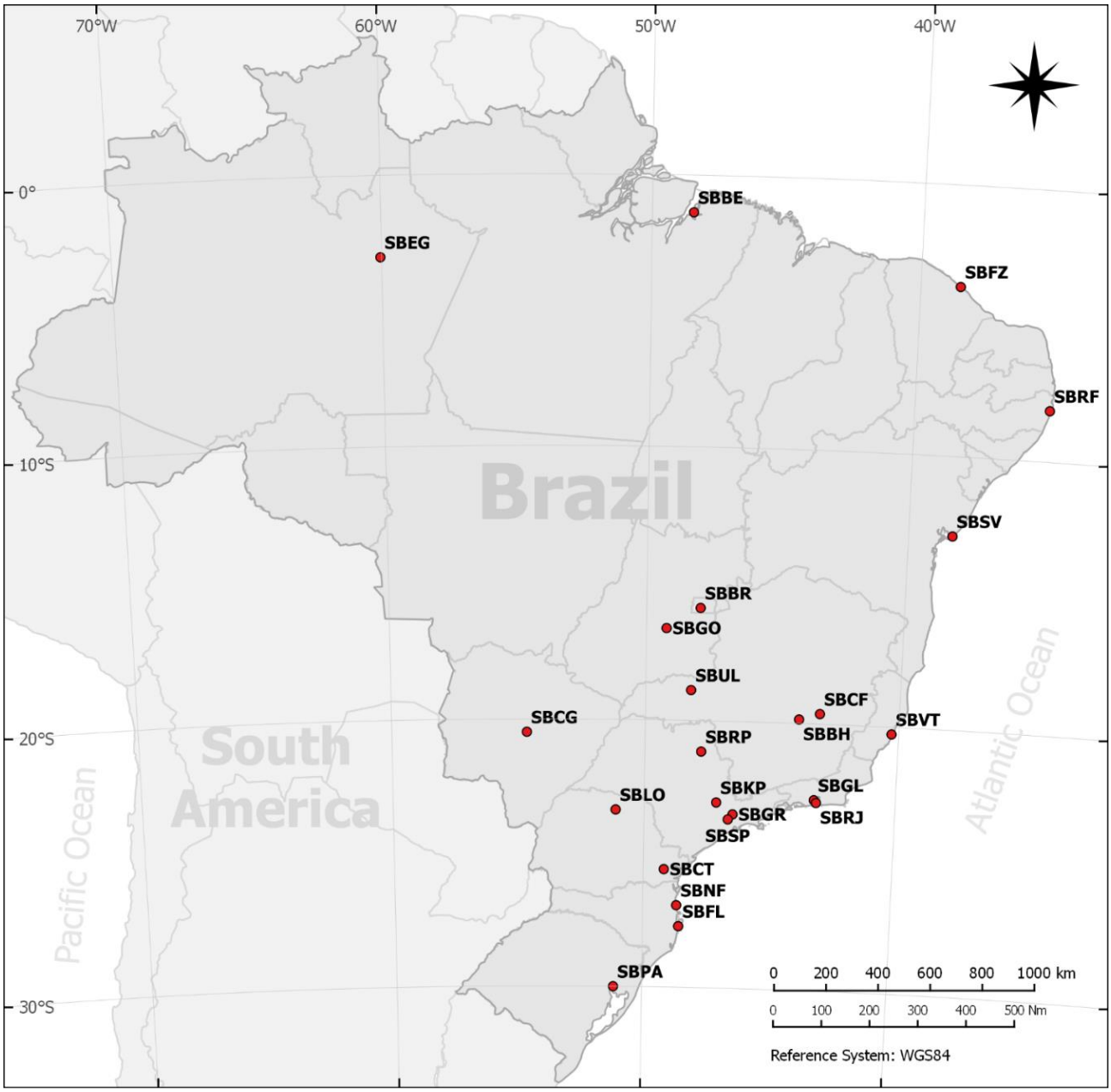


Figure 1: Location of the top quartile aerodromes in Brazil considered for this investigation (see Table 1).

Meteorological Aerodrome Report (METAR) data have been downloaded in text format from the Brazil's National Institute for Space Research (INPE, 2017) website. It required registration and contains historical data backed in July 1999 (there are lacks of data in the dataset, such as 2007 data for the SBNF aerodrome). We downloaded more than 1.5 million observations from 2009 to 2016 for the top quartile aerodromes in Brazil (see Table 3). Number of observations per aerodrome per year are detailed in Table 2. The data contained in the METAR dataset is reported hourly with information regarding date and time, and weather condition with detailed info such as cloud type, horizontal visibility, base of cloud height and wind velocity among others.

It was assumed that the weather minimums (ceiling and visibility) would be the baseline to define which approach procedure should be executed. From all the information reported in the METAR data, the height of base of clouds (BASE), which may be understood as the ceiling, is one of the most crucial to determine conditions for landing approaches. Operational regulations in Brazil, defined by the National Civil Aviation Agency (ANAC, 2010) in harmonization with DECEA, state the minimum meteorological requirements for commercial aircraft to initiate Instrument Flight Rules (IFR) approach procedures. DECEA (2017) modified these requirements on June 22nd, 2017 to not consider the ceiling as a requirement. From that date on, ceiling is not a

requirement as operators should then follow the visibility. Although the METAR reports visibility, it refers to horizontal visibility, which is different from the slant visibility perceived by the pilot to land the airplane. In that sense, in this study it is considered the ceiling as it would be the best estimator (from the METAR data) to the visibility the pilot would experience at the decision altitude when approaching for a landing procedure. Table 3 summarizes the rules defining the landing procedures as considered in this investigation. These rules were generically applied to every aerodrome listed in Table 1 to find what landing approaches are more likely to occur in a specific aerodrome.

Table 3: Landing procedures considered for this research.

Acronym	Description	Condition*
VMC	Visual Meteorological Conditions	*BASE* ≥ 1500 ft
NPA	Non Precision Approaches	1500 ft > *BASE* ≥ 300 ft
CAT I	Instrument Landing System (ILS) – Category I	300 ft > *BASE* ≥ 200 ft
CAT II	Instrument Landing System (ILS) – Category II	200 ft > *BASE* ≥ 100 ft
CAT III	Instrument Landing System (ILS) – Category III	*BASE* < 100 ft

**BASE* is the height of base of cloud reported in the METAR data in meters (m). We used 3.28084 to convert to feet (ft).

R Software (R Core Team, 2016) was used to perform all data analysis, which was done per aerodrome (all years at once). Indeed, for each one out of the 23 aerodromes listed in Table 1, we counted the number of observations reported in the METAR classifying the landing approach based on the ceiling as defined in Table 3. METAR reported the value "zero" for BASE when ultra-severe weather condition (low visibility) was observed and also when no data was available. Thus, we used horizontal visibility to determine what cases it regarded to severe weather conditions (i.e., when visibility was < 550 m) and when it referred to no data available (visibility >= 550 m). When BASE was reported as greater than "zero" we classified the landing approach based only on BASE. Instances were counted and statistics were performed. In that manner, we calculated the percentage of the time that every aerodrome would perform under conditions of VMC, NPA, CAT I, CAT II and CAT III (as defined in Table 3) averaged over the last eight years (i.e., 2009 to 2016). With the assumption that those percentages might represent an averaged weather condition for the aerodromes investigated, we assume that the percentages might represent probabilities for the aerodrome to operate under the considered conditions (Table 3) during the year.

Total number of movements (landing, take off, crossing and go-around) per aerodrome, related to the Brazilian commercial aviation in 2016, were extracted from the last report published by DECEA (2016). It is worth mentioning that we used the commercial aviation statistics that do not include general nor military aviation. By assuming that 50% of operations regards to landings, we calculated the total number of landings, per year, performed at each aerodrome listed in Table 1 under the conditions listed in Table 3. Weather condition may cause diversion of an airplane if the aerodrome is not equipped with precision instruments to be used for instrument landings. With the purpose to estimate the business value related to every procedure we calculated the yearly cost regarding all diversions, per aerodrome. Eventually, we considered the current implemented capability for the aerodrome and then what would be the business case to implement GBAS to augment capability in top quartile aerodromes where ILS landings are not considered for all the three categories investigated.

3. RESULTS AND DISCUSSION

Table 4 lists the 23 aerodromes investigated (see Table 1) with calculated percentages representing occurrence of weather events that would require landing approached procedures as listed in Table 3. It also lists current capability implemented in each one of the aerodromes investigated.

Table 4: Summary of the averaged landing approach % estimation based on meteorological conditions for the period of 2009 to 2016 in all the 23 aerodromes considered (see Table 1). For the capabilities already implemented the percentages were shown in grey whereas red represent capabilities not yet implemented.

ICAO Code	VMC %	NPA %	CAT I %	CAT II %	CAT III %	Current capability implemented[1]
SBGR	69.27	26.05	2.41	1.10	1.17	ILS CAT III-A in Rwy 09R (CAT II in Rwy 09L); ILS CAT I in Rwy 27L
SBSP	67.89	25.50	3.46	2.59	0.56	ILS CAT I in Rwy 17R and Rwy 35L
SBBR	81.81	17.29	0.52	0.30	0.09	ILS CAT II in Rwy 11R (CAT I in Rwy 11L); ILS CAT I in Rwy 29L
SBGL	71.43	26.34	1.42	0.60	0.21	ILS CAT II in Rwy 10; ILS CAT I in Rwy 28; ILS CAT I in Rwy 15
SBRJ	69.26	28.43	1.52	0.71	0.09	RNAV RNP 0.1 in Rwy 20L and Rwy 02R
SBKP	87.05	11.35	0.58	0.69	0.33	ILS CAT I-AR in Rwy 15; RNAV GNSS in Rwy 33
SBCF	85.16	12.82	0.75	0.72	0.56	ILS CAT I-AR in Rwy 16; RNAV GNSS in Rwy 34
SBSV	63.84	35.82	0.26	0.06	0.01	ILS CAT I in Rwy 10 and Rwy 28
SBPA	78.89	17.32	2.06	0.84	0.89	ILS CAT II in Rwy 11; RNAV GNSS in Rwy 29
SBRF	67.35	32.25	0.34	0.04	0.02	ILS CAT I in Rwy 18; RNAV GNSS in Rwy 36
SBCT	51.41	33.34	6.47	4.69	4.09	ILS CAT III-A in Rwy 15; ILS CAT I in Rwy 33; RNAV GNSS in Rwy 11 and Rwy 29
SBGO	85.21	13.57	0.67	0.39	0.16	RNAV GNSS in Rwy 14 and Rwy 32
SBFZ	69.57	30.23	0.14	0.04	0.02	ILS CAT I in Rwy 13; RNAV GNSS in Rwy 31
SBFL	72.46	25.37	1.11	0.75	0.31	ILS CAT I-AR in Rwy 14; RNAV GNSS in Rwy 32
SBVT	75.44	23.63	0.66	0.25	0.02	ILS CAT I in Rwy 23; RNAV GNSS in Rwy 05
SBBH	89.03	10.36	0.46	0.14	0.02	LOC in Rwy 13; RNAV GNSS in Rwy 31
SBBE	70.58	28.73	0.46	0.18	0.04	ILS CAT I in Rwy 06; RNAV GNSS in Rwy 24, Rwy 02 and Rwy 20
SBRP	90.36	08.44	0.46	0.37	0.36	RNAV GNSS in Rwy 18 and Rwy 36
SBEG	59.78	36.51	2.50	0.72	0.48	ILS CAT I in Rwy 11; RNAV GNSS in Rwy 29
SBLO	81.61	14.17	1.66	1.39	1.17	RNAV RNP0.2 in Rwy 13 and Rwy 31
SBNF	67.19	26.22	3.40	2.26	0.93	RNAV RNP0.2 in Rwy 02 and Rwy 25
SBCG	81.72	14.47	1.45	1.34	1.01	ILS CAT I in Rwy 06; RNAV GNSS in Rwy 24
SBUL	84.92	11.26	1.62	1.08	1.12	ILS CAT I in Rwy 04; RNAV GNSS in Rwy 22

[1]Extracted from Instrument Approach Charts (IAC) available for each aerodrome on AIS (2017).

VMC and NPA, together, averaged 97% of the conditions to which the aerodromes investigated operate under over the last eight years (i.e., 2009 to 2016). Aerodromes operated under CAT I, in average, 1.5% of the time; whereas CAT II and CAT III represented 0.9 and 0.6% of operations, respectively. SBCT presented the most severe averaged weather conditions with 15.25% of the time operating under ILS (CAT I + II + III). It was followed by SBSP (6.61%), SBNF (6.59%), SBGR (4.68%) and SBLO (4.22%). From those top five adverse weather condition aerodromes listed, SBGR and SBCT are the only cases with ILS CAT III capability currently implemented (at least at one runway). SBSP has ILS CAT I capability implemented for its two main runways (i.e., Rwy 17R and Rwy 35L). On the other hand, SBNF and SBLO currently operate with RNAV RNP0.2 capability implemented for all runways. As listed in Table 4, besides SBGR and SBCT already mentioned, SBBR, SBGL and SBPA have ILS CAT II capability implemented. In total, 17 out of the 23 aerodromes investigated have ILS CAT I currently implemented in one runway at least.

One case to be mentioned is SBRJ (Santos Dumont airport in Rio de Janeiro), which is the 5th aerodrome in Brazil (DECEA, 2016) and operates with RNAV RNP0.1 in its two main runways (Rwy 02R and Rwy 20L). To note that the runway has 4,341 ft (1,323 m) and that the aerodrome is located between the Rio-Niterói Bridge (to the north) and the Sugarloaf Mountain (to the south). Operations in SBRJ are preferable in Rwy 02 as the aerodrome location, considering its proximity to SBGL (Galeão airport) to the north-west, requires the airspace to be managed as there was only one airport in Rio de Janeiro when SBRJ is using Rwy 20 for landing operations.

It is worth mentioning that the distance between SBGL and SBRJ (about 7.7 Nm – i.e., 14.3 Km) is within what is theoretically considered for GBAS to operate with one single station shared (limit radius of 23 Nm). Thus, a GBAS station installed in SBGL would be able to augment SBRJ capability to perform precision instrument landing operations (at least CAT I). Indeed, DECEA has spent USD 2.5 million since the late 90's on equipment and tests (DECEA has a Honeywell SLS-4000 GBAS station) and, although tested punctually before, DECEA wants to make the equipment operational in SBGL by January 2019.

Table 4 is complemented by Table 5, which lists the total number of operations (sum of landing, take off, crossing and go-around) related to commercial aviation reported by DECEA (2016) for every aerodrome investigated. Assuming the total number of landings as half

the total number of operations, the number of landing operations under every condition listed in Table 3 can be estimated using the percentages shown in Table 4.

Table 5: Total number of commercial aviation operations (sum of landing, take off, crossing and go-around) as reported by DECEA (2016), and estimated yearly cost associated with deviations caused by meteorological limitations in the top quartile aerodromes in Brazil (see Table 1).

ICAO Code	# of operations for commercial aviation in 2016	CAT I ($)[1]	CAT II ($)[1]	CAT III ($)[1]	CAT I + II + III ($)	CAT I + II + III ($) discounting current capability implemented (Table 4)[2]	
SBGR	254,566	61,350,406	28,002,260	29,784,222	*119,136,888*	---	---
SBSP	175,945	60,876,970	45,569,755	9,852,920	*116,299,645*	**55,422,675**	**(1)**
SBBR	140,852	7,324,304	4,225,560	1,267,668	*12,817,532*	**1,267,668**	**(15)**
SBGL	118,845	16,875,990	7,130,700	2,495,745	*26,502,435*	**2,495,745**	**(12)**
SBRJ	92,918	14,123,536	6,597,178	836,262	*21,556,976*	**21,556,976**	**(2)**
SBKP	113,182	6,564,556	7,809,558	3,735,006	*18,109,120*	**11,544,564**	**(4)**
SBCF	98,396	7,379,700	7,084,512	5,510,176	*19,974,388*	**12,594,688**	**(3)**
SBSV	63,417	1,648,842	380,502	63,417	*2,092,761*	**443,919**	**(18)**
SBPA	65,623	13,518,338	5,512,332	5,840,447	*24,871,117*	**5,840,447**	**(6)**
SBRF	57,972	1,971,048	231,888	115,944	*2,318,880*	**347,832**	**(19)**
SBCT	62,183	40,232,401	29,163,827	25,432,847	*94,829,075*	---	---
SBGO	29,481	1,975,227	1,149,759	471,696	*3,596,682*	**3,596,682**	**(8)**
SBFZ	42,772	598,808	171,088	85,544	*855,440*	**256,632**	**(20)**
SBFL	30,779	3,416,469	2,308,425	954,149	*6,679,043*	**3,262,574**	**(11)**
SBVT	27,742	1,830,972	693,550	55,484	*2,580,006*	**749,034**	**(16)**
SBBH	3,468	159,528	48,552	6,936	*215,016*	**215,016**	**(21)**
SBBE	29,745	1,368,270	535,410	118,980	*2,022,660*	**654,390**	**(17)**
SBRP	17,409	800,814	644,133	626,724	*2,071,671*	**2,071,671**	**(14)**
SBEG	27,949	6,987,250	2,012,328	1,341,552	*10,341,130*	**3,353,880**	**(9)**
SBLO	10,295	1,708,970	1,431,005	1,204,515	*4,344,490*	**4,344,490**	**(7)**
SBNF	13,894	4,723,960	3,140,044	1,292,142	*9,156,146*	**9,156,146**	**(5)**
SBCG	14,230	2,063,350	1,906,820	1,437,230	*5,407,400*	**3,344,050**	**(10)**
SBUL	11,336	1,836,432	1,224,288	1,269,632	*4,330,352*	**2,493,920**	**(13)**
TOTAL	**1,502,999**	**259,336,141**	**156,973,474**	**93,799,238**	**510,108,853**	**145,012,999**	

[1]Loss ($) associated with diversions estimated to occur as a consequence of weather restrictions in the aerodrome. Capability already implemented are in grey whereas red text were used to represent capability not yet implemented; [2]Estimated loss ($) related to diversions to which the capability is not already implemented (implemented capabilities are listed in Table 4). The number in parenthesis represent the rank, e.g., (1) represents the aerodrome with largest loss ($) amount associated, (2) represents the second largest loss ($) amount, and so on.

To have a flavor of the business case associated with landing operations under severe weather conditions, we estimated the cost associated with diversions that would be required if the aerodrome would not have ILS capability implemented. To simplify the calculations we used a fixed cost of USD 20,000.00 per diversion in Brazil, which was based on the opinion of Boeing experts in Boeing Commercial Airplanes (BCA) and BR&T. According to IATA (2014) a diversion may range from USD 15,000.00 for narrow-body domestic flights up to USD 100,000.00 for a wide-body international flight. As national flights represent the massive amount of operations (e.g., 71.7% of all flights from/to SBGR, which is the most busy aerodrome) in Brazil and are all narrow-body (almost all international flights with destination in South America – e.g., 47.3% of all international flights from/to SBGR – are also narrow-body) our assumption of an averaged cost of USD 20,000.00 per diversion simplifies the calculation as all the diversions were then considered as national narrow-body aircraft operations (do not taking into account wide-body cases).

Aerodromes SBGR, SBSP (both in SP State) and SBCT (in PR State) presented the most significant numbers. Although SBGR has currently ILS CAT I, II and III implemented, it would cause a yearly cost of around USD 120 million related to diversions due to severe weather conditions as a consequence of its high number of landing operations. SBCT also has ILS CAT I, II and III capability currently implemented. SBSP, on the other hand, has ILS CAT I currently implemented. In fact, the total loss for demanding ILS landing operations in SBSP would be USD 116.3 million per year, but discounting CAT I (USD 60.9 million) the aerodrome has an

estimated yearly loss of USD 55.4 million due to diversions related to CAT II and III operations that are requested to be diverged as a consequence of severe weather conditions. SBSP diversions might be accommodated by SBGR due to its ILS capability and proximity to SBSP. However, SBGR has the most congested airspace in Brazil, making the logistics to accommodate diversions costly ineffective and very complicated.

Eventually, we discounted costs associated with capabilities currently implemented for each aerodrome, finding out that SBSP would be the most expensive aerodrome in Brazil in which regards to diversions caused by severe weather conditions (Table 5, last two columns). SBRJ presented the second largest cost associated. As discussed before, SBRJ would be an interesting study case for GBAS in Brazil as DECEA is going to implement GBAS capability in SBGL by January 2019 and it is close enough to SBRJ – 7.7nm – to allow GBAS operations in SBRJ using the GBAS station to be implemented in SBGL. SBCF and SBKP, both with ILS CAT I-AR (which requires special authorization) already implemented at one runway each, were listed 3rd and 4th more expensive aerodromes among the 23 investigated as the CAT II + III costs would sum USD 12.6 and 11.5 million per year for SBCF and SBKP, respectively. SBNF and SBLO, previously listed among the top five aerodromes operating under severe weather conditions in Brazil, were listed 5th and 7th, respectively. Although the total number of landing operations per year are not comparable to the most congested aerodromes in Brazil (6,947 for SBNF and 5,147 for SBLO in 2016), the frequent severe weather condition associated to those locations makes the cost significant.

The top quartile aerodromes in Brazil represent a business case of around USD 510 million per year. If we consider only the augmentation capability to be added to all the ILS already implemented, it would represent an amount of more than USD 145 million per year (as detailed in Table 5, last two columns). It is worth mentioning that we haven't extended the discussion to accomplish all the benefits of GBAS-based procedures such as noise reduction, obstacle avoidance, fuel consumption optimization, etc (Balvedi et. al., 2016).

4. FINAL REMARKS

We proposed a method to assess demand for instrument approaches based on historical reported meteorological conditions. The top quartile aerodromes in Brazil (see Table 1) were investigated to test and validate the proposed methodology. It uses information reported in the Meteorological Aerodrome Report (METAR) historical data available for the investigated aerodromes over the last eight years (i.e., 2009 to 2016). Results showed that, on average, Visual Meteorological Condition (VMC) and Non-Precision Approach (NPA) together represented around 97% of the conditions to which the aerodromes investigated operate under over the last eight years. Aerodromes operated under CAT I, on average, 1.5% of the time; whereas CAT II and CAT III represented 0.9 and 0.6% of operations, respectively. Most critical cases were SBCT, SBSP, SBNF, SBGR and SBLO (see Table 1 for airport name and location). However, SBCT and SBGR have current ILS CAT III-A capability implement; whereas SBSP has ILS CAT I and SBNF and SBLO operates under RNAV RNP0.2 capability.

We estimated the business case related to diversions as a consequence of severe weather conditions for all the 23 aerodromes investigated. In total, diversions may sum up to USD 510 million per year in the top quartile aerodromes in Brazil. If we consider only the augmentation capability to be added to the current ILS already implemented (listed in Table 4), it would still represent an amount of more than USD 145 million per year (see Table 5). A strong study case may be SBRJ. The aerodrome is located 7.7 nm from SBGL, where DECEA is going to implement a GBAS station to be operational before January 2019. The distance is within the theoretical radius where a GBAS station might operate (i.e., 23 Nm) meaning that the GBAS station to be implemented by DECEA in SBGL might be able to augment SBRJ for, at least CAT I. Moreover, SBRJ is listed as the second most important business case related to severe weather conditions (USD 14.1 million for CAT I, USD 6.6 million for CAT II, and USD 0.8 million for CAT III,

totaling USD 21.6 million per year) considering that no ILS is currently implemented in that aerodrome.

5. ACKNOWLEGMENTS

Boeing Research & Technology - Brazil acknowledges DECEA and Mirus Technology for the invitation to the GBAS Safety Case Working Group.

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