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GLS Approaches using SBAS: a SBAS to GBAS converter

Thomas Dautermann, Thomas Ludwig, Robert Geister, Lutz Ehmke, Max Fermor
German Aerospace Center (DLR)
Institute of Flight Guidance,
Lilienthalplatz 7
38108 Braunschweig, Germany

Matthew Bruce, Markus Schwendener
Flight Calibration Services
Hermann-Blenk-Straße 32 A
38108 Braunschweig, Germany

***Abstract*—We build a prototype system intended to bring together the advantages of both the ground based and satellite based augmentation systems (GBAS, SBAS). It combines an SBAS-capable global navigation satellite systems receiver with a database and a GBAS-compatible data link. The correction and integrity data received from the SBAS satellite are automatically translated into GBAS-compatible structures and sent to the airborne multi-mode receiver using the final approach segment data block. This receiver can now send deviations directly to the autopilot making automated landings possible. The device can be installed on the ground as well as in the aircraft. As commercial air transport aircraft are rarely equipped with SBAS capable receivers but are increasingly fitted with GBAS receivers our System adds the SBAS capability to a GBAS equipped aircraft. Here, we present algorithms and data collected during validation flights and a case study on the economic impact for airport operators.**

Keywords-GLS, GBAS, SBAS, Converter, RNP, PBN

I. Introduction

At present, automated landings can only be carried out with precision guidance systems such as the Instrument Landing System ILS, Microwave Landing System MLS, or the GBAS (Ground-Based Augmentation System) landing system GLS. All of these systems have in common is that the guidance signals are routed to the autopilot directly from the receiving device. The autopilot then takes over control of the aircraft during landing. Receivers for these three systems are often combined in a multimode receiver or MMR.

Navigation using satellite signals is based on signal propagation time measurements from the satellite to the receiver, knowledge of the satellite position, and subsequent triangulation. However, due to atmospheric interference and noise this is only possible with an accuracy of several meters in the horizontal direction. Position resolution in the vertical direction is even more imprecise due to the absence of signals originating below the receiver.

For ground-based GLS, corrections for the signals from the individual satellites are transmitted from a ground station via VHF. These corrections can be used within a radius of around 50 km from the ground station. On board the aircraft they are applied to the propagation time measurements received. A highly accurate position is then calculated based on the corrected measurements, the accuracy of which is also adequate in the vertical direction enabling aircraft guidance in three dimensions. The ground station further transmits integrity information which guarantees the reliability of the correction signals. Finally, the GBAS station also transmits approach information such as runway threshold coordinates, landing direction and approach angle in what is known as the final approach segment (FAS) data block for each approach.

For a wide area augmentation system (called WAAS in the United States of America), also known as satellite based augmentation system (SBAS), GNSS reference stations are distributed over a wide area at precisely known locations. They measure the GNSS signals and send the data to a master control station. The master control station computes correction and integrity information which is broadcast to the user via a geostationary satellite. For all SBAS systems, the FAS data block is stored in the aircraft's navigation database and the guidance provided by the system is called Localizer Performance with Vertical guidance (LPV).

In both systems, instant integrity information is provided by estimating protection levels, a high probability bound for the computed position. This is then compared to the alert limit of the respective system. Implementation standards for airborne receivers using SBAS are governed by the relevant documents of EUROCAE and RTCA, EASA AMC 20-28 [7] and AMC 20-27 [9]. The standards for GBAS ground stations, VHF data broadcast and airborne user receivers are laid out by EUROCAE ED114A [8] and RTCA DO245A [4], DO246D [5] and DO-253C [6]. Instrument approaches using either SBAS or GBAS are currently approved to be flown down to a decision height of 200ft and a runway visual range of 550 meters. It is important to note that SBAS does currently not support automatic landings and GBAS research and development will enable low visibility operations in the near future. Interestingly, the core principle of both systems is identical: pseudorange corrections are provided to the user, who in turn applies those corrections to improve position accuracy and integrity. In addition to those corrections, each system makes available real time information about the quality of the GNSS signal in the form of a Gaussian variance for each pseudorange. With very few exceptions, SBAS is not available in Part 25 aircraft used for commercial air transport and GBAS is not installed in small business and general aviation airplanes. A notable exception is the Satellite Landing System (SLS), available as an option on the new Airbus A350 and soon to be available on new A320s. Boeing does currently not offer SBAS on its production airplanes, but GBAS has been a standard option on all 737 since the -800 model as well as on the 747-8 and 787.

Since both systems are quite similar, and the SBAS signal can nowadays be decoded by even low cost receivers, one could receive the augmentation data from the SBAS, slightly modify it to fit into the GBAS data structure and broadcast this data to a GBAS equipped aircraft. Said aircraft could execute a RNP approach with the Localizer Performance and Vertical guidance (LPV) final approach segment which would otherwise not be available. This may come especially handy in places where no non-precision minima are published, such as the RNP-E approach into Innsbruck (cf. AIP Austria, AIRAC 09/2018). Since there are slight differences between the two systems, we need to make sure that integrity for the safety-of-life approach service is ensured. As similar concept was used by [12] for the local airport monitor concept for GBAS, but with the view angle of a monitoring facilitator. Here, we focus on really make the SBAS signal usable for GBAS equipped aircraft, a concept which was called "bent pipe" in [12] and never fully explored.

We named the system GLASS (GLS Approaches using SbaS), built a prototype and tested it with real GBAS avionics hardware. In the following, we present a brief introduction to integrity with the appropriate reference to [2]; show data collected during bench and flight test and discuss economic impacts if our system was commercially available.

II. Integrity Considerations

In order for an airborne GNSS receiver to provide the required performance, it needs to compute position uncertainty at the allocated integrity risk. This is called a protection level, and is subsequently compared to a maximum allowable value, the alert limit. If the protection level exceeds the alert limit, the system cannot maintain the required integrity and becomes unavailable. In order to ensure the full compliance with ICAO standards, the GBAS receiver onboard the aircraft should output protection levels identically or larger than the one computed by a pure SBAS based receiver. A larger protection level, however, may lead to a reduced availability.

At each epoch, an airborne user receiver utilizing SBAS and certified according to RTCA DO229D [3] computes Vertical and Horizontal Protection Levels (VPL, HPL) as

$$HPL_{SBAS} = K_H \sqrt{\frac{\sigma_E^2+\sigma_N^2}{2} + \sqrt{\left[\frac{\sigma_E^2-\sigma_N^2}{2}\right]^2 + \sigma_{EN}^2}}$$

$$VPL_{SBAS} = K_V \sigma_U$$

with $\sigma_E^2 = \sum_i S_{E,i}^2 \sigma_i^2$ the post correction variance of the modeled error in the east direction, $\sigma_N^2 = \sum_i S_{N,i}^2 \sigma_i^2$ the north direction, $\sigma_U^2 = \sum_i S_{U,i}^2 \sigma_i^2$ in the direction of the local vertical and $\sigma_{EN}^2 = \sum_i S_{E,i} \sum_i S_{N,i} \sigma_i^2$ the post correction covariance of the modeled error between east and north. K_H and K_V are set to $K_H = 6.0$ and $K_V = 5.33$ for approach applications with vertical guidance and represent an integrity error bound at the probabilities $p_{vertical} = 0.5 \times 10^{-7}$ and $p_{horizontal} = 0.5 \times 10^{-9}$. The σ_i are the post correction range uncertainties and are composed of the individual errors whose distributions are overbound by zero mean Gaussians. They consist of

$$\sigma_i^2 = \sigma_{i,UIRE}^2 + \sigma_{i,UDRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

$\sigma_{i,UIRE}$ is the value extracted from the ionosphere grid data by interpolating the transmitted grid uncertainties σ_{GIVE} and mapping them to the satellite elevation angle. $\sigma_{i,UDRE}$ is the residual user differential range error and is computed by the ground segment and transmitted as part of the fast correction message. It describes the residual error that remains after application of the fast corrections. The airborne receiver noise and multipath characterized by $\sigma_{i,air}$ which varies with airborne equipment quality. $\sigma_{i,tropo}$ is derived from a constant modeling uncertainty of 12 cm for the troposphere vertical error and converted to a slant value using an elevation mapping function. The square root term is the standard deviation of the positioning error in the direction of the largest horizontal eigenvector of the position domain variance-covariance matrix.

On the other hand, the GBAS approach service type C protection levels are calculated as the maximum over a set of individual protections levels assuming normal operation (H_0) and ground station reference receiver fault (H_1). In GBAS the reference receiver performance is characterized by B(ias) values, which are constantly computed by the ground subsystem and transmitted via VHF radio. There is one B value per satellite i in view of receiver j. Details of the GBAS protection level calculation are stated in [6] or [8], for example, and are summarized here. For approach services we have as expression for the lateral and vertical protection levels ($X \in \{L, V\}$):

$$VPL_{GBAS,appr} = max\left[VPL_{GBAS,appr,H0}, VPL_{GBAS,appr,H1,j}\right]$$

with

$$VPL_{GBAS,apr,H0} = K_{ffmd} \sqrt{\sum_{i=1}^{n} s_{appr,vertical,i}^2 \, \sigma_i^2}$$

and K_{ffmd} the fault free missed detection multiplier. The protection levels of in the reference receiver fault case are

$$VPL_{GBAS,appr,H1,j} = |\sum_{i=1}^{n} s_{appr,vert,i}\, B_{ij}| + K_{md}\sqrt{\sum_{i=1}^{N} s_{appr,vert,i}^2\, \sigma_{i,H1}^2}$$

and the difference between $\sigma_{i,H1}$ and σ_i is a $\sigma_{pr\_gnd,i}$ inflated by number of reference receivers divided by number of reference receivers minus one. In the GBAS case, σ_i^2 is again the post correction range model error variance, but different from the ones used in SBAS aided positioning. In GBAS,

$$\sigma_i^2 = \sigma_{pr\_gnd,i}^2 + \sigma_{tropo,i}^2 + \sigma_{pr\_air,i}^2 + \sigma_{iono,i}^2$$

$\sigma_{pr\_gnd,i}$ characterizes the post smoothing pseudorange error, $\sigma_{tropo,i}$ describes the remaining troposphere error after applying the GBAS troposphere model, $\sigma_{pr\_air,i}^2$ is model for airborne pseudorange noise and multipath and $\sigma_{iono,i}$ models the remaining ionosphere error after application of the correction terms.

In order to use SBAS via a GBAS receiver and ensure integrity, we must inflate standard deviations of the GBAS data broadcast such that the lateral protection level computed by the GBAS receiver is equal or larger than the horizontal protection level of a SBAS receiver. For details on the broadcast content and message structure, see [5] . The same is true for the vertical protection level; however unlike the difference between vertical and lateral, here we need not be concerned as much about the difference in direction of the largest error. Moreover, we must compute the pseudorange corrections (PRC) and range rate corrections (RRC) from the individual components of the SBAS broadcast.

Details on the inflation and computation of corrections and a bench test can be found in [2]

III. Ground and Flight Test

We implemented the system in C++ on a 64 bit Linux PC and connected this PC to a Telerad VDB Transmitter. The necessary correction data was obtained from a Septentrio AsteRx3 GNSS receiver. We used the standard final approach segment (FAS) data blocks as published for Braunschweig-Wolfsburg Airport (ICAO Identifier EDVE) in the German AIP for runway 08 and runway 26. Details on the required FAS data can be found in [3],[8] and [6], for example. The FAS vertical alert limit was modified to 25.3 meters in order to be near the maximum allowed value of 25.4 meters. 25.5 meters is theoretically possible according to DO246, but airborne equipment interprets this value as “Do not use”. SBAS Standards [3] would allow a value as high as 50m for the FAS VAL but the GBAS VDB specifications are limiting in this case. The station identifier was chosen to be GLAS (GLS approaches via SBAS)

We ran ground bench tests, using customized software to calculate SBAS and GBAS Positions and Protections Levels using standard algorithms published in [DO253C] and [DO229D]. In order to have a better picture of the 25.4 meters GBAS VDB datalink limitation of the VAL, we set this value when creating integrity plots.

Figure 1 shows these Stanford plots [1] with data recorded during one week starting on 24 October 2018. The show a 99.96% percent availability for the standard EGNOS approach service and a reduction to 92.4% availability using the converter system with the inflated protection levels. If it were possible to increase the VAL to the SBAS standard of 50m, the availability of the system would increase to 99.95%

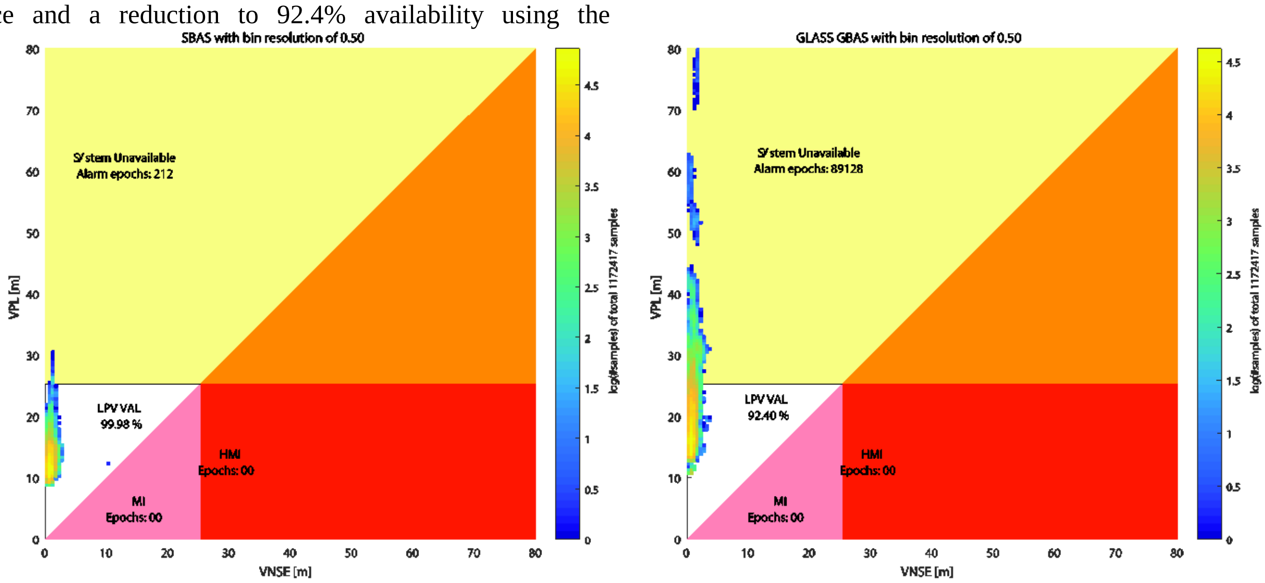

Figure 1 Stanford Type Integrity Diagrams for the converter system showing the most limiting vertical component with a vertical alert limit of 25.3 m

Figure 2 shows a histogram of the ratio of lateral protection level GBAS to horizontal protection levels SBAS and the ratio of vertical protection level GBAS to vertical protection level SBAS. As expected from our inflation method described in [2], the ratio is always above 1 and larger for the vertical component due to the limited possibility of introducing only one inflation factor.

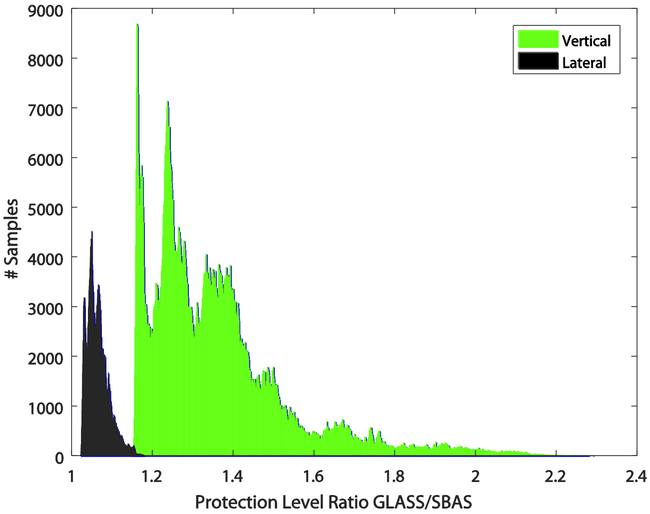

Figure 2 Histograms of the protection level ratio xPLGBAS/XPLSBAS, which must always be at or above 1 in order to ensure navigation integrity

Rover tests using a minivan with installed Rockwell GLU925 and Honeywell INR multi mode receivers showed standard performance values as expected from any GLS system in nominal conditions.

Next, for a flight validation, we contracted the German Flight Inspection company Flight Calibration Services (FCS) to provide a standard GBAS Flight Validation program using their King Air, D-CFME with the Aerodata AD-AFIS-220 (Figure 3 and 4). On November 12 and November 16th, FCS tested our SBAS to GBAS converter system just as they would a standard GBAS station. This included approaches to either runway end in Braunschweig as well as field strength measurement arcs at 20 and 15 nautical miles and level runs at high and low altitude.

The flight inspection could detect any differences between the new system and a standard GBAS installation. Figure 5 and Figure 6 shows the measurements during the approach to Braunschweig's runway 26 as an excerpt from the flight testing results report. We can see that the system performed well with in GBAS limits. Also, a saw tooth pattern in the protection levels as calculated by the flight inspection system is visible. This is characteristic for SBAS based corrections and integrity information as the system provides degradation factors to bridge the time gap between successive correction data sets.

Figure 3 FCS Flight Test Aircraft during Taxi and Low Pass at Braunschweig Airport

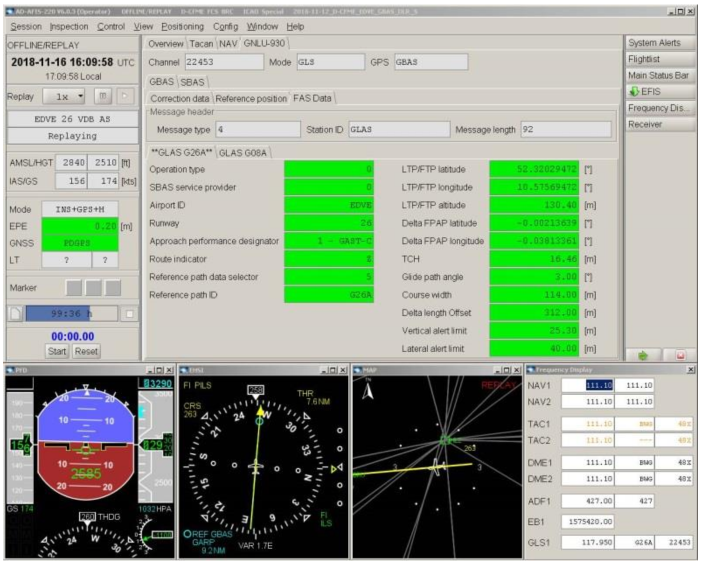

Figure 4 Screenshot of the flight inspection system engineer display during the GLS Approach to runway 26.

The conclusions of the flight validation reports are [10]:
"1. Assessment of DLR Test Installation, GBAS GAST-C look-a-like with GPS corrections via. SBAS. FAS Design based on RNP08 Approach.
2. Assessment completed against GBAS GAST-C ("Cat I") flight inspection criteria as there are no flight inspection criteria for a system such as GLASS. The classification of "Limited Use" reflects this discontinuity in standards even though the GLASS fulfils all flight inspection relevant requirements of a GBAS GAST-C installation.

3. During flights on 12.11.18 the GLAS was configured with a VAL of 25.5m in the FAS Data Block for RWY08, this caused the receiver to flag the vertical channel, even though the VPL was sufficiently low, as 25.5m is outside of the valid range for GBAS installations (maximum expected is 25.4m). The flights were conducted with the GNLU in "Test Mode" such that the HALA/AL was ignored. The GLAS was later reconfigured to set the VAL to 25.3m and the approach was re-flown on 16.11.18 with all indications as expected and no flags observed during the approach."

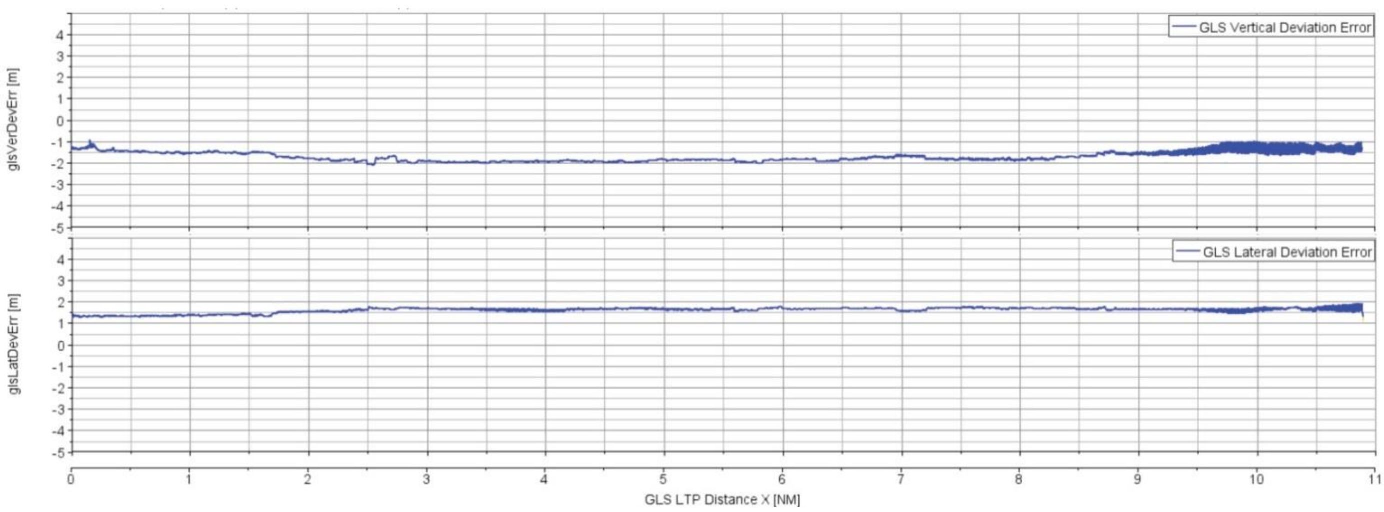

Figure 5 Errors of the positioning during the flight inspection campaign (bottom) Error of the lateral deviation from the centerline provided by the FAS data block. (top) Error of the calculated deviation from the three degree glide path provide by the FAS Data block

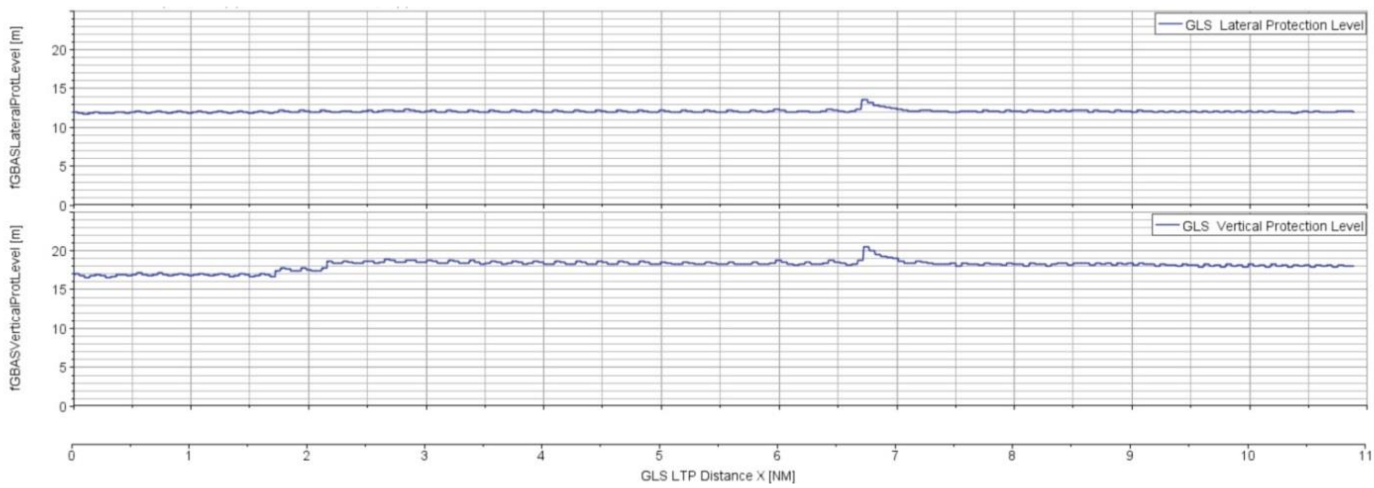

Figure 6 Lateral and Vertical Proctection Levels calculated by the Flight Inspection System FIS during a level run in 3000ft MSL, 2713 ft above the aerodrome.

IV. ECONOMIC IMPACT

Since GLASS is intended to be an alternative for precision landing systems we performed a cost-benefit analysis by comparing GLASS to other landing systems for precision approaches such as ILS and GLS. Comparable services provided by these systems are mainly an ILS category I as well as a GBAS approach service type B.

First, we identified influencing factors for all of the landing systems. The most important are the equipment level of the aircraft with the necessary approach technology, the number of runway ends, the economic growth of the aviation sector over the next years ([13], [11]) and the average number of day/hours with bad weather conditions. For the collection of the data necessary for the analysis we used two different online tools provided by EUROCONTROL. First the PBN Approach Map Tool (https://ext.eurocontrol.int/pbn/) which offers a visualization of the installed landing systems for all European airports. Second the CNS Dashboard (https://www.eurocontrol.int/services/communication-navigation-surveillance-cns-dashboard) which allows the determination of equipment of the aircraft based on all flight plans of the last four years in anonymous manner. The CNS

Dashboard allows the search for available technologies, airports, airframe manufacturer, as well as aircraft types. The output of the tools gives then an overview about the real utilization of technologies for all scheduled flights and on airports in Europe and allows the analysis of the proportion of the different technologies for all approaches. The data show that for mid-range aircraft like A319/A320/A321 and B737 consist the best potential for using GLASS. Here we have the most aircraft available with GBAS capabilities which allows the use of GLASS without further modifications. In conjunction with an expected yearly growth of the aviation sector of 5% the use of GLASS will be economically reasonable for the next years.

In a next step we estimated the costs for ILS, GBAS, and GLASS in order to determine a possible economic benefit of the new system. One obstacle we encountered was the fact that there is no real market for landing systems installations. The prices result from local conditions, installation specifications and price negotiations. Because of this we made some assumptions based on the few official available information as well as interviews with experts from airports and air service providers to get a qualitative description of the possible benefits and its effect mechanism. The overall costs for a landing system can be divided into following subgroups: purchasing, construction works, first flight inspection, annual flight inspection as well as annual maintenance. For each group we estimated the minimum and maximum costs for a component life span of 10 years and 20 years, respectively. These result in 4 scenarios with following combinations: min. initial costs and min. annual costs, min. initial costs and max. annual costs, max. initial costs and min. annual costs, and max. initial costs and max. annual costs.

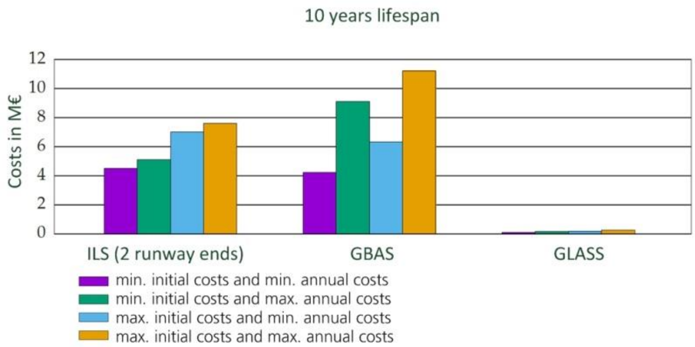

Figure 7 Comparison of the costs of ILS, GBAS and GLASS for 20 years and a lifespan of the systems of 10 years. GLASS is clearly more inexpensive than the two other systems. A GBAS station is only more inexpensive in scenarios with the lowest initial costs.

Figure 7 and Figure 8 show as an example these costs for all 4 scenarios for an expected lifespan of 10 and 20 years over the next 20 years based on summarizing of all gathered information. It can be seen that for the evaluation based on pure costs, GLASS is always much cheaper than all other systems. Certification cost can vary widely and the authors have no experience in certification of a commercial aviation product. However, since we only found a different channel for an existing technology, we estimate that cost to not be too high. Therefore, we expect that even with the additional costs for certification of GLASS the cost levels of ILS and GBAS will not be reached.

In this context interesting side information occurs: the diagram shows also that the installation of a GBAS system is only useful from economic point of view if the annual costs are less than annual costs for an ILS. This is changing only for airports with more than two runway ends. The results of the analysis show that also with the assumption of most unfavorable conditions, a use of GLASS is more economical. However in this calculation, further costs for accomplishing a certification as well as a price increases for generating a profit were not considered. Nevertheless the advantages of using GLASS depend from many factors which have to be considered for each airport individually.

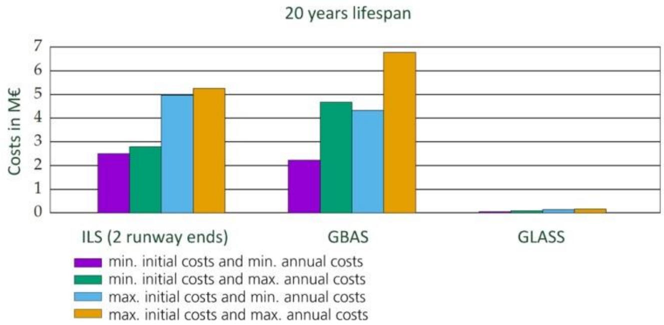

Figure 8 : Comparison of the costs of ILS, GBAS and GLASS over 20 years at a lifespan of the systems of 20 years.

V. CONCLUSIONS

The system works as intended with some restrictions in availability due to the protection level inflation. It maintains the SBAS integrity and time to alert is only affected by the transmission interval of the SBAS signal. Since the SBAS signal is provided free of charge by most authorities and can be obtained with low cost receivers, the system provides a cost-effective way to provide GLS approaches based on SBAS (GLASS).

The GLASS system provides the LPV final approach segment to GLS-only equipped aircraft such as the 737-800. This can enable increased access to airports that are currently not equipped with an xLS type approach such as Innsbruck (LOWI). Especially approaches in France could be of interest, since the government has officially declared to decommission all category 1 ILS installations in favor of RNP approaches with LPV.

The standards for data transmission in a GBAS system only allow a maximum value of 25.4m to be entered as a Final Approach Segment Vertical Alert Limit (FASVAL) as opposed to the SBAS LPV approach service FASVAL of 50 m. However, GBAS final approach segment alert limits are scaled with distance from the glide path intercept point with the runway surface (GPIP), which is typically about 1000ft upwind of the landing threshold. The scaling equation is 0:095965Hp +FASV AL−5:85 where Hp is the height of the aircraft on above the GPIP location. This may lead to an availability and continuity issue which has to be further evaluated. One possible solution is to find an acceptable height/distance combination, below which alert levels are more stringent than LPV and above which they are more relaxed. Setting the FASVAL to its maximum, this would occur at approximately 320m above aerodrome level without the penalty in availability being greater than discussed above.

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