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THE GBAS SYSTEM CONCEPT IN THE CONTEXT OF FRANKFURT MAIN AIRPORT

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This paper provides a comprehensive analysis of the Ground-Based Augmentation System (GBAS) as a modern alternative and supplement to traditional Instrument Landing Systems (ILS). It explores the architecture and operating principles of GBAS, focusing on its ability to enhance positioning accuracy to sub-meter levels, provide flexible approach trajectories, and reduce airport infrastructure maintenance costs. Given that Frankfurt Airport was the first airport in Europe to implement the GBAS system in its landing approach procedures, this article presents an analysis of GBAS data for that airport. Utilizing operational data from Frankfurt Airport spanning 2014–2024, the study evaluates the adoption rates of GBAS-equipped aircraft (increasing from 4.1% to 9.4%) and the actual operational utilization of the system (growing from 4.15% to 21.89%). Furthermore, the environmental benefits of Continuous Descent Approaches (CDA) enabled by GBAS are quantified, including fuel savings of 50–150 kg per approach, reduced noise levels, and lowered emissions, alongside the system's impact on airspace capacity and delay reduction. Finally, the article highlights the primary legislative, financial, and certification challenges (GAST D/CAT III) currently hindering global fleet-wide implementation.

Keywords: GBAS system, GNSS, safety, airport

List of Symbols/Acronyms

CAT - Commercial Air Transport
CDA - Continuous Descent Approach
DFS - Deutsche Flugsicherung GmbH
GAST - GBAS Approach Service Types
GBAS - Ground-Based Augmentation System
GBSS - Ground-Based Surveillance Systems
GNSS - Global Navigation Satellite System
GPS - Global Positioning System
HUD - Head-Up Display
ILS - instrument landing system
VDB - transmission in the 108–117.975 MHz band
VHF - Very High Frequency

1. INTRODUCTION

The Ground-Based Augmentation System (GBAS) is a ground-based support system designed to enhance aircraft safety and efficiency during approach and landing operations. The system comprises ground-based components, GNSS satellite constellations, and specialized on-board avionics. The ground infrastructure includes multiple GNSS reference receivers, a GBAS processing and correction calculation center, and a Very High Frequency (VHF) transmitter that broadcasts correction signals to approaching aircraft. On board, specialized GBAS avionics receive and integrate these corrections with the aircraft's primary navigation systems. A fully configured GBAS system enables positioning accuracy of one meter or less, significantly improving navigation precision and operational flexibility while reducing installation and maintenance costs compared to traditional Instrument Landing Systems (ILS) [1].

GBAS is engineered to support all flight phases within the terminal area, including approach, landing, departure, take-off, and surface ground operations. It provides high-precision navigation coverage within a standard operational range of 23 nautical miles from the airfield. Thanks to this wide-area coverage, a single GBAS ground installation can serve multiple runways and complex approach profiles simultaneously, enabling dual-direction landings and supporting operations at nearby secondary airports within its service volume [1].

In terms of structure, the GBAS architecture is divided into three primary segments:

- GNSS Satellite Segment: Provides raw space-based navigation signals and orbital parameters across available constellations.
- Ground Segment: Comprises several reference receivers at precisely surveyed locations, a centralized processing station, and a VHF Data Broadcast (VDB) transmitter station [3].

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- Aircraft Segment: Equipped with specialized GBAS avionics and VDB receivers that process incoming ground corrections to compute a high-integrity differential position.

The operational flow relies on the continuous interaction between these three segments. Reference stations, installed at fixed coordinates known with millimeter-level precision, continuously track visible GNSS satellites [PS1]. By measuring the precise time elapsed between signal transmission and reception, the system determines the apparent range (pseudorange) to each satellite [5].

The collected pseudorange data is forwarded to the processing station, which compares the measured satellite positions against the known geometric positions of the reference antennas. This comparison isolates signal propagation errors, enabling the calculation of differential corrections and integrity parameters [5]. The corrected data is then sent to a VDB antenna operating in the 108–117.975 MHz frequency band under a unique GBAS identifier (GBAS ID) [3]. The VDB transmission includes final approach segment (FAS) data referenced to the WGS-84 coordinate system, approach path definitions, real-time differential corrections, and signal integrity limits [14]. Aircraft within range select the appropriate dataset using a five-digit channel number, generating lateral and vertical guidance deviations relative to the target runway threshold point [14].

To achieve sub-meter positioning accuracy and satisfy stringent integrity requirements, GBAS relies on advanced GNSS signal processing techniques:

Code-Based Differential GNSS (DGNSS): The primary mechanism involves calculating spatial pseudorange errors at the ground station and broadcasting these corrections to airborne receivers. Applying these differential corrections removes common-mode errors, such as satellite clock drifts, ephemeris errors, and atmospheric (tropospheric and ionospheric) delays.

Carrier-Smoothed Code Filtering (Hatch Filter): Standard pseudorange code measurements are susceptible to thermal noise and multipath interference. GBAS employs carrier-smoothing algorithms (such as the Hatch filter) to combine the unambiguous pseudorange code with highly precise carrier-phase measurements, reducing measurement noise to decimeter-level precision without introducing phase ambiguity risks.

Multi-Receiver Spatial Averaging: By averaging pseudorange measurements across 3 to 4 independent reference antennas, the ground segment mitigates localized multipath and antenna-specific noise. This multi-receiver setup also acts as a real-time integrity monitor: any receiver generating anomalous data is instantly excluded from correction calculations.

Dual-Frequency Multi-Constellation (DFMC) Evolution: Modern GBAS developments utilize dual-frequency signals (e.g., L1/L5 or E1/E5a) to directly eliminate ionospheric delay errors through linear signal combinations, while multi-constellation tracking (GPS, Galileo) improves satellite geometry (DOP) and system availability. Figure 1 shows Ground Based Augmentation System (GBAS): satellites segment, aircraft segment and ground segment.

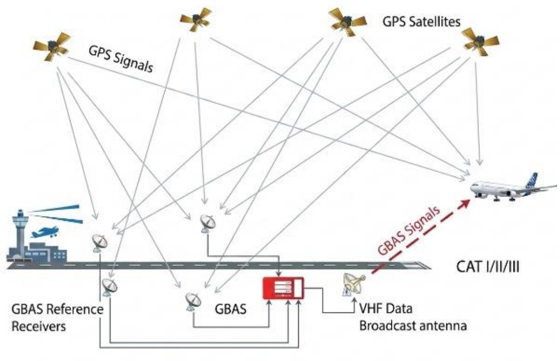

Fig. 1. Ground Based Augmentation System (GBAS): satellites segment, aircraft segment and ground segment [29]

GBAS delivers operational capabilities through standardized service levels known as GBAS Approach Service Types (GAST). Each GAST defines specific technical, performance, and integrity requirements for ground and airborne hardware:

GAST A, B, and C: Correspond to Approach with Vertical Guidance (APV I, APV II) and Category I (CAT I) precision approach minima, respectively [3].

GAST D: Designed for advanced precision guidance in severely restricted visibility, supporting full Category III (CAT III) operations [3].

Notably, there is no separate GAST category dedicated exclusively to Category II (CAT II) operations. Equipment certified for GAST D natively covers both Category II and Category III minima, offering a flexible and unified architecture. Alternatively, Category II operations can be executed under GAST C specifications when combined with appropriate airborne enhancements, such as Head-Up Displays (HUD), subject to national operational approvals [3]. Fig. 2 shows an example of a GBAS reference station.

2. GBAS SYSTEM AT FRANKFURT AIRPORT

Frankfurt Airport was the first airport in Europe to have a GBAS system installed. Fraport, the company that manages the airport, attaches particular importance to the rational and sustainable management of natural resources, recognising the reduction of CO_2 emissions as one of the most important areas of environmental protection. Furthermore, Frankfurt Airport is one of Europe’s most important airports and serves as a major hub within the international air transport network. For several years now, Frankfurt Airport has remained among the ten largest airports in Europe in terms of passenger numbers. In 2025, it ranked 6th on this list, recording passenger traffic of around 63 million people. In terms of the number of flight movements, 460,273 flight movements were recorded at the airport in 2025, representing an increase of over 4 per cent- based on annual report from Frankfurt airport website. Figure 3 shows the number of flight operations carried out at Frankfurt Airport between 2015 and 2025.

Fig. 2. GBAS reference station [8]

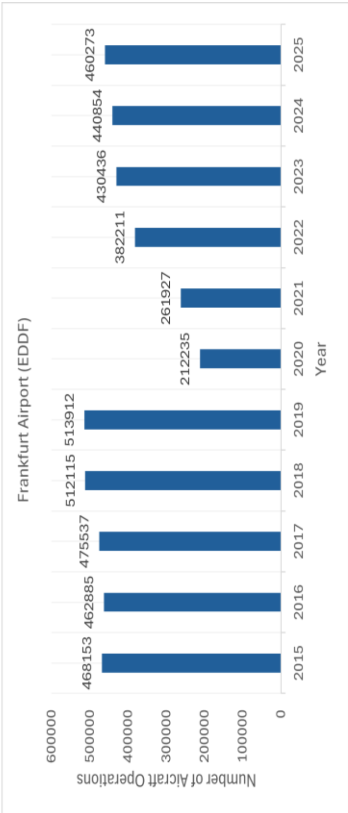

Fig. 3. number of flight operations carried out at Frankfurt Airport between 2015 and 2025 [Own study]

The GBAS system was approved for operational use at Frankfurt Airport in 2014, making Frankfurt Airport the second airport in Germany to allow landings with the aid of the GBAS system. Two years earlier, the system had been certified for use at Bremen Airport. Initially, the GBAS system at Frankfurt Airport was operated in CAT I, which means that the decision height for landing or a potential aborted landing procedure cannot be lower than 60 m (200 ft) and visibility must not be less than 800 m, or visibility along the landing path must not be less than 550 m. A breakthrough in the use of the GBAS system at Frankfurt Airport came in July 2022, when CAT II approaches were approved for use with the GBAS system. CAT II means that the relative decision height may be less than 60 m (200 ft), but may not be less than 30 m (100 ft), and visibility along the landing path may not be less than 300 m. According to plans, CAT III GBAS is to be in use by 2030. [6].

Table 1 presents the GBAS system specifications at Frankfurt Airport for variable components

Table 1. Characteristics of the GBAS system station at Frankfurt Airport [Own study based on [8]

Type of aid, cat. ILS/MLS (MAG VAR VOR/ILS/MLS)	ID	Freque ncy	Comments
Frankfurt Main GBAS 07C (CAT I/II)	G07M	CH293 79	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 07C (CAT I/II)	G07P	CH310 23	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 07L (CAT I/II)	G07K	CH277 35	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 07L (CAT I/II)	G07O	CH326 67	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 07R (CAT I/II)	G07J	CH285 57	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main BAS 07R (CAT I/II)	G07N	CH334 89	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 25C CAT I/II)	G25M	CH289 69	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main BAS 25C (CAT I/II)	G25P	CH314 34	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 25L (CAT I/II)	G25J	CH281 46	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 25L (CAT I/II)	G25N	CH322 56	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main BAS 25R (CAT I/II)	G25K	CH273 24	GFC: C/G1/0/H Useful approach service: do 20 NM od THR
Frankfurt Main GBAS 25R (CAT I/II)	G25O	CH318 45	GFC: C/G1/0/H Useful approach service: do 20 NM od THR

The GBAS system is located on the western side of the airport. Figure 4 shows the exact location of the GBAS system at Frankfurt Airport.

Fig. 4. Location of the GBAS system at Frankfurt Airport from a bird's eye view [7]

2. ASSESSMENT OF GBAS CAPABILITIES BASED ON OPERATIONAL DATA FROM FRANKFURT AIRPORT

Since 2014, when the GBAS system was certified, aircraft approaching Frankfurt Airport have been able to use the GBAS system for their approaches. However, it is worth noting that, due to the fact that the GBAS system has not been widely used in aviation for many years, unlike the ILS system, for example, the equipment of aircraft with the on-board segment of the GBAS system is very limited. Fig. 5 shows the annual percentage of aircraft equipped with GBAS performing landing approaches at Frankfurt Airport. The statistics come from DFS, the company that controls air traffic in Germany. In addition, 2024 does not include an analysis of November and December.

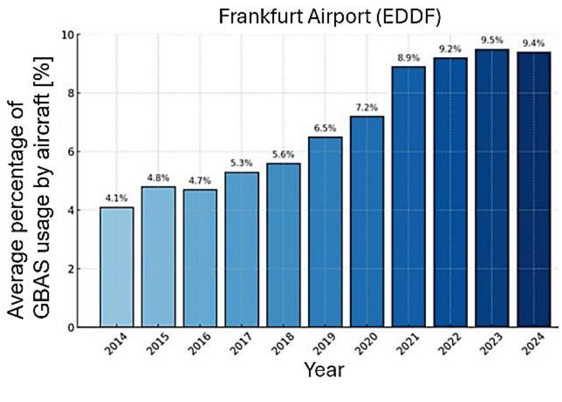

Fig. 5. GBAS equipment rate for aircraft at Frankfurt Airport [Own study]

Over the last decade, an increase of 5.3 percentage points has been observed. Between 2014 and 2018, the average annual percentage increase in GBAS usage at Frankfurt Airport was gradual, from 4.1% in 2014 to 5.6% in 2018, indicating moderate technology development or slower implementation during this period. Since 2019, there has been a significant acceleration, from 6.5% to 9.2% in 2022, suggesting a larger scale of use and implementation of this technology. As shown in Figure 3, the fleet equipage rate (E) rose from 4.1% in 2014 to 9.5% in 2023. Between 2014 and 2024 (9.4%), this represents an absolute increase of 5.3 percentage points and a relative growth of:

$$\text{Relative Growth}_{\text{equipage}} = \frac{9.4\% - 4.1\%}{4.1\%} \times 100\% \approx 129.3\% \tag{1}$$

Figure 6 illustrates the operational utilization rate (U) among equipped aircraft. In 2014, only 4.15% of equipped aircraft conducted GBAS approaches. By 2024, this value reached 21.89% (peaking at 23.78% in 2023). The relative increase in system utilization from 2014 to 2024 is calculated as:

$$\text{Relative Growth}_{\text{utilization}} = \frac{U_{2024} - U_{2014}}{U_{2014}} \times 100\% = \frac{21.89\% - 4.15\%}{4.15\%} \times 100\% = 427.47\% \tag{2}$$

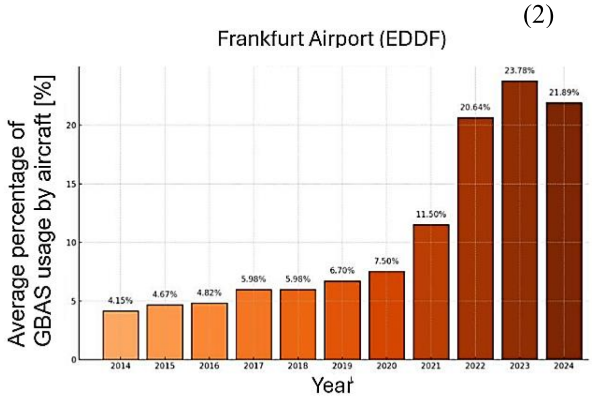

Fig. 6. The average annual percentage of GBAS system usage by aircraft equipped with the system, as recorded in the EDDF [Own study]

Between 2014 and 2020, there was an increase in the use of the GBAS system, from 4.15% to 7.5%. However, the years 2020-2022 proved to be a turning point, with an increase in the use of the GBAS system by more than 13 percentage points. The highest usage was in 2023, but as mentioned, the data for 2024 does not cover all twelve months, which may affect the full-year summary. Consequently, between 2014 and 2023, there was an increase of approximately 19.6 per cent in the use of the GBAS system. Furthermore, in 2023, according to data published by Frankfurt Airport (www.fraport.com), 430,436 flight operations were carried out, of which 215,222 were landings. Consequently, 20,445 of these were operations carried out using the GBAS system. (calculated as 9.5 per cent of 215,222). This figure shows that GBAS still does not have a major impact on landing operations at Frankfurt Airport, but significant progress has been observed over the last decade since GBAS was implemented at Frankfurt Airport. More effective use of the system is also crucial in terms of environmental benefits and increased capacity

In terms of environmental protection, the GBAS approach allows for the implementation of Continuous Descent Arrival (CDA), which means that the aircraft is not in a horizontal flight phase, thus reducing the level of noise generated. Arrival routes have also been modified. By raising the minimum sector altitude, aircraft will remain at a higher altitude for longer, which will reduce fuel consumption. An additional benefit will be the reduction of carbon dioxide and other chemical compounds produced by fuel exhaust emissions [2]. According to data from Eurocontrol, the European Organisation for the Safety of Air Navigation, the use of CDA compared to the traditional approach allows for a one-time saving of 50 to 150 kilograms of aviation fuel. The amount of savings depends on the type of aircraft and the altitude at which the CDA procedure was initiated. The use of this environmentally friendly landing method also translates into a reduction in exhaust emissions and the type of aircraft, distance from the airport and weather conditions. Currently, CDA is already used at many airports in the United States and Europe, and other airports are preparing to implement it [9]. Fig. 7 shows visualisations of the CDA approach and the step-by-step approach.

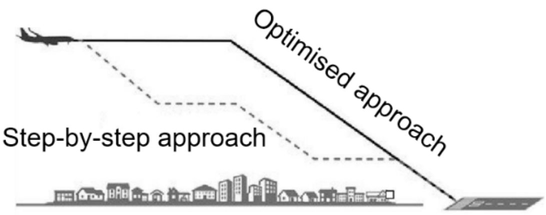

Fig. 7. Visualisation of the CDA approach and the step-by-step approach [10]

DFS conducted a simulation to determine how airport capacity would change during operations, depending on hourly demand and, consequently, on the number of operations performed in each hour. The simulation was designed to analyse whether the theoretical assumptions would be confirmed in practice and whether, in fact, capacity would improve with increased use of the GBAS system. Figure 8 shows how the use of the GBAS system can change airport capacity.

It can be clearly seen that during the simulation, when aircraft are equipped with GBAS above 60%, they are able to meet the demand, thus confirming the theory regarding the use of the system. During the simulation, the average delay per aircraft was also calculated, considering the use of the GBAS system. Figure 9 shows the changes depending on the percentage of equipment.

As demonstrated in Figure 9, increasing GBAS equipage from 0% to 60% drastically reduces average arrival delays from ~24 minutes to 5.5 minutes per aircraft. Beyond 60% equipage, delay reductions diminish (4 min at 80%, 3 min at 100%), establishing 60% as the critical operational threshold for eliminating peak-hour air traffic congestion at major hub airports.

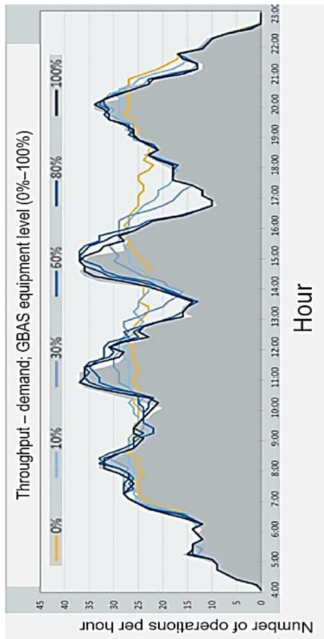

Fig 8. Airport capacity depending on the number of operations performed, depending on the level of GBAS equipment [11]. Grey colour- demand

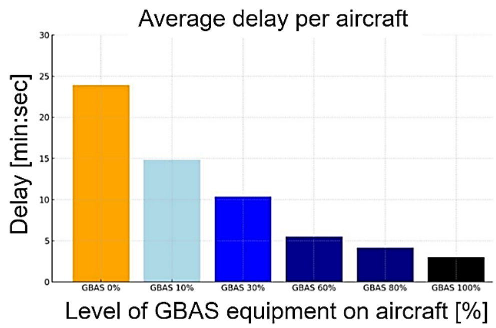

Fig 9. Average flight arrival delay per aircraft in terms of GBAS equipment [11]

GBAS allows curved flight paths and customized glide slopes (up to 3.2°--3.5°), enabling Continuous Descent Approaches (CDA). Comparative operational studies [9, 10] confirm that CDA eliminates low-altitude level flight segments:

- Fuel Savings: 50--150 kg of jet fuel saved per approach.
- Noise Abatement: 2--5 dB noise reduction along the arrival corridor.
- Emissions Reduction: Proportional decrease in CO_2 and NO_x emissions.

Despite demonstrated technical advantages, widespread GBAS adoption is constrained by three main barriers:

1. Absence of Mandatory Retrofit Timelines: EASA has mandated ADS-B Out and PBN capability, but lacks binding mandates for GBAS (GLS) avionics retrofits on legacy commercial fleets. Retrofit costs ($50,000–$100,000 per aircraft) discourage airlines in the absence of regulatory requirements.

2. GAST D Certification Harmonization: Regulatory alignment between the FAA and EASA regarding GAST D (CAT III autoland) validation remains incomplete, creating uncertainty for long-haul transatlantic operators.
3. Infrastructure Financing: Air Navigation Service Providers (ANSPs), including DFS, rely heavily on EU co-funding mechanisms (e.g., SESAR, Connecting Europe Facility) to finance redundant ground stations for full CAT III resilience.

4. CONCLUSION

Based on the interpretation and data analysis, it can be concluded that the GBAS system can be an alternative to other landing approach support systems. It is a forward-looking solution that can complement airport operations thanks to the wide range of possibilities it offers, as illustrated by the example of Frankfurt Airport. One of the objectives of the study was to determine whether GBAS can be a functional alternative to the ILS system, and this thesis can certainly be confirmed based on theoretical analysis and research in which simulations were carried out to improve capacity and reduce delays for arriving aircraft. These simulations showed that increased use of the GBAS system will significantly improve these indicators. The paper also pointed out the differences between GBAS and ILS, which allowed for a deeper understanding of the unique features of both systems, highlighting many advantages and possibilities of the GBAS system. In addition, the ecological and economic benefits of using GBAS were emphasised, such as reduced greenhouse gas emissions and lower operating costs thanks to greater precision of approaches. At the same time, attention was drawn to the significant problem of the low percentage of aircraft equipped with GBAS and its limited use by aircraft already adapted to this solution. However, both the percentage of aircraft equipped with GBAS and its use by aircraft approaching Frankfurt Airport are steadily increasing. Overcoming the financial barrier associated with implementing the system on a larger scale would, however, open up enormous opportunities for the development of aviation worldwide, including increased safety of flight operations in difficult weather conditions. Support from international organisations and cooperation with aircraft manufacturers and airport operators will be key here.

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- Non-Destructive Testing (NDT) Methods: Exploring advanced diagnostic techniques to ensure structural integrity and safety in transport systems

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- Alternative Fuels: Researching the utilization and integration of sustainable and alternative energy sources in modern transportation.
- Cybersecurity: Focusing on the protection of transport infrastructure, communication networks, and digital systems.
- Artificial Intelligence (AI): Implementing AI methodologies and machine learning algorithms to solve complex engineering and diagnostic problems.

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