Preparation for GBAS at Braunschweig Research Airport – First Flight Test Results

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BIOGRAPHY

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Carsten Butzmuehlen is the Managing Partner of IntegNav GmbH, a technological spin-off company of the Institute of Flight Guidance of the Technical University of Braunschweig established in 2004. He works in the field of precision navigation with particular focus on Space Based and Ground Based Augmentation Systems. He is mainly involved in the area of certification and validation aspects for satellite navigation systems.

ABSTRACT

Global Navigation Satellite Systems (GNSS) are becoming an integral part of the navigation infrastructure available to civil aviation. The Ground Based Augmentation System (GBAS) is an augmentation system and is designed to support precision approach operations.

It is planned to install a GBAS Ground Segment at the Braunschweig Research Airport. Further intentions are to develop a better understanding of the services that GBAS can provide for advanced operations. To gain a better insight of the inner processes of a GBAS ground segment, the Institute of Flight Guidance (IFF) of the Technical University of Braunschweig is performing preparatory work, including flight tests.

In order to simulate the processing, several reference receivers are installed in locations at the Braunschweig Research Airport and data has been recorded. Using the relevant ILS installation and flight calibration data, an equivalent GBAS final segment has been defined. In order to obtain the GBAS message types for pseudorange corrections and final approach segment data blocks, the PEGASUS software developed by EUROCONTROL has been used to simulate the processing steps which have to be performed inside a GBAS ground segment.

Flight trials have been executed using a multimode receiver onboard the research aircraft of the Technical University, performing ILS approaches at Braunschweig Research Airport. The deviations displayed for the pilot from these flight trials have been recorded for later analysis. In this paper, first results of these ILS flight trials and the resulting GBAS analyses will be presented.

INTRODUCTION

Intention of on-going Research

The Institute of Flight Guidance participates in activities to establish a GBAS Ground Segment at
the Research Airport Braunschweig to support R&D on GBAS CAT II/III subjects and thus to gain insight and knowledge on the working of GBAS Ground segments.

The Research Airport Braunschweig is equipped with an Instrument Landing System (Localizer and Glideslope), providing certified CAT I approach guidance capability.

In order to prepare forthcoming GBAS activities, the possibility to execute ILS approaches has been used to “simulate” the inner processes of a GBAS Ground / Airborne segment using the PEGASUS tool. This allows the comparison of the recorded ILS approach guidance capability with the GBAS “simulated” approach guidance functionality.

**Research Airport Braunschweig**

The Research Airport Braunschweig serves as a regional airport for the commercial transport as well as a test site for research institutes of the DLR, the Technical University of Braunschweig and small to medium size companies. The airport itself features one runway in the “26” and “08” directions (length 1680 m) and an additional parallel 900m grass strip.

The airport’s unique selling point is the concentration of major research organizations specializing in different modes of transportation. One focal point here is aviation, of course. Braunschweig is the home base of several airplanes and helicopters especially equipped for research projects as well as further facilities in the laboratory allowing the simulation and testing of applications in air traffic and traffic on the ground, both under virtual conditions and on real aircrafts.

The airport's development to a recognized test center for the application of the European positioning and navigation system GALILEO will also increase the importance of this facility significantly (see [7] for more information)

**Research Aircraft DORNIER Do 128-6 “D-IBUF”**

The Institute of Flight Guidance of the TU Braunschweig operates two research aircrafts for testing, measuring, and surveying purposes. One of them is a DORNIER DO 128-6 type (see figure 1), which is equipped with several different navigation systems (HONEYWELL LASERNAV, several GPS receivers, etc.) and has air data sensors mounted on a nose boom (standard) and at wing tip stations (optional).

The aircraft features sophisticated measuring and recording systems that can be utilized for a vast range of research projects. The crew comprises two pilots, a flight engineer and a maximum of two test system engineers for the respective payload. It has been used for numerous measuring campaigns in the last 15 years. The interested reader is referred to [6] for more information.

The Rockwell Collins MMR GLU-925-330 (owned by EUROCONTROL and currently under tests at the Institute of Flight Guidance) supports the use of the ILS and GBAS guidance systems. As shown in figure 2, the MMR is contained in a 19” rack together with a NovAtel OEM4 receiver (as well supplied by EUROCONTROL).
the data – even at intermediate stages of the data evaluation – and its display and visualization. The following figure 3 shows a conceptual vision of the PEGASUS tool (and [4], [5] and [8] for more information).

The raw data come from a number of different sources, from ground and airborne receivers (including the MMR) to GBAS ground transmissions, NANU/NOTAMs, and from independent truth systems. The Converter module translates these data sets into the PEGASUS format, and the data can then later be validated using the PlausibilityCheck module. After this, the core processing tasks begins, as defined by the user selecting a combination of different modules. The Analysis phase uses MATLAB routines called by the M-FileRunner module, reports generated by First Glance, and the Filewatch tool to directly inspect files’ contents.

The raw data from the reference receivers have been collected and stored on hard disk. At the same time, the raw data from the airborne equipment, two GPS receivers (NovAtel OEM3 and OEM4) and a LITEF LLN-G1 inertial measurement unit (IMU), have been recorded as well. All together three different antennas have been used onboard the aircraft for the execution of the flight trials (two GPS antennas and the ILS LOC/GS antenna). The aircraft Guidance Reference Point (GRP) has been selected to be at the location of the ILS Localizer (LOC) / Glideslope (GS) antenna.

![Figure 3: PEGASUS Architecture](image)

The PEGASUS frame program allows the operation of modules within a unified interface, providing scheduling and sequencing functions to automate tool operation. It allows the user to define complex processing scenarios and provides a generic interface for adding additional components.

**ILS/GBAS IN BRAUNSCHWEIG**

**Equipment Concept**

The underlying motivation of the executed flight trials was given by the motivation that the ILS installation can be used to perform approaches using the research aircraft, whereas the operation of a GBAS Ground / Airborne segment can be “simulated” off-line.

Several GPS reference receivers have been operated to collect raw range measurements. The simulated GBAS ground station consisted of four reference receivers (NovAtel OEM3, OEM4 and LGF4 receivers) – the reference receivers RR1 and RR2 were permanent installations on the Institute’s roof; RR3 and RR4 were mobile stations. The figure 4 shows the locations of the LOC/GS transmitters of the airport and the selected sites for the location of the reference receivers.

![Figure 4: ILS and GBAS Geometry](image)

Strapdown inertial sensors together with data of one GPS receiver have been used to determine the attitude of the aircraft in order to provide aircraft body-fixed lever arm corrections to correct the GPS antenna locations.

The PEGASUS modules have been used to generate the GBAS message types MT 1 (differential corrections), MT 2 (station data) and MT 4 (FAS data blocks). The GBAS airborne segment’s position was determined by using PEGASUS modules as well. The reference path of the aircraft was established using proprietary or COTS carrier phase positioning software. Having achieved a GBAS position track, a desired flight path (FAS data) and the reference position track, the error profiles for NSE, FTE and TSE can be determined. The overall equipment concept that has been used is shown in figure 5.
Approaches using ILS
The flight trials took place in October 2005 and consisted of three approaches to the runway 26 of the Research Airport Braunschweig. Before the approaches the aircraft passed the glide slope lobe and the localizer lobe for calibration purposes. The first two approaches were performed until the flare without the actual touchdown. The last one was a short approach out of the aerodrome circuit. The circling above the city of Königslutter (south of the extended center line) was due to traffic. The complete flight path can be seen in figure 6.

The two main approaches had been flown with different intentions: the first one (in the following text referred as “approach #1”) had been flown on center line, while the second one (“approach #2”) had been flown with constant offsets on both the glide slope and localizer indicators. The vertical profiles of the approaches are shown in Figure 7.

The guidance reference point of the aircraft had been defined as the position of the ILS/GS antenna at the trailing fin of the aircraft. The offset of the GPS antenna had been corrected by using attitude information of the inertial measurement unit (IMU) onboard of the aircraft.

The reference flight path has been processed using COTS carrier phase positioning software for the onboard NovAtel OEM3 receiver and the reference receiver RR1. The software was able to provide fixed ambiguity solutions for the entire flight.

GBAS Geometry
The intention of the flight trials was to simulate a GBAS flight path with the same geometry as the ILS installation in order to achieve a best-possible fit between the ILS-recorded deviations and the
GBAS-generated deviations. Therefore the geometry of the ILS installation had been used to define the necessary navigation points (e.g. LTP, FPAP, GPIP, etc.) as shown in figure 8.

The geographical data has been provided by Flight Inspection Services (FIS). It should be mentioned that the ILS approach path geometry had been established by FIS using CAT I flight inspection procedures ([9]), where the approach path possibly has been calibrated down to the decision height, and not completely down to the touchdown point. In particular, the Threshold Crossing Height TCH parameter had been calculated using an assumption of a linear approach flight path between the Decision Height and the Touchdown Point.

Using the ILS Localizer transmitter location for the Glidepath Azimuth Reference Point GARP, the Flight Path Alignment Point FPAP and the MT 4 parameter “LengthOffset” and “CourseWidth” could be determined.

The threshold “26” is used as Landing Threshold Point LTP. Thus, the Threshold Crossing Height TCH together with the Glidepath Angle GPA determined the Glidepath Intercept Point GPIP.

With the navigation points thus determined, the desired flight path of the simulated GBAS approach could be calculated and the necessary MT 2 and MT 4 parameters could be established.

GBAS SIMULATION

GBAS Ground Segment

With the collected data from the four reference receivers, the PEGASUS modules were used to simulate “off-line” a GBAS Ground Segment, selecting a Ground Continuity and Integrity Designator GCID 1. The GAD (Ground Accuracy Designator) was determined automatically by PEGASUS to be C4, which was noteworthy, since the selection of the locations for the reference receivers was done without much deliberation (due to time constraints) and the equipment employed did not make use of multipath limiting/eliminating techniques. The reason for the determination of the GAD value to be C4 is still not clearly known and remains a factor to be investigated.

The figure 9 shows the determined pseudorange corrections of the simulated Ground Segment.

GBAS Airborne Segment

With the PEGASUS-created GBAS messages, the GBAS Airborne segment could be simulated “off-line” and GBAS-corrected position solutions and the associated protection levels could be calculated using an Airborne Accuracy Designator (AAD) model A model of the airborne receiver.

The figures 10 and 11 are showing the Navigation System Errors (NSE), for the airborne NovAtel OEM3 and NovAtel OEM4 receivers, i.e. the GBAS-corrected flight path versus reference flight path with reference to the GRP or the aircraft.

Figure 10: Horizontal Navigation System Error approach #1
The difference between the position errors of the two used airborne receivers is still not completely clear. However, one of the main contributing reasons is assumed to be the number of tracked and used satellites: The NovAtel OEM4 receiver tracked (and used) consistently one or two satellites more than the NovAtel OEM3 receiver as shown in figure 12. Other contributing factors might be the newer and better hardware and software of the NovAtel OEM4 receiver (versus the NovAtel OEM3 receiver). The different airborne receiver performance remains another factor to be investigated.

The Protection Levels for the Precision Approach Service have not been determined for this approach and remain another factor to be investigated. However, Protection Levels for the Differential Positioning Service vary between 12 and 20 meter for the airborne NovAtel OEM4 and between 50 and 130 meter for the airborne NovAtel OEM3 receivers.

The difference between those performances is assumed to be mainly due to difference in the number of used satellites. No Hazardously Misleading Information HMI and no Misleading Information MI had been encountered during the flight trials.

GUIDANCE SIGNALS OF ILS VS. GBAS

Lateral Guidance Signals

Using the GBAS-corrected position solution, the lateral and vertical deviations were calculated according to the recommendations given in RTCA DO-253A Appendix C ([3]). Furthermore the recorded deviation output of the ILS subsystem of the MMR has been analysed.

Shown in Figure 13 and 14 are the lateral deviations over the distance to the threshold crossing point (TCP) for the first approach (and second, respectively). The second approach was flown with a constant offset of one dot above and one dot right of the centerline.

Both the ILS lateral guidance (recorded) and the GBAS lateral guidance (simulated) appear to be correlated to a significant extent. The only notable difference is the decreased noise level of the GBAS simulated lateral guidance signal. It should be mentioned that the ILS guidance signal was recorded as the output of the standard ILS equipment of the aircraft (thus not influenced by any display instrument property).

Vertical Guidance Signals

Shown in Figure 15 are the vertical deviations over the distance to the threshold crossing point (TCP) for the first approach. In contrast to the lateral deviations, which appear to be correlated to a great
extent, the vertical deviations differ significantly and display a systematic offset.

One of the possible explanations of this offset is the algorithm which was used to determine the vertical deviations. Having noticed the offset between the GPIP and the GERP, it is obvious that the equations used to calculate the vertical deviations (contained in RTCA DO 253A Appendix C, [3]) must be modified, if the intention is still to achieve a similar approach guidance geometry and thus comparable deviations between the ILS- and GBAS-guidance signals. In particular, the coordinates of the GERP are derived now as follows:

\[ r_{ECEF}^{GERP} = r_{ECEF}^{LTP} + \left( \frac{TCH}{\tan(GPA)} + D_{GERP} \right) u_{rv} + d_{GERP} u_{lat} \]

with the parameters \(D_{GERP}\) and \(d_{GERP}\) set to appropriate values for the geometry of the ILS installed at the Braunschweig Research Airport.

With the modifications as discussed above, the vertical deviations for the approaches # 1 and #2 are given in Figure 16 and 17. In direct vicinity of the TCP the vertical deviation increases, which is the typical effect of the use of angular deviations.

**Figure 15:** Vertical Deviations, Approach #1 with original equations for deviations

**Figure 16:** Vertical Deviations, Approach #1

**Touchdown Performances**

As shown in figures 13 and 14, the lateral deviations for approaching aircraft do not differ significantly (using either the “real” ILS or the “simulated” GBAS). This can be mainly explained by the flexibility to describe the GBAS lateral approach path geometry in MT 4, in particular to the parameters “ALengthOffset” and “Course-Width” and the location of the Flight Path Alignment Point FPAP.

However, the vertical deviations do differ significantly (as shown in figure 15). It is quite possible that these differences can be explained by (a) the geometry of the approach path being derived by FIS data obtained using CAT I approaches and (b) the assumption of a linear ILS approach path geometry between the CAT I decision height and the touchdown point or the landing threshold point.

This difference will lead to different vertical touchdown performance results, which should be avoided from an operational point of view (in particular, in a mixed-mode ILS/GBAS operation at an airport). Those differences can only be aligned if additional parameters coming from the particular airport installation of the ILS are “transmitted and applied” by the GBAS Airborne Segment, in particular the runway alongtrack- and crosstrack-offset of the Glidepath Elevation Reference Point GERP.

**OUTLOOK**

Although the results appear to be promising, there are a couple of issues which have been determined to the open and remain to be investigated.

The PEGASUS modules provide the capability to automatically determine the Ground Accuracy Designator GAD based on the raw measurement data of the ensemble of the reference receivers. However, having utilized this capability for these flight trials, a GAD factor C4 was determined, although the location of the reference receivers was not optimal and the employed hardware did not
make use of any multipath limiting/eliminating techniques.

The performance of the GBAS airborne segment was calculated using two different airborne receivers and significant differences have been noticed. Possible explanations include the number of used satellites in the GBAS position solution, newer and improved GNSS receiver hardware and software.

The Protection Levels have been calculated for the Differential Positioning Service. The Precision Approach Protection Levels are yet to be determined.

Further analyses of GBAS Ground Segment architecture design can be performed using the PEGASUS modules. In particular, the impact of different numbers of reference receivers and the evaluation of the site locations for the reference receivers remain an important factor to be investigated.

Finally, the flight tests performed at the Research Airport Braunschweig have shown that vertical deviations of the ILS and GBAS guidance signals are only comparable, if the location of the ILS Localizer (LOC) and the GBAS Glidepath Elevation Reference Point (GERP) are identical. Additional flight trials should be performed at different airports (i.e. using different airport geometries) in order to provide comparable results. This might be possible to achieve, since flight tests are planned at airports near Frankfurt in January under a EUROCONTROL contract for GBAS/SBAS flight trials.

CONCLUSION

Ground Based Augmentation System (GBAS) are designed to support precision approach operations. It is planned to install a GBAS Ground Segment at the Braunschweig Research Airport. To gain a better insight of the inner processes of such a GBAS ground segment, the Institute of Flight Guidance of the Technical University of Braunschweig has performed preparatory work, including flight tests.

Flight trials have been executed at the Research Airport Braunschweig, using the CAT I capable Instrument Landing System for the generation of the guidance signals. Raw GNSS measurement data from four reference receivers installed in the vicinity of the airport and two airborne receivers had been recorded, thus providing the “off-line” capacity to simulate a GBAS Ground Segment and Airborne Segment.

As the focal tool to simulate the GBAS Ground Segment and the GBAS Airborne Segment, the PEGASUS modules have been used. Thus, PEGASUS has proven itself as a design and analysis tool, which provides valuable insights. In particular, variations on the quality of the reference receivers (GCID and GAD parameters), the number of the reference receivers and the location of the installed reference receivers can be easily established and analyzed. The results of a GBAS airborne segment can be determined without difficulty as well.

Navigation System Errors for the GBAS airborne position solution have been obtained using Carrier Phase Positioning software. The achieved accuracy performance was determined to be in the meter range. No Hazardously Misleading Information HMI and no Misleading Information MI had been encountered during the flight trials.

In order to achieve “ILS look-alike” performances, the GBAS approach path geometry was modeled to be identical to the ILS geometry at the Research Airport Braunschweig. Data on this geometry have been obtained by CAT I flight inspection data, most likely using the approach path geometry above the decision height and assuming a linear approach path geometry down to the touch down point.

The lateral deviations for approaching aircraft do not differ significantly (using either the “real” ILS or the “simulated” GBAS). However, the vertical deviations will differ significantly. It is quite possible that these differences can be explained by the assumption of a linear ILS approach path geometry between the CAT I decision height and the touchdown point or the landing threshold point.

This difference will lead to different vertical touchdown performance results, which should be avoided from an operational point of view (in particular, in a mixed-mode ILS/GBAS operation at an airport).

Those differences can only be aligned if additional parameters coming from the particular airport installation of the ILS are “transmitted and applied” by the GBAS Airborne Segment, in particular the runway alongtrack- and crosstrack-offset of the Glidepath Elevation Reference Point GERP.

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Finally, personnel from Flight Calibration Services FCS provided valuable support in the establishment of the geometry of the ILS installation at the Braunschweig Research Airport.
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[9] Flight Inspection Data provided by Flight Calibration Services FCS, October 2005

ABBREVIATIONS

AAD  Airborne Accuracy Designator
COTS  Commercial Of The Shelves
FAS  Final Approach Segment
FIS  Flight Inspection Services
FPAP  Flight Path Alignment Point
FTE  Flight Technical Error
GAD  Ground Accuracy Designator
GARP  Glidepath Azimuth Reference Point
GBAS  Ground Based Augmentation Systems
GCID  Ground Continuity & Integrity Designator
GERP  Glidepath Elevation Reference Point
GNSS  Global Navigation Satellite Systems
GPIP  Glidepath Intercept Point
GPS  Global Positioning System
GRP  Guidance Reference Point
GS  Glideslope Transmitter / Receiver
HMI  Hazardously Misleading Information
ILS  Instrument Landing Systems
IMU  Inertial Measurement Unit
LOC  Localizer Transmitter / Receiver
LTP  Landing Threshold Point
MI  Misleading Information
MT  Message Type
NSE  Navigation System Error
RR  Reference Receiver
TCH  Threshold Crossing Height
TCP  Threshold Crossing Point
TSE  Total System Error