FLIGHT TESTING OF STEEP PRECISION APPROACHES BASED ON GBAS

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Abstract

As the international air traffic becomes more and more complex (a growth of 2.3% from 2006 to 2007, 57% from 1997 to 2007 [7]) there is a growing demand for new operational procedures. Especially quiet and fuel efficient approaches are desired. A Ground Based Augmentation System (GBAS) provides more flexibility than current precision landing systems. Therefore, it is identified as a potential key technology for providing different approach procedures tailored for unique demands at a special location. Especially steep precision approaches have a high noise reduction potential as the aircraft can stay at a higher altitude for a longer time.

During this work approach procedures based on GBAS with slightly higher glide path angles than usual (4.5° - 5.5° instead of 3° - 3,5°) were investigated. Therefore a simple software simulator of a Multi Mode Receiver (MMR) was created and integrated into a Generic Experimental Cockpit (GECO) simulator. The Final Approach Segment (FAS) data for an ILS look-alike approach (glide path angle 3.5°) and for approaches with steeper glide path angles were validated in this simulator. Pilots were familiarized with the new approaches in the simulator and some questionnaires were filled out regarding the workload and flight technical demands for the pilots. The simulation architecture is going to be described in this paper and the results of the simulator trials are going to be presented.

After the GBAS Landing System (GLS) Approaches were validated in the simulator the FAS data blocks were transferred into an actual ground installation at the research airport Braunschweig-Wolfsburg. The FAS Data was checked with ground trials and some flight trials were conducted to verify the data gathered in the simulator trials.

1 General Introduction

In December of 2008 a Ground Based Augmentation System (GBAS) ground station has been installed by the German Aerospace Centre and Thales Air Traffic Management (ATM) at the research airport Braunschweig-Wolfsburg. In this paper the technical aspects of the installation at the airport as well as the means taken to validate the installation through simulator and flight trials will be presented. The design of the final approach segment data that has been installed and which is being broadcasted by the station will also be described.

After the optimal site for the ground station had been chosen and the physical installation had been completed according to [3], the proper reception of the GNNS signals by the reference receivers has been ensured and the Very High Frequency (VHF) transmission of the GBAS messages has been validated through flight trials. A first GBAS approach has been designed for the airport Braunschweig-Wolfsburg. Due to simplicity and obstacle clearance reasons it has been developed as a straight in ILS-look-alike approach having the same parameters as the existing ILS approach on runway 26 at the airport. It has been designed to start at a final approach fix (FAF) 2500 ft above mean sea level (MSL) and has a straight decent with a glide path angle of 3.5°.

Furthermore the experimental setup and the created functionality are going to be shown. With the described equipment some straight in GBAS approaches have been carried out at the research airport. The operational procedures used to test the broadcasted approach will be shown and the results of the flight trials are going to be presented.

As a second step the new approach paths with steeper glide path angles were created and integrated into the GECO and simulator trials were conducted to evaluate the new approaches. Different pilots conducted different approaches with different glide path angels. After each approach the pilots were questioned about the subjective work load and the flight technical demands. The approaches were transferred to the real station and flight trials were carried out. The results of the flight trials are going to be presented and a comparison of the position deviations during different approaches with different glide path angles will be shown.

Concluding an outlook on the planned research activities by the German Aerospace Centre with the installed GBAS ground station will be given. Various research activities that will include work on the ground installation as well as work on the operational procedures based on GBAS are going to be conducted.

2 Ground Station Installation

The research airport Braunschweig-Wolfsburg is in the north of Braunschweig in northern Germany. The airport has one concrete runway (26/08) with a length of approx. 1500 meters. Five different shelters within the airport territory are owned and operated by the DLR and were inspected with respect to GBAS suitability. Due to existing plans for a runway expansion two shelter positions were not included in the siting process. Measurement campaigns at the other shelter positions were carried out and a qualitative data evaluation regarding the suitability as position for a GBAS ground station was done. This evaluation concentrates on the assessment of the visibility of the satellites, the quality of a GNSS stand alone position solution, the analysis of the quality of reception of slant range measurements as well as a first qualitative computation of multi-path effects.

For the data recording a NovAtel OEM4 ProPak G2Plus receiver as well as a NovAtel L1/L2 choke ring antenna GPS-533 with radome on a stand was used [14]. Contrary to receivers of a GBAS ground station, that can receive only the carrier frequency L1, the NovAtel OEM4 receiver can receive raw data on the carrier frequencies L1 and L2. This makes it possible to eliminate ionospheric errors later. The choke ring antenna and the height of the used stand are also decreasing the influence of multipath effects. The NovAtel OEM4 receiver and a laptop for the recording of the serial data were installed in respective shelters. For the serial data recording a proprietary terminal program by NovAtel was used (SLOG, Scripted Logger). The number of visible satellites for all three selected positions moves between 8 and 13 satellites with an average value between 10 and 12 satellites. There is no restriction of the visibility regarding the local environment due to the noted elevation and azimuth masks recognized. For the data recording only a minimum elevation angle of 5 degrees was preselected. In the comparison of the three positions, the shelter 3 has a slightly increased number of visible satellites. The quality of reception of the slant range measurements for all three selected positions shows a good signal-to-noise ratio of 40 db(W), with few epochs of smaller signal strength. The evaluation of the channel status flag shows only in the epochs with smaller received signal strength some bad quality of reception (L1 code/phase or L2 code/phase not usable). In the comparison of the three positions the shelter 3 shows a better quality of reception of the slant range measurements and was chosen for the GBAS installation [11]. Multi-path is generated by reflection of the GPS SIS at ground, buildings, objects and water surfaces. Multi-path signals are always delayed signals. Depending on the signal strength and on the delay time different large error contributions are generated in the GPS SIS evaluation function of the GMS. To reduce the influence of multi-path signals the locations of the GBAS antennas must be carefully selected and the design of antennas and GPS receivers should use appropriate multi-path mitigation techniques. The logged data was post-processed by an appropriate tool provided by Thales ATM. This tool is able to calculate sigma and mean of the CMC values. The test measurements for this purpose were performed by Thales ATM with the GPS antenna placed 40m westward of the shelter at a height of 1.2m [10].

The sigma values were calculated over a sliding averaging window of 1000 samples. The core distribution is always better than 0.1m. The mean CMC value is in all cases better than 0.05m. Satellites with low elevations (from 5 ° through 10°) and some satellites from 55° through 60° do have more measurement noise and multi-path is impacting the measurement to some extent. In summary the site provides an excellent quality of GPS reception. After the siting analysis was performed, three GPS antennas and the VHF transmit antenna was installed at the chosen shelter. Inside the components of the ground installation were integrated and the approach procedures were designed.

3. GLS Procedure Design

After the GBAS ground station was installed, operating GLS approach procedures were designed according to [2]. This included one ILS look-alike procedure and three straight in procedures with higher Glide Path Angles (GPA). The coordinates for the Final Approach Segment (FAS) were taken from the Aeronautical Information Publication (AIP) Germany [5]. As there is an existing ILS installation at the airport Braunschweig Wolfsburg, the goal was to design a GBAS procedure which is very similar to the existing ILS Procedure for an easy comparison between the ILS and the GLS approach. The airport has one concrete runway and an ILS installation for one runway end. The ILS installation has a 3.5° glide path angle for the runway 26 (true Heading 264.9°). The localizer antennas are located at the opposite side of the runway. The procedure has its final approach fix 5.8 nautical miles away from the threshold. It starts at 2500ft above mean sea level (MSL). The glide path antenna mast is located approximately 310m away (projected on the runway) from the runway threshold. If the following formula is applied

$$\tan\theta = TCH \,/\, \overrightarrow{AB} \qquad (1)$$

with TCH being the threshold crossing height, $\overrightarrow{AB}$ being the distance between the runway threshold and the touch down point corresponding to the position of the glide slope antenna and θ being the Glide Slope Angle of the approach, the TCH calculates to 62ft. In contrast, on the official ILS approach chart, published with the AIP Germany [5] a Reference Datum Height (RDH) of 50ft is given. With the descriptions given in [13] it was assumed that as a RDH of 50ft is observed with the ILS installation it would be consequent that the TCH of the designed GBAS approach was also set to 50 ft instead of the calculated 62 ft.

With this design the Final Approach Point (FAP) for the GBAS approach was at the same coordinates and on the same altitude as the final approach fix for the standard ILS approach at the airport. The flight path alignment point was set to the location of the ILS localizer antennas. The alert limits were set to the maximal values valid for CAT I approaches. Therefore, the Vertical Alert Limit (VAL) was set to 10m and the Horizontal Alert Limit (HAL) was set to 40m for all approaches. With the Landing Threshold Point (LTP) being the threshold of the runway 26, the GBAS approach had nearly the same parameters as the existing ILS approach.

For the transition from the initial approach to the final approach the existing area navigation (RNAV) approach was adapted and a precision segment was integrated.

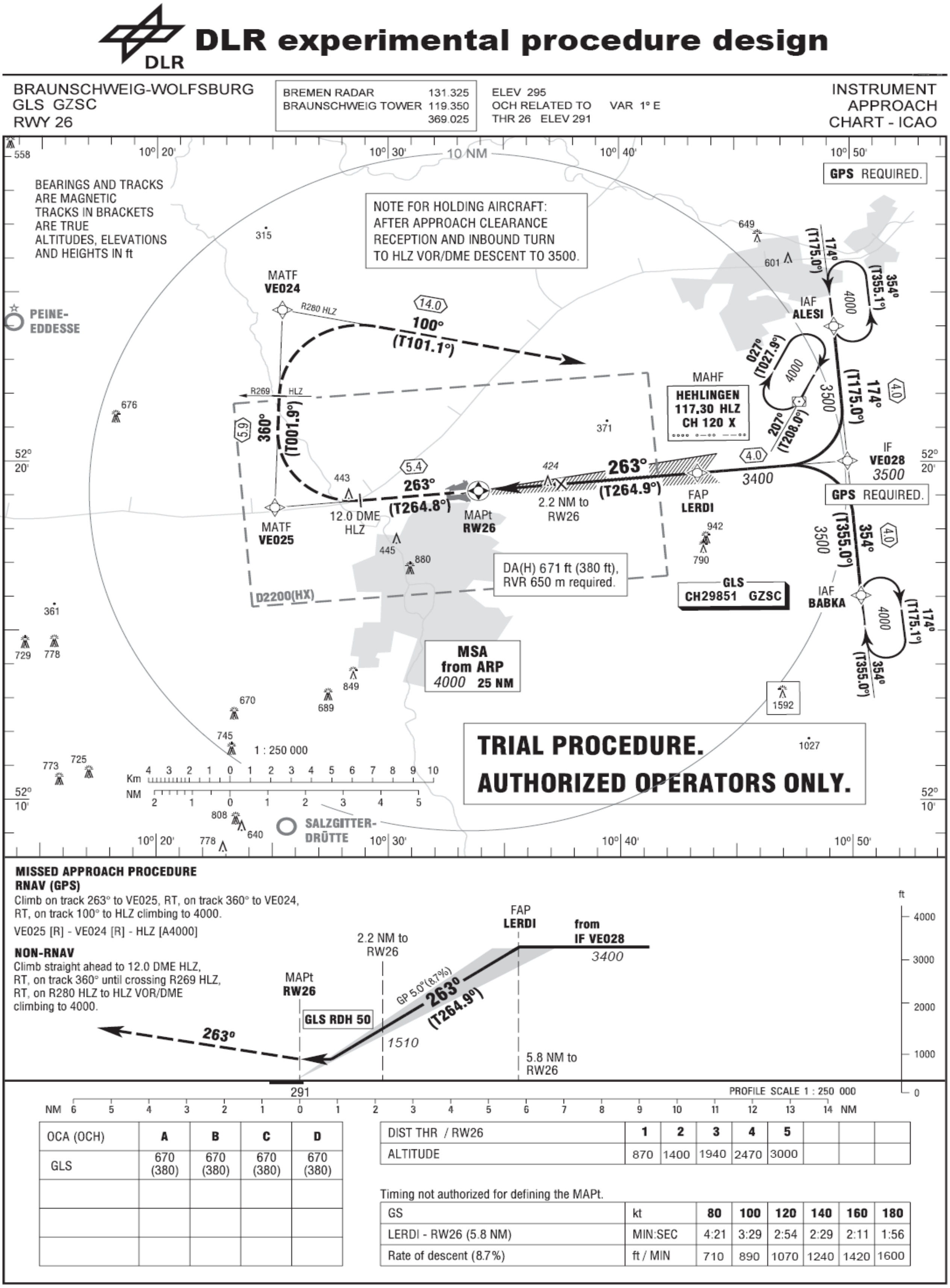

Fig 1: GLS Approach Chart

As the RNAV approach is a non-precision approach, the charted obstacle clearance altitudes/heights (OCA/H) are higher than those for a precision approach. For simplicity the altitudes were conservatively maintained. For the simulator trials the OCH was used as the decision height (DH) for all approaches. For the GLS approaches with a higher GPA a safety margin was added.

Based on this final approach segment, three additional GLS approaches were designed. Those approaches have the same horizontal layout as the ILS approach at the airport but the vertical profile is different. All approaches have a TCH of 50ft. This point is used as the centre of rotation for the final approach path. As the GPA is changed so is the location of the aim point or the Glide Path Intersection Point (GPIP) on the runway. As the GPA is increased the closer the GPIP is to the runway threshold. With this architecture and the idea to keep the horizontal profile equal for all approaches the Final Approach Point (FAP) has the same lateral position for all approaches but the final approach starts at different altitudes. Figure 1 shows the approach chart for a GLS approach with a GPA of 5°. The altitudes for the different segments are adapted. It is noteworthy that the altitude for the initial approach remains the same for all approaches. Only the segments from there to the FAP are affected. The GLS channel number was included in the chart and the GPA as well as the vertical velocities were adapted for each approach.

As an identifier four letters according to [1] were used. The letter "G" identifies a GLS approach, the two letters in the middle are arbitrary and the last letter is different for every approach for a runway end. So the created approaches had the Reference Path Identifiers (RPID) "GZSA", "GZSB", "GZSC" and "GZSD". They have a GPA of 3.5°, 4.5°, 5° and 5.5°. According to the description above they have the same FAP but the decent starts at 2500ft MSL, 3100ft MSL, 3400ft MSL and 3700ft MSL respectively. The missed approach procedure remains the same for all approaches and is identical to the RNAV missed approach procedure.

4 Simulation Environment

The simulator trials were conducted in the Generic Experimental Cockpit (GECO) of the Institute of Flight Guidance of the DLR. The GECO is a fixed simulator that is built in a modular fashion. The flight technical model integrated in the simulator is the one of the Advanced Technologies Testing Aircraft (ATTAS), a VFW 614, owned and used by the German Aerospace Centre for over 20 years. Therefore the parameters of the modes were well refined over time. The model can be exchanged with models of other aircraft and is currently being adapted to DLR's Advanced Technology Research Aircraft (ATRA), an Airbus A320.

The simulator includes six 15.4'' high resolution liquid crystal displays and several standard controls which consist of Side Sticks, Thrust Lever, Tiller, Flap Lever, Gear Lever and more. Furthermore, two Radio Management Panels (RMPs) are integrated. Figure 2 shows the layout of the simulator. The GLS approaches can be tuned via those panels with the charted channel number.

Fig 2: Generic Experimental Cockpit

A simulation of the existing navigation aids, i.e. the ILS receiver is integrated in the GECO. For the GLS trials a simulated Multi Mode

Receiver (MMR) was additionally connected to the simulation. The MMR simulator can be tuned through the RMP with the appropriate channel number. Once tuned to an approach, the receiver calculates the deviation signals from the desired flight path depending on the position and the altitude provided by the simulation. To be able to do so, the coordinates are transformed into a local Cartesian coordinate system that has its origin in the touch down point (the GPIP) and an x-axis that is aligned with the runway centreline. The horizontal deviations are calculated with respect to the x-z-plane of that coordinate system (i.e. based on the y-value). The vertical deviations are calculated with respect to the provided altitude and the position projected on the x-axis.

The deviation signals are shown on an experimental Primary Flight Display (PFD) on an experimental Navigation Display (ND). The displays are in-house developments and provide full access to the displayed data. Besides the deviation signals (in an ILS look-alike fashion) the tuned approach was displayed during the trials. This included the selected channel number and the RPID of the approach.

5 Flight and Ground Test Environment

After the ground installation was completed and the Final Approach Segment (FAS) data was programmed onto the station, ground trials were carried out to verify the broadcasted data and the deviations calculated based on that.

In order to do so, a test van of the DLR was equipped with a Multi Mode Receiver (MMR) by Rockwell Collins (GLU-925). The van provides among other aviation equipment an 115V AC power supply, a differential GPS (DGPS) and several antennas. Control software that was developed for ground and flight tests was integrated into a PC in the van as well. With this setup the van was driven around the airport area and the output data was recorded and analyzed.

With the basic transmission and reception verified, the equipment was integrated in one of the flight test aircraft of the German Aerospace Centre. The aircraft used was a Dornier 228. It was modified to use it for taxi trials. A rack was installed in the cabin with a differential GPS, a control PC, the MMR and a Keyboard–Video–Mouse switch integrated into the rack. Most importantly, two displays were integrated on the right side of the cockpit to show an experimental Primary Flight Display (PFD) and Navigation Display (ND). The displays are fed with aircraft data and the observed deviations from the MMR. The displays used were the same as in the simulation trials.

With this experimental setup the GBAS procedure “GZSA” was verified during some taxi tests. The aircraft was taxiing several times from the threshold RWY 26 on the centreline to the opposite end of the runway. The data was recorded and analyzed.

For the flight tests three different aircraft were used. A Hawker Beech King Air 350 from Flight Calibration Services (FCS) was used for first flight inspections of the ground installation. The aircraft provides a data system that is optimized for flight inspections. A Rockwell Collins MMR (GLU-930) is integrated into the system and provides the deviation information to the PFD of the basic avionics system. With this setup, some flight trials according to [9] were carried out. As the GLS deviations can be routed to the autopilot of the aircraft via the Microwave Landing System (MLS) channel, it is planned to perform some flight trials with an automated steep GLS approach.

The second aircraft used was a Boeing 737 -700 from the German airline Air Berlin. The aircraft has two MMRs (Rockwell Collins GLU-925) integrated into the basic avionics system. Therefore, the GLS approaches could be flown fully integrated. A demonstration flight was carried out to verify the operation of the ground installation against the standards. In addition first steep GLS approaches were conducted and the pilots were interrogated afterwards.

Finally, a Dornier 128 from the Institute of Flight Guidance of the Technical University Braunschweig (TUBS) was used for flight trials. The aircraft has a flight test installation installed as well as a MMR (Rockwell Collins

GLU-925). The output signals are recorded and the deviation signals can be displayed on a Course Deviation Indicator (CDI).

6 Results

In this chapter the various results from the simulator, ground and flight trials will be presented. For the described investigations the Generic Experimental Cockpit (GECO) of the Institute of Flight Guidance was used to validate the operational procedures in the simulator. For flight and ground trials three different aircraft were used as described above.

6.1 Simulation Results

The trials in the GECO were focusing on flight technical and operational requirements as well as the workload requirements of the steep precision approaches. Different scenarios were used to investigate the differences between usual and steep approaches. As described earlier, four different GLS-Approaches were designed for RWY 26 in Braunschweig-Wolfsburg. During the simulations Standard-ILS-Approaches were used as a baseline for the comparison to the new GLS-Approaches. All approaches were flown with the autopilot in the selected mode, meaning that the autopilot is maintaining speed, heading and altitude unless otherwise selected by the pilot via the Flight Control Unit (FCU). The simulation was started on a Standard Arrival Route (STAR) for a standard ILS approach or for a RNAV approach. The transition to the final approach was flown with the autopilot in selected mode. The pilot was cleared for the requested approach or for a different GLS approach by a pseudo air traffic controller. As soon as the localizer was intercepted, the approach mode of the autopilot was engaged and the autopilot was following the calculated localizer and glide slope signals. At a height of around 800ft the autopilot was disconnected and the approach was continued manually. In some cases a landing was conducted, in other cases a pseudo air traffic controller was giving a go around command. A weather simulation was excluded from the simulation to focus on the pure flight technical requirements.

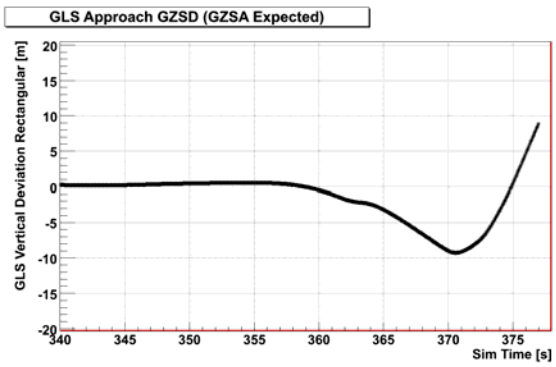

Fig 3: GLS Vertical Deviation (GECO)

The pilots were asked to answer two questionnaires regarding the subjective workload and the flight technical demands. The deviation signals were recorded and also investigated. The simulator trials showed that the MMR simulator generates similar deviations as the ILS simulator does in case of an ILS look-alike approach. The horizontal deviations remain the same for steeper GLS approaches but the vertical deviations vary obviously.

Figure 3 shows a typical graph of the recorded vertical deviation that is rectangular to the desired flight path. In the moment the pilots continued the approach manually, they pushed the nose down for an aiming point closer to the runway. The reason for that is the desire to save runway length. Especially at Braunschweig-Wolfsburg the runway is rather short for the simulated type of aircraft. As the vertical velocity is increasing for higher Glide Path Angles (GPA) the flare before the touchdown is prolonged and therefore it was observed, that the mean distance from the desired touch down point to the actual touch down point was approximately 290m for approaches with a GPA of 5.5° whereas it was approximately 150m for approaches with a GPA of 3.5°.

Besides the touch down points the deviations during the manually flown part of the approaches were investigated. It could be seen, that the deviations were not varying too much with different GPAs. Only the desired touch down point was passed with a slightly greater altitude with higher GPAs which led to larger touch down distances as described above. The examination of the questionnaires showed that the subjective workload does not increase dramatically with higher GPAs. The pilots stated that the requirements increase especially in case of a go around after a steep approach but generally they remained on a medium level. The questionnaire used was very similar to the standard workload assessment tool provided by NASA [8].

Furthermore, with the analysis of the System Usability Scale (SUS) questionnaire, it was discovered that the charts should be modified to show the differences in the approaches more clearly. The GPA should be displayed bigger for example. Furthermore the RPID should include the runway for with the approach is valid. So instead of “GZSA” the approach should be identified by “G26A”. The letters “C”, “L” and “R” should be omitted in case of parallel runway systems. This is similar to [4]. Regarding the phraseology it was stated that the phrase “cleared for GLS approach [last letter of the RPID] RWY 26” was most convenient. Those text blocks correspond to those in [6] but have a slightly different phraseology.

The pilots stated in addition that steeper approaches increase the flight technical demands slightly and the display of the deviation signals should be extended by displaying the desired rate of sink, for example. It can be stated though that the steep approaches can already be conducted with today’s aircraft without extensive adaption of existing structures.

6.2 Ground Test Results

The ground test with the test van showed a good signal reception and expected deviations in the airport area. The developed software showed the desired behaviour. During the taxi tests with the research aircraft D-CODE (a DO 228) it was discovered that the lateral deviations were calculated correctly. While taxiing on the runway centreline there was no lateral deviations indicated and the vertical deviations had the desired values as well taking the antenna height of the aircraft into account.

6.3 Flight Test Results

First flight inspections of the ground installation were performed by Flight Calibration Services (FCS). The flight test profile used was according to [9]. The results in [12] showed, that the signal reception and the calculated deviations were as desired. With the basic setup validated, flight trials with a 737-700 from Air Berlin were carried out. Several GLS approaches were performed. Mostly ILS look-alike procedures with a GPA of 3.5° were flown. They were flown party manually and partly with the autopilot engaged. The trials showed that the installation can be used by fully integrated avionic systems.

In addition some steep GLS approaches with a GPA of 4.5° and 5° were carried out. Due to safety reasons the approaches were discontinued at an altitude of 1000ft MSL. The pilots stated that the deviation signals were very stable and could be followed all the time but the vertical velocity with the required approach speed was demanding. They also stated that the perceived geometry with the runway in sight was unfamiliar.

Finally further flight trials regarding steep GLS approaches are planned. The Do 128 from TUBS shall be used to validate the results obtained in the simulator. Therefore, the aircraft will perform several approaches similar to the ones flown in the simulator. The approaches will be set up at the initial or intermediate segment in the appropriate altitude. From there the final approach will be conducted manually, following the displayed deviations on the Course Deviation Indicator (CDI). The height loss during a go around and the touch down points will be investigated besides the actual deviations encountered during the approaches. In addition the pilot flying will fill out the same questionnaires as in the simulation trials.

To investigate the differences between an automated and a manual approach, the same experiment will be repeated with the King Air

350 from FCS. The aircraft will be used to perform automated steep GLS approaches the deviations received and the touch down points recorded will be compared to the manual approaches as well as the subjective workload and the flight technical demands.

7 Further Research

It is planned to conduct further research in the area of steep precision approaches. Further simulator trials are going to be carried out with additional pilots that are employed in an airline to gather a larger variety of opinions regarding workload and flight technical demands during steep GLS approaches. In addition simulator trials are planned that investigate the transitions from the arrival or initial segment to the final approach segment. Therefore, preceding steep continuous decent approaches (SCDA) that result in a steep precision approach are going to be analysed. Besides steep GLS approaches also segmented curved and real curved approaches are going to be created and tested in the simulators of the DLR. The focus of the research will not only include the workload and the operational requirements of the approaches but also the displayed information of the deviation signals during the approaches.

In addition to simulator investigations, real flight trials are planned in the area of steep and curved GLS precision approaches. The flight trials are ought to include the analysis of the simulator trials and confirm the flight technical observations. Therefore, approaches that are flown manually and automatic approaches are going to be carried out and compared with each other and the simulator trials. The DLR is also investigating missed approach, departure and taxi procedures based on GBAS as well as closely spaced parallel precision approaches.

Next to the research in the area of operational procedures based on GBAS as described above further investigations regarding GBAS itself are going to be conducted. The DLR's activities include signal in space analysis and system monitoring to make GBAS available for adverse weather operations (CAT II and CAT III equivalent).

Further work will be carried out regarding the signal in space architecture affecting the ground station. Effects of multipath and interference will be examined and advanced approach procedures will be developed. This will include for instance curved approaches as well as parallel approaches with automated separation tools.

8 Summary

In this work the research regarding steep precision approaches and their integration into existing Air Traffic Management (ATM) structures is presented. After the actual GBAS ground installation at Braunschweig-Wolfsburg airport was installed, the created Final Approach Segment Data was validated with ground, flight and simulation trials. The results show that the FAS data have the desired horizontal and vertical profile and the deviations calculated are as expected.

Furthermore, simulations showed that steep GLS Approaches can already be conducted with current aircraft. With aircraft being developed that have the potential for short Take Offs and Landings the full potential of steeper GLS approaches can be used. Due to its flexibility a Ground Based Augmentation System provides the opportunity to design different approach procedures tailored for the demands at a special location. Especially steep precision approaches have a high noise reducing potential as the aircraft can stay at a higher altitude for a longer time. They have some operational requirements and a slightly higher workload than usual approaches.

9 Abbreviations

ATM	Air Traffic Management
ATTAS	Advanced Technologies Testing Aircraft System
CDI	Course Deviation Indicator
DH	Decision Height
DLR	German Aerospace Centre
FAP	Final Approach Point
FAS	Final Approach Segment
FCS	Flight Calibration Services

FCU	Flight Control Unit
GBAS	Ground Based Augmentation System
GECO	Generic Experimental Cockpit
GLS	GBAS Landing System
GPA	Glide Path Angle
GPIP	Glide Path Intersection Point
HAL	Horizontal Alert Limit
ILS	Instrument Landing System
MMR	Multi Mode Receiver
MSL	Mean Sea Level
ND	Navigation Display
OCH	Obstacle Clearance Height
PFD	Primary Flight Display
RDH	Reference Datum Height
RMP	Radio Management Panel
RNAV	Area Navigation
RPID	Reference Path Identifier
RWY	Runway
STAR	Standard Arrival Route
SUS	System Usability Scale
TLX	Task Load Index
TUBS	Tech. University Braunschweig
VAL	Vertical Alert Limit
VHF	Very High Frequency

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