

Combining Advanced-RNP with SBAS Guided Precision Terminal Area Paths and Final Approach Guidance

Exploiting All Benefits From Performance Based Navigation

Thomas Dautermann, Robert Geister

Institute of Flight Guidance
German Aerospace Center (DLR)
Braunschweig, Germany

Thomas.Dautermann@dlr.de, Robert.Geister@dlr.de

Abstract—Satellite Based Augmentation Systems (SBAS) for Global Navigation Satellite Systems (GNSS) currently enable precise vertical and lateral guidance for aircraft during the final approach. The newly established advanced-Required Navigation Performance (RNP) concept allows all aircraft to follow repeatable ground tracks even during curved segments in the approach. This was previously only possible with special aircraft and aircrew authorization. Terminal Area Paths (TAPs) allow the path definition and vertical guidance during the arrival and initial through intermediate approach segment. Here, we report on the design and flight test results of advanced procedures that employ combinations of the three aforementioned possibilities. We include TAPs, originally a concept from the Ground Based Augmentation System (GBAS), into the onboard Flight Management System (FMS) database in order to use them with an SBAS based navigation solution. The TAPs transition to a localizer performance with vertical guidance final approach segment, thus enabling vertically guided continuous descent approaches from cruise level at selectable descent angles down to 200ft. During the flight trials, an A320 research aircraft was able to follow the desired trajectory with vertical and lateral total system accuracy of less than 20 meters. Secondly, we show that combinations of advanced RNP with SBAS final approach segments can effectively decouple runways in dense traffic environments where these runways previously were procedurally dependent. Sufficient obstacle clearance can also be achieved despite power lines with a height of ~300ft passing just south of the airport. While performing the flight trials, we recorded a lateral precision better than 44.5 m during a curved missed approach using automatic flight control in a Hawker 750XP business aircraft.

Keywords: *satellite navigation; GNSS; GPS; RNP; performance based navigation; PBN; flight trials, curved approach, segmented steep approach*

I. INTRODUCTION

A. PBN and advanced RNP

Today, precise area navigation (RNAV) systems are common in aircraft ranging from a small single engine piston airplane through helicopters and large transport aircraft. Area

navigation permits the aircraft to navigate on a route that is independent of ground infrastructure, unlike the classical navigation involving radio beacons. Most installations are currently driven by GNSS and their respective augmentation systems as primary means of obtaining a position in space and time. While standalone GNSS are sufficient for en-route and terminal applications, the GNSS navigation solution must be augmented for providing final approach vertical guidance. Here, the most stringent requirements apply for accuracy, integrity, continuity, and availability of the system.

Most large transport aircraft augment their navigation system with inertial navigation units and the ground based augmentation system (GBAS) to serve large airports and major hubs. General and business aviation often use satellite based augmentation systems (SBAS) as they normally fly to smaller airfields with little infrastructure. SBAS systems provide regionally valid differential corrections [1] and integrity [2] information for GNSS by means of a satellite downlink. A detailed review of SBAS use for aviation can, for example, be found in [3].

Recently, the International Civil Aviation Organization (ICAO) recognized the potential for exploiting additional benefits from these systems and introduced the Performance Based Navigation (PBN) concept for a new generation of procedures [4]. The practical implementation of PBN for the lateral track keeping performance is called Required Navigation Performance (RNP, [5]) and usually specified with a numerical value expressing the 95% total aircraft system error accuracy requirement in nautical miles. For example, RNP 0.3 means that the aircraft must be certified to maintain a given track within 0.3 nautical miles during 95% of the time.

Within the established RNP concept from a procedure design point of view the behavior of an aircraft when turning during the transition between two straight legs with different ground tracks is not defined and each onboard flight management system (FMS) will calculate its own optimal trajectory.

This leads to a spread between ground tracks during turns flown by different aircraft in different wind conditions. Thus, the turn area has to be especially protected by equipping it with larger buffer zones. [6]. This issue with the curved segments led to the definition of an additional leg type to enable precise path following. These are called the radius-to-fix (RF) path terminators or Fixed Radius Transitions (FRT) [7],[8].

If an aircraft is able to fly RF turns, it is advanced-RNP capable under the PBN rule set forth in Doc 9613. In order to use RF during final approach as well as in the initial and intermediate phase of the missed approach close to the ground, additional training of the crew and higher requirements for aircraft equipment are imposed by all regulators through a special approval process ([9], (RNP AR, AR stands for Authorization Required)).

B. Final Approach Segment using GNSS

Lateral and vertical final approach guidance using GNSS augmentation systems such as SBAS (called Wide Area Augmentation System (WAAS) in the US [10], European Geostationary Navigation Overlay Service (EGNOS) in Europe [11]) is already possible by means of a final approach segment (FAS) data block. The set of parameters contains, amongst others, the coordinates of the runway threshold, glide path angle, threshold crossing height, course width at the threshold and a flight path alignment point which is usually the opposite runway threshold [12]. The FAS data is stored as part of the approach procedure in the FMS' navigation database. The computation of angular deviations from FAS data block data is described, for example, in [13], [14] or [15]. Based on the FAS data block and the present position, the FMS can compute angular deviations from a centerline and a desired glide path. Those deviations are then displayed to the pilot in the same way as data from the instrument landing system. This final approach segment guidance based on the FAS data block and the SBAS augmented navigation solution is called SBAS Localizer Performance with Vertical guidance (LPV) and enables decisions heights as low as 200ft.

C. Terminal Area Path

The concept of the Terminal Area Path (TAP) based on satellite navigation was introduced within the GBAS context. The idea is to broadcast a set of paths (defined by the end-waypoints of the individual segments) that lead to the final approach segment in the terminal area of an airport. This is similar to current published RNAV or RNP routes/transitions as they already exist at almost all large airports. The main difference envisaged was, that these paths broadcast by the GBAS ground station could also provide vertical path guidance. Additionally, they also wouldn't have to be stored (and updated) in the aircraft database. The GBAS can thus provide precision guidance (vertically and laterally) throughout the terminal area. Approaching aircraft could be guided to the final approach segment based on one single navigation system.

The transmission structure for TAPs is described, for example, in [16]. A TAP allows the definition of different leg types jointly with a vertical path angle. The three most important ones are: Initial Fix (IF), Track-to-Fix (TF) and Radius-to-Fix (RF). Using these types, straight and curved segments

can be designed with both lateral and vertical guidance. As GBAS TAPs are described in the signal-in-space interface document [16] but not standardized by ICAO, they are also not implemented in current certified GBAS ground stations. Still, the way to describe a desired flight path is similar to RNP AR and A-RNP operations. As the used waypoint types in a TAP are compliant to current standards for navigation databases [17], it is imaginable that such a TAP can also be stored in the database of a FMS. While tracking this desired flight path from the FMS, the aircraft can be guided based on SBAS navigation. Therefore, it becomes possible to enable a precise transition from the terminal area to the final approach segment of a LPV procedure with a continuously provided desired descent path also without GBAS. This proposed transition/approach procedure would be based on a single navigation system again, but in this case on SBAS instead of GBAS. In addition, the TAP functionality can be used for missed approach and departure procedures as well.

Within the GBAS TAP concept, an additional parameter, the displacement sensitivity can be set. With this parameter the maximum rectangular deviation (laterally and vertically) from the desired flight path can be specified, at which a full scale deflection will occur (as described in [18] and [19]). Therefore, the same value can be used that will occur at the transition from the TAP to the final approach segment where angular deviations are generated in an ILS-look-alike fashion. In this manuscript, we assumed a lateral and a vertical displacement sensitivity which matches the angular deviation of the LPV segment at the Final Approach Point (FAP). This avoids significant steps in the deviation indication at this point. The values used here were 227m laterally and 28m vertically.

In this manuscript, we firstly explore the use of SBAS based guidance for TAP and the transition to LPV final. Secondly, we show how advanced RNP can be used to provide instrument procedures for airports at which an IFR procedure was not possible with classical flight guidance options.

II. SEGMENTED STEEP AND CURVED PATHS IN BRAUNSCHWEIG

A. Boundary Conditions

Current landing aids usually provide guidance for a straight-in approach with a fixed glide path angle. This is rather inflexible especially in places where mountainous terrain is present. Over the last few years, noise abating procedures have become increasingly important as well. To cope with terrain and noise issues it is desirable to have more flexibility in the landing guidance aid while maintaining or increasing the precision. This flexibility can be provided by GNSS systems as they allow the free design of waypoints in space. In addition, with the TAP design pattern curved segments and different glide path angles can be implemented to, on the one hand, circumnavigate densely populated areas and on the other hand to fly higher for a longer time. The combination with augmented systems like GBAS and SBAS allows flexible precision approaches. As GBAS TAPs are not standardized, but the functionality itself is used already in PBN applications, we believe that TAPs can be used in conjunction with SBAS to enable flexible precision approaches. In contrast to actual RNP (AR)

operations the lateral as well as the vertical guidance would then be based on SBAS.

As approaching aircraft will use their barometric altimeter in the en-route and initial descent phase of their flight, there must be a transition from vertical guidance based on the barometric geoidal altitude to the SBAS ellipsoidal altitude. Therefore, the design of the SBAS TAP should incorporate an initial descent segment. The aircraft can then approach the initial fix of the TAP in a level flight and intercept the glide path from below as done nowadays at the final approach point of precision approaches.

B. Procedure Design

We designed approaches for Braunschweig-Wolfsburg airport (ICAO code EDVE), home base of DLR’s flight test fleet. The path starts at an initial approach fix north-east of the runway. To avoid the mentioned issues with the baro-SBAS transition, the approach starts with a 3° glideslope. An approaching aircraft flies level at 6000ft mean sea level and intercepts the glideslope from below. This is the design pattern used for the glide slope intercept in the final approach segment for common precision approaches. Here, this happens at the Initial Approach Fix (IAF) rather than at the FAP.

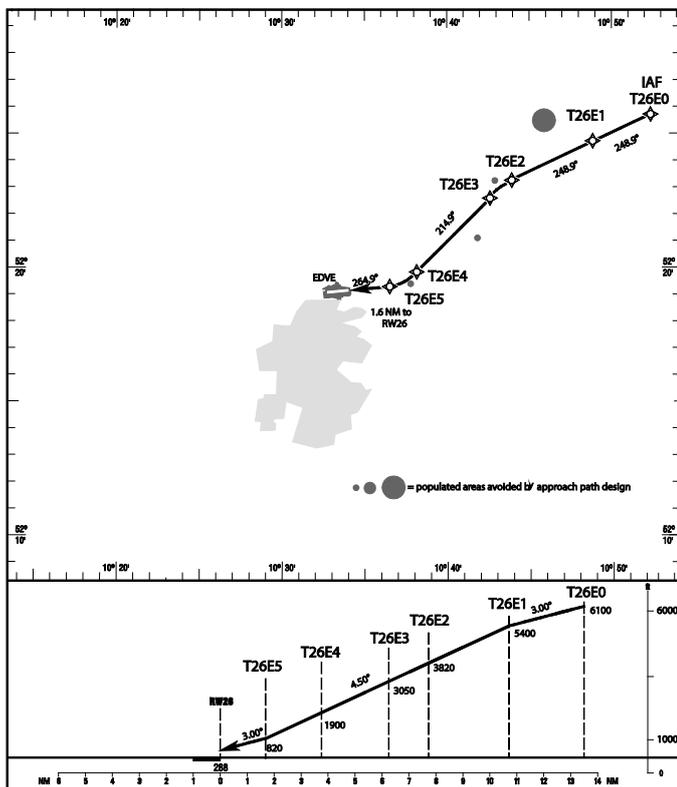


Figure 1: Horizontal approach profile

The lateral profile for runway 26 in Braunschweig is depicted in Figure 1 (top). We can see here, that populated areas are avoided and the straight final approach segment is with 3km rather short. After the initial 3° segment, the approach path transitions to a 4.5° glideslope. During the steep descent, two radius-to-fix turns are flown. The 2nd and final turn aligns with the extended runway centerline in 500ft above ground. At this

point the glideslope is reduced back to 3° for a normal landing. The vertical profile of the approach is shown in Figure 1 (bottom). The same approach path was mirrored for runway 08 in EDVE. The approach is completely symmetrical to the one for runway 26. Therefore, for simplicity reasons, the approaches to the different runway ends are treated equally in this paper.

C. Flight Test Setup

Flight trials were conducted in order to investigate the designed approach path. Three different aircraft types were used to fly the designed approach. One of them was the DLR flying test bed D-ATRA, an Airbus A320 [20]. All approaches were flown manually by the test pilots. The flight path and deviation data was shown to them using various display options (please refer to [21] for a detailed description of the different display options used). As the display setup used has a direct influence of the flyability and the flight path following accuracy (i.e., using a “tunnel-in-the-sky” display yields a high flight path following accuracy but special cockpit systems would be required or the current display architecture would have to be altered), for the analysis in this manuscript, we consider only flights with a the same setup, namely only approaches flown with a flight director for flight technical error analysis. As the navigation system error is independent from the flight technical error, all approaches can be used for the analysis of the navigation system error.

The usage of different aircraft also has an effect on the flyability of the approach. It is obviously easier to follow the profile with a slower aircraft than with a faster aircraft. In addition, the workload perceived by the pilots might increase in a faster plane. Therefore, here we focus on approaches flown with only one aircraft type, the Airbus A320. Table I. shows the dates and number of approaches conducted with D-ATRA. During all approaches conditions for Visual Flight Rules (VFR) prevailed and light head winds (in terms of runway direction) were observed (3 – 8kts).

TABLE I. FLIGHT TRIAL DATES

Date	ATRA SBAS approaches		
	# of appr.	Usable Flight Director (FD) approaches for FTE analysis	Runway
07/07/14	2	1	26
07/22/14	4	2	08

The aircraft was equipped with a GNSS receiver, a computer to store the experimental approach and to calculate the deviations from the desired flight path and an experimental cockpit display to provide the deviations to the pilot. The GNSS receiver used was a Septentrio PolaRx3e. This receiver is a SBAS capable, L1/L2 receiver which transmits the SBAS corrected position in real-time to the installed computer. Based on this position estimation, the deviations from the described approach path were calculated. A standard primary flight display with flight director was shown to the pilots on the experi-

mental cockpit display. The flight director includes rudimental turn anticipation for a better flight path following accuracy during the start of a turn.

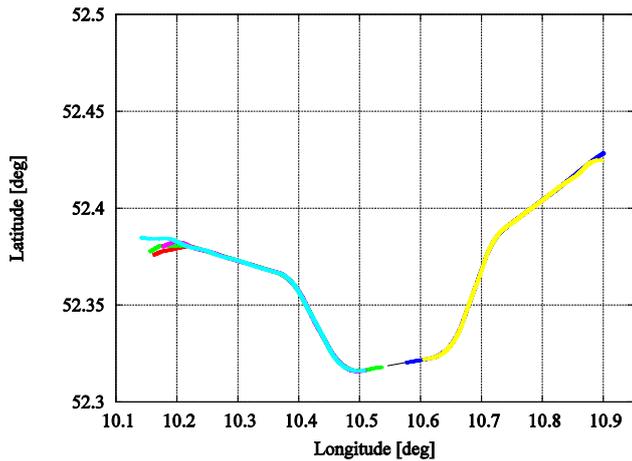


Figure 2: Horizontal flight track of all approaches, each approach is shown in a different color

As truth reference, a post-processed dual frequency solution was used that was obtained by the commercial software Graf-Nav [22]. As base station data, recordings of the GBAS experimental test bed operated by DLR’s Institute of Communication and Navigation [23] was used. With the truth reference, the observed real-time SBAS position and the calculated deviations, we analyzed the Total System Error (TSE). The TSE consists mainly of the Navigation System Error (NSE), the error between the true position and the estimated position by the navigation system and the Flight Technical Error (FTE), the error between the estimated position and the desired flight path. Data was compared and synchronized with EUROCONTROL’s Pegasus toolset [24]

D. Results

Figure 2 shows the ground track of the conducted approaches and Figure 3 shows the flown WGS-84 altitude profile with respect to the along track distance to the runway threshold (runway 08 or runway 26). It can be seen, that the approaches to the runway 26 were initiated at a lower altitude than planned as instructed by air traffic control due to airspace restrictions on that day. As described before, only approaches conducted with engaged flight director are considered for the FTE analysis. It can be seen (magenta line in Figure 3) that approaches with raw data (without the help of a flight director) of this complex nature can yield larger FTEs.

TABLE II. NSE AND TSE STATISTICS

	NSE [m]		TSE [m]	
	Mean	Std	Mean	Std
horizontal	0.678	0.374	-0.03	16.313
vertical	0.997	0.669	5.651	15.418

The statistical characteristics of the both NSE and TSE can be found in Table II. In addition, it is obvious, that the FTE is the by far larger component of the TSE when compared to the NSE. Furthermore, the lateral errors stay well below the values for RNP0.1 and are therefore smaller than required for RNP-AR operations.

The standard deviation of the vertical NSE is significantly lower than the 15.36m derived by [25] for a vertical RNP concept (0.669m, see Table II). The TSE standard deviation is only less than 10cm larger than this value, but here the approaches were hand flown. Performance is expected to increase significantly with the use of an autopilot.

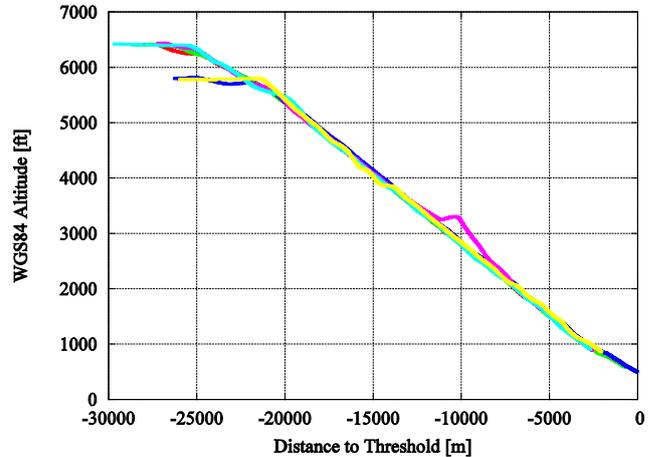


Figure 3: Altitude profile of all approaches, each approach is shown in a different color

Especially the NSE shows a very good performance during our approaches. Figure 4 shows a histogram of the vertical NSE distribution during all six conducted approaches, which is the critical component in terms of accuracy when compared to the horizontal performance. It can be seen that the mean vertical NSE is 0.997m. This indicates that the receiver was estimating the aircraft’s position to be always a little lower than reality, which is favorable in terms of safety.

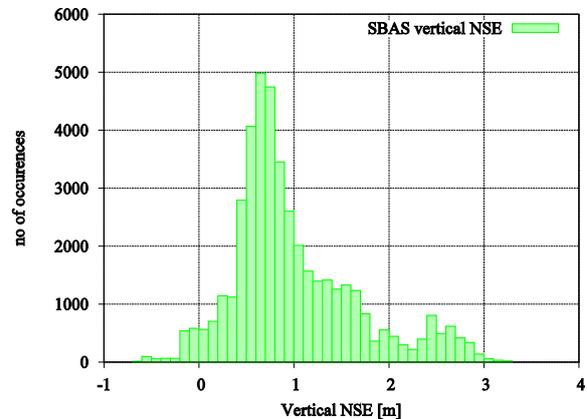


Figure 4: Vertical SBAS NSE distribution during all 6 approaches, lateral NSE shows a superior performance and is therefore not shown.

Figure 5 shows the vertical and horizontal TSE, FTE and NSE

for the three approaches conducted with a flight director. All six parameters are depicted for the three approaches with respect to the along track distance to the runway threshold. It can be seen, that the largest observed horizontal TSE is approx.

20m whereas the largest observed vertical TSE is approx. 18m, both in only one instance.

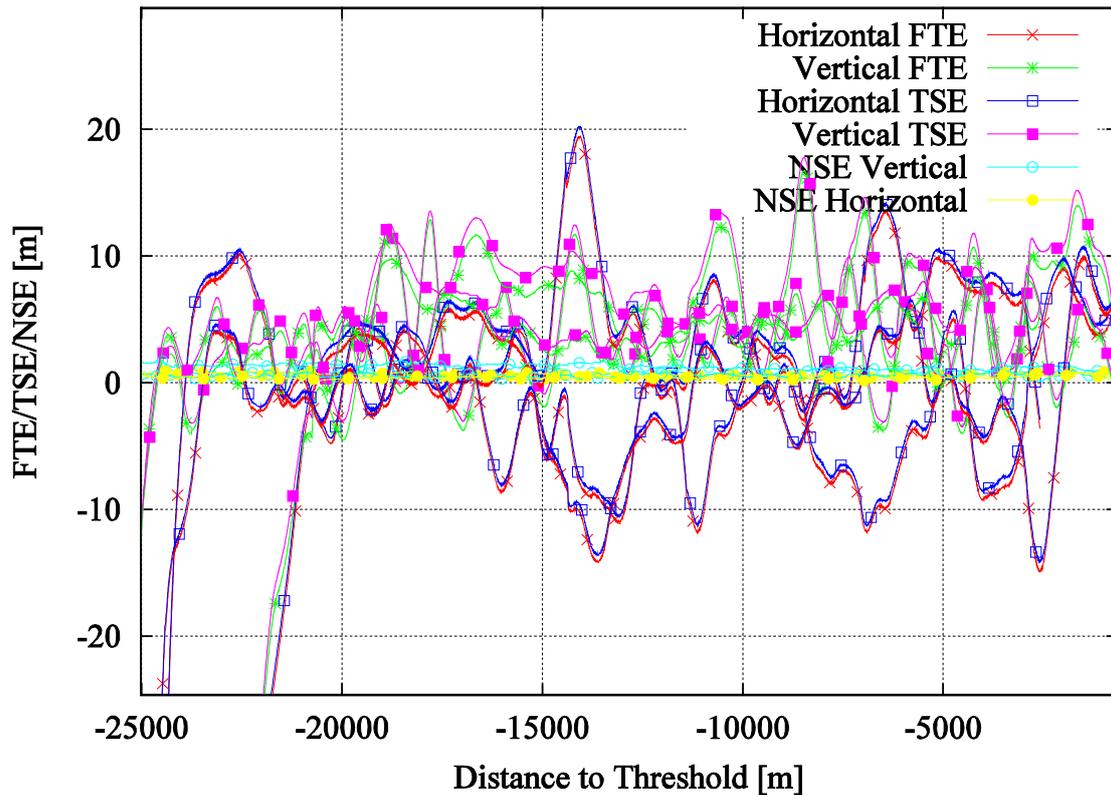


Figure 5: Horizontal and vertical FTE/TSE/NSE of the three flight director approaches (see Table I)

As the proposed approaches were investigated in terms of LPV requirements, we also looked the integrity of the SBAS position. Figure 6 shows the Stanford plot of the vertical navigation system integrity for all six approaches. In the diagram, the Vertical Protection Level (VPL), the vertical error bound is plotted against the calculated vertical NSE. If the VPL is greater than the calculated vertical NSE and the VPL stays below the specified Vertical Alert Limit (VAL) the system can be used for LPV operations. It can be seen in Figure 6 that the VPL always bounds the vertical VNSE and stays below 35m which is the VAL for LPV 200 operations.

It has to be stated, that this NSE analysis only represents six approaches but our results indicates, that the navigation performance as well as the manual flight path following accuracy (for three conducted approaches with the FD engaged) could be used for complex approach procedures which are precisely guided. In the trials with ATRA, the aircraft was fully configured before reaching the steep (4.5°) segment to avoid acceleration during the descent. This is not optimal for the avoidance of excessive noise. Satellite navigation would enable the generation of multiple approach paths for a single runway end and approaching aircraft could then use the most suitable approach. Currently research is conducted within the SESAR framework to enable steeper approaches on a more regular basis, so more aircraft could be able to conduct the proposed approaches in the future. It would then have to be investigated

how well air traffic controllers are able to clear and monitor several complex approach procedures for a single runway end.

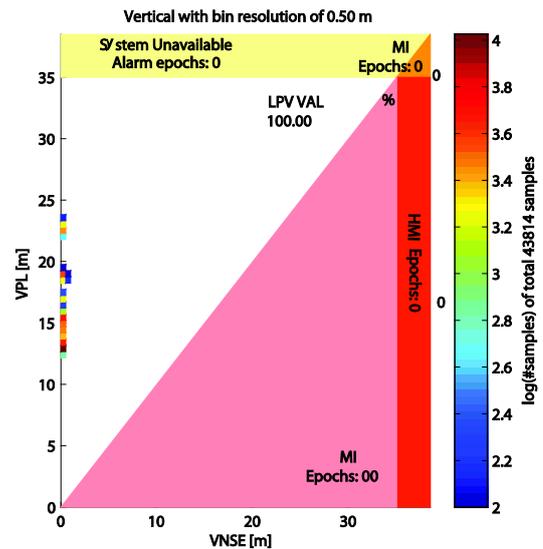


Figure 6: Vertical integrity plot of all approaches. No misleading information (MI) or hazardous misleading information (HMI) occurred, Lateral NSE shows a superior performance and is therefore not shown.

III. MISSED APPROACH GUIDANCE AT EGELSBACH

Egelsbach is a VFR only airport, situated within a Class D airspace in the corner of Frankfurt/Main international airport (ICAO code EDDF) control zone (Figure 7). Egelsbach airfield is mainly used by general and business aviation and has a single runway oriented 264° magnetic. The departure end of runway 26 is located on 1.36 NM east from the edge of the control zone established for aircraft departing runway 18 at Frankfurt.

A. Boundary Conditions

Due to the proximity of Frankfurt international airport a multitude of departure and arrival routes cross over or near Egelsbach airport. Operationally this leads to many constraints for an IFR approach procedure into Egelsbach. An approach to runway 08 at Egelsbach is not possible, since a stabilized approach would need to cross the departure sector of EDDF. For a procedure to runway 26, it is desirable to remain in airspace C and D during the final approach segment in order to protect the aircraft from unknown VFR traffic. The class D sector of the EDDF control zone shall not be entered. The missed approach must also remain at or below 1500ft MSL in order to achieve vertical separation from EDDF departures via runway 18 which have a 2500ft or above constraint at point DF159. Lastly, just south of the airport, a 380kV power line with masts as high as 712 ft MSL (327 ft above threshold elevation) crosses the VFR departure route to the south.

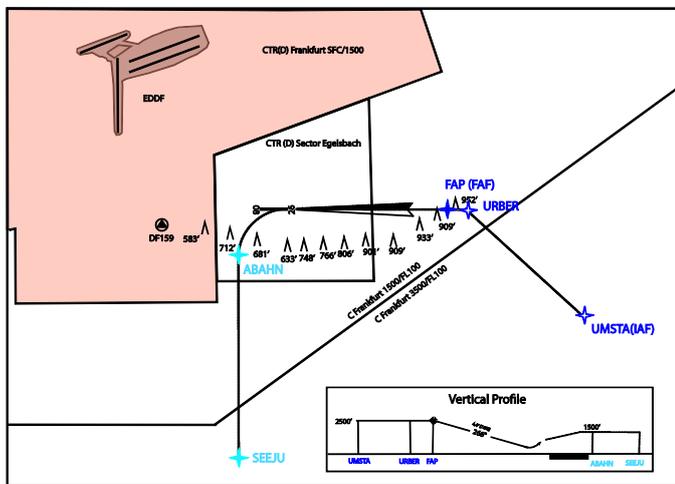


Figure 7 Procedure design plus airspace and obstacle situation around Egelsbach airport. Airspace Coordinates from [26]

B. Procedure Design

The advanced RNP with SBAS approach procedure track is also included in Figure 7. It begins in 2500ft MSL or above at point UMSTA with a 10nm straight leg on magnetic track 298° to point URBER, which should be crossed at 2500ft MSL. This track also parallels the departure track leaving Frankfurt International Airport's runway 18 towards KNG NDB with a lateral offset of 5.1~nm. URBER lies on the extended runway center-line and was coded as fly-by waypoint in order to intercept the LPV final approach course. The glide path is intercepted at the final approach point (FAP) located 0.8~nm into the direction of the runway threshold from URBER. A 4.4° glide path angle

keeps the aircraft in class C and D airspace. Minimum descent altitude on the LPV glide path was set to 1000 ft mean sea level (615 AGL) in to allow a sufficiently long time for the flight crew to re-engage the LNAV functionality in order to fly the RF turn from a fictitious threshold point (FTP26) to ABAHN. Also, this altitude provides sufficient clearance to the masts of the power lines. The distance from the missed approach point at the MDA to FTP is approximately 1~nm. This allows the turn protection area of $\pm 2 \times \text{RNP}$ to remain clear of EDDF class D. The aircraft must stay below 1500ft MSL in the missed approach in order to avoid the departing traffic of EDDF which can cross the Egelsbach airfield as low as 2500 ft with a vertical separation of 1000~ft.

C. Flight Test Setup

We performed the flight validation experiment with two approaches in a NetJets Europe Hawker 750XP equipped with a Rockwell Collins ProLine Avionics suite including the FMS6000 in Software Version 4.0 capable of advanced RNP and SBAS LPV in June 2014. Departing from Egelsbach, the approach path was intercepted between points URBER and UMSTA at 2500ft. Auto flight was activated and the aircraft followed the FMS generated trajectory. At 1300ft MSL the missed approach procedure was initiated by climbing to 1500ft MSL, reactivate the LNAV and autopilot functionality in order to follow the RF Leg starting at point FTP26. The aircraft followed the track till about halfway between ABAHN and SEEJU at which point the pilots started a left turn to intercept the approach. The approach procedure was not reactivated in the FMS so that the LPV final approach segment did not activate during the second approach. Thus, the second approach was flown using only LNAV/VNAV guidance provided by the FMS. During the missed approach part, the pilot flying followed the flight director indications provided by the FMS. We recorded the ground track using a Wintec G-Rays 2 GPS 1Hz Logger. The logger was fixed to the top of the center right part of the glare shield using 6mm adhesive tape.

D. Results

Figure 8(a) shows a top view of the respective ground tracks and the prescribed path during the RF turn in the missed approach part. Figure 8(b) and (c) shows the cross track total system error to the perfect path for the two test flights. Note that the TSE scales are different in those two figures. Data is plotted vs. time commencing when the aircraft was initially estimated to be on the initial approach course. We then separated the data into the individual legs by determining the closest approximation to each ARINC path terminator point (i.e. to URBER, FAP, the threshold and ABAHN). We marked each such timestamp with a vertical black line, thus separating the data for each segment. This technique in combination with the 2nd approach having also been flown at a lower speed, the segment separators in Figure 8 (b) and (c) do not align exactly. We computed the path deviation for each recorded GPS data point by determining the perpendicular distance to the closest route segments. Curved segments were approximated by straight segments that covered 0.5° of arc angle.

When flying on autopilot, the maximum path deviation was 44.5 meters lateral on the RF leg in the missed approach. When

flying manually, this error increased to 133.8 meters due to the pilot flying following the flight director through manual steering inputs. During the autopilot flown LPV final, lateral deviation ranged from -4 to +12 meters, during the manually flown LNAV/VNAV final lateral deviations ranged from -25 to +65 meters. It is evident from Figure 8 that during the initiation of the missed approach, the southerly wind (indicated in the FMS as 180°/20kts) caused the aircraft to drift north of the desired course. The autopilot performed much better in re-establishing the desired track than the pilot manually following the flight director. The missed approach procedure imposed a high workload onto the cockpit crew. Usually, the standard procedure

when conducting a missed approach is to add full power, start the climb and clean up the airplane. This leads typically to climbs of 2000 to 3000ft at the best climb speed before further adjustments. With the final approach speed being 120kts indicated airspeed the present procedure poses some challenge to the pilot to not exceed the 145kts for the turn and not to overshoot the target altitude of 1500ft MSL which is only 500ft above the decision height. At the same time, the FMS must be triggered to enable the missed approach track guidance and the lateral and vertical navigation functions of the autopilot must be re-engaged.

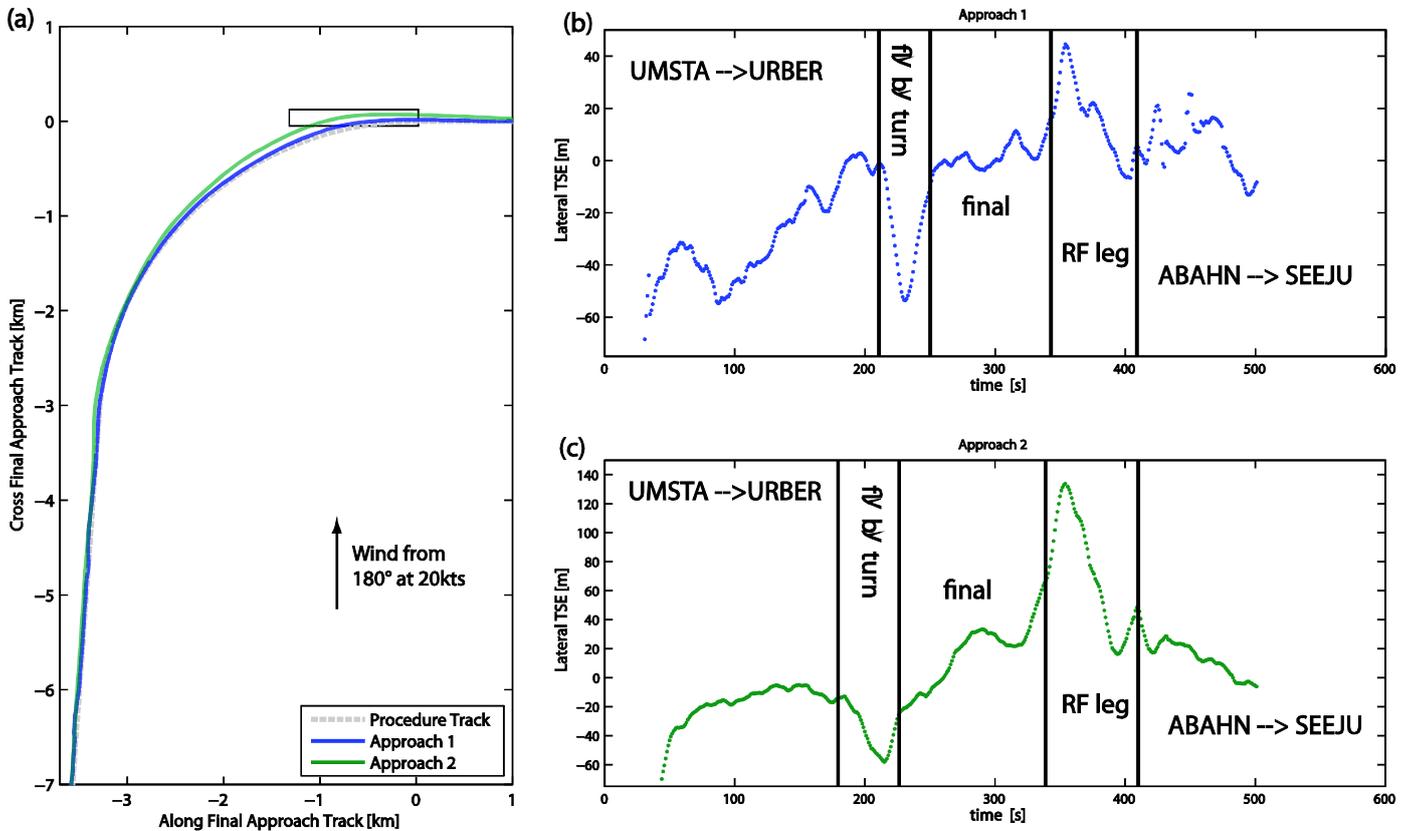


Figure 8 Lateral track deviations and flight technical error during the flight validation experiment. The blue curve shows the first approach, which was flown using the autopilot. The data shown in green was recorded when the pilot was flying manually using the flight director on the primary flight display. Panels (b) and (c) show time on the x-axis and are therefore dependent on the speed at which the aircraft was flown and the estimated time of initial approach path intercept.

IV. GREATER IMPACT AND CONCLUSIONS

In this manuscript, we showed that SBAS based advanced-RNP navigation can be used to provide highly precise guidance on laterally straight and curved segments laterally as well as vertically for aircraft in the terminal and approach phases of flight.

In the United States WAAS is already certified to provide guidance on LPV approaches down to 200ft decision height (LPV200). EGNOS in Europe is set to declare LPV200 operational in the core European Civil Aviation Conference (ECAC) region in 2016 according to the EGNOS roadmap [27]. With

this certification SBAS can provide a 3D Type B approach not very different from current GBAS capabilities but requiring almost no ground infrastructure to be present at the airport with the exception of runway markings and the appropriate lighting system. Moreover, we have shown that the TAPs known from GBAS can also be stored in the onboard navigation database. By themselves they constitute a set of parameters from which the aircraft can compute its lateral and vertical deviations from a desired path and the guidance system can steer as close to this path as possible. They can also easily be included into an onboard database similarly to the FAS data blocks. Then, the vertical guidance can also be provided by an SBAS backed navigation solution. This can make it easier for the pilots to fly continuous descent final approaches (CDFA) since a descent

path is available already at large distances from the airport while in the coverage area of the SBAS system. This would enable vertical guidance not only on the straight final approach segment but during all desired flight phases. However, there is one drawback. As stated, within the GBAS TAP concept, an additional parameter, the displacement sensitivity can be set. This parameter is not intended in the aircraft database. Therefore, a RNP value would have to be used. But with that, the transition point to the FAS is fixed and some flexibility is lost. In addition, there are currently no vertical RNP values defined. So this would be a topic for further investigations. A first proposal to introduce vertical RNP is made in [25]

Using the new possibilities provided by this generation of augmented satellite navigation, airports which otherwise are procedurally dependent (due to their runway layouts and location like, for example, Egelsbach and Frankfurt/Main) can effectively be decoupled. Continuous Descent Operations (CDO) can be performed with vertical guidance commencing at long distances from the airport of intended landing. This removes the need for precise wind forecasts along the flight route, which if predicted wrongly may require the flight management computer (FMC) to insert a costly level segment.

Advanced FMCs as they are necessary today for CDO are only available in large air transport aircraft due to their high cost. SBAS enabled TAPs can provide this capability even to small general aviation airplanes. Lastly, with vertical guidance, separation from terrain and other aircraft could potentially be reduced to a lower margin as large buffer zones due to inaccurate navigation are no longer required.

ACKNOWLEDGEMENTS

We would like to thank Michael Felux and the DLR Institute of Communications and Navigation for providing the ground reference station data. Thanks also to the test pilots Hans Jürgen Berns, Jens Heider, Spencer Davies and Kevin Buddle as well as the ground support team. Lastly we would like to acknowledge DFS, the German air traffic control agency for facilitating our flight trials and Thorsten Mühlhausen for the internal review of the manuscript. The work pertaining Egelsbach airport was performed as part of the project FILGAPP lead by INECO SA, funded under grant agreement number 287212 of the 3rd FP7 Call FP7-GALILEO-2011-1.4-1-GSA.

REFERENCES

- [1] C. Kee, B.W. Parkinson, P. Axelrad, Wide area differential GPS, *Navigation*, 38 (2) (1991), pp. 123–146
- [2] T. Walter, P. Enge, and F. van Graas, "Integrity for the wide area augmentation system", *Proc. 4th Int. Conf. on Differential Satellite Navigation Syst.*, 1995
- [3] T. Dautermann, Civil air navigation using {GNSS} enhanced by wide area satellite based augmentation systems, *313 Progress in Aerospace Sciences* 67, (2014), p. 51 – 62. doi:10.1016/j.paerosci.2014.01.003
- [4] ICAO, "Doc 9613 - Performance-based Navigation Manual", International Civil Aviation Organisation, advance fourth (unedited) edition, 2012, Montréal, Quebec (Canada)

- [5] R.J. Kelly, J.M. Davis, Required navigation performance (RNP) for precision approach and landing with GNSS application, *Navigation*, 41(1), 1994, pp. 1–30
- [6] Eurocontrol Network Manager, [Introducing Performance Based Navigation \(PBN\) and Advanced RNP \(A-RNP\)](#), January 2013
- [7] International Civil Aviation Organization. Procedures for air navigation services, vol. 2. Doc 8168-ops/611; 2006.
- [8] International Civil Aviation Organization. Procedures for air navigation services, vol. 1. Doc 8168-OPS/611; 2006.
- [9] ICAO Doc 9905, Required Navigation Performance Authorization Required (RNP AR) Procedure Design Manual, First Edition (2009).
- [10] P. Enge, T. Walter, S. Pullen, C. Kee, Y.-C. Chao, Y.-J. Tsai, Wide area augmentation of the global positioning system, *Proc IEEE*, 84 (8) (1996), pp. 1063–1088, doi: 10.1109/5.533954
- [11] L. Gauthier, P. Michel, J. Ventura-Traveset, J. Benedicto, EGNOS: The first step in Europe's contribution to the global navigation satellite system, *ESA Bull*, 105 (2001), pp. 35–42
- [12] RTCA DO229D, Minimum Operational Performance Standards for Global Positioning System / Wide Area Augmentation System Airborne Equipment, 2006
- [13] Felux, M.; Dautermann, T. & Becker, H. GBAS landing system – precision approach guidance after ILS Aircraft Engineering and Aerospace Technology, 2013, 85, 382-388
- [14] EUROCAE ED75C, Minimum aviation system performance specification required navigation performance for area navigation, 2000
- [15] RTCA DO253C, Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment, 2008
- [16] RTCA, "DO-246D - GNSS Based Precision Approach Local Area Augmentation System (LAAS) – Signal-in-Space Interface Control Document", RTCA, Incorporated, 2008, Washington D.C. (USA)
- [17] Navigation system database, ARINC specification 424-20, December 5, 2011, Aeronautical Radio Inc.
- [18] R. Geister, T. Dautermann, V. Mollwitz, C. Hanses, and H. Becker, "3D-Precision Curved Approaches: A Cockpit View on ATM," Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), 10. - 13. Jun. 2013, Chicago, IL (USA)
- [19] R. Geister, C. Hanses, and H. Becker, "Curved approach procedures enabled by a ground based augmentation system", 31st DASC 2012, October 14th – 18th 2012, Williamsburg, VA (USA)
- [20] http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10203/339_read-277/#/gallery/1719
- [21] R. Geister, and T. Kapol, "Cockpit Visualization of Curved Approaches based on GBAS," *Navigation, Journal of the Institute of Navigation*, vol. 60 (4), pp. 305-317, DOI: 10.1002/navi.48, ISSN 0028-1522, December 2013
- [22] <http://www.novatel.com/products/software/grafnav/>
- [23] Dautermann, T.; Felux, M. & Grosch, A. Approach service type D evaluation of the DLR GBAS testbed GPS Solutions, Springer-Verlag, 2012, 16, 375-387; doi: 10.1007/s10291-011-0239-3
- [24] David Duchet, [The Pegasus Toolset](#), Eurocontrol, 2013
- [25] Dautermann, Thomas (2014) Extending Required Navigation Performance to Include Time Based Operations and the Vertical Dimension. In: Proceedings of the 2014 IEEE/ION Position, Location and Navigation Symposium, Seiten 712-720. IEEE ION Position Location and Navigation Symposium, 05.05.2014-8.05.2014, Monterey, CA, USA.
- [26] <http://www.daec.de/fachbereiche/luftraum-flugbetrieb/luftraumdaten/>
- [27] EGNOS safety of life service roadmap, October 2014, Version: 3.0, http://www.essp-sas.eu/download/printed_documents/essp_com_7463_03_00_egn_sol_roadmap.pdf