3D-Precision Curved Approaches:
A Cockpit View on ATM

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Pre-defined curved approach procedures represent an essential measure for noise abatement and may reduce the risk of controlled flight into terrain (CFIT) for today's aviation considerably. In addition, a Ground Based Augmentation System (GBAS) supports the desired accuracy for the desired flight path. While the lateral guidance during current curved approach procedures is usually based on a position solution provided by satellite navigation systems in conjunction with inertial navigation systems, the vertical guidance is still based on measurements of a barometric altimeter. This type of approach with vertical guidance is supposed to enhance the situational awareness for pilots compared to non-precision approach procedures and reduce the risk for controlled flight into terrain. However, the accuracy of the barometric vertical guidance is inferior compared to precision approach procedures, temperature dependent and requires the correct pressure setting. Therefore, novel curved approach procedures are supposed to rely solely on satellite navigation augmented by either a ground based or satellite based system and only optionally by inertial measurement systems. Such coupled (hybrid INS and GNSS) systems are usually highly integrated and monitored by a flight management system. Therefore, the requirements for the equipment of aircraft that are conducting such approach procedures are very stringent. Using only GBAS could relax those requirements. In this work, an option for *precision* curved approach procedures was investigated and tested in flight trials. This option is based on a GBAS. In general, different possibilities are imaginable to enable GBAS based curved approaches. For instance, GBAS could only serve as means to enhance the navigation performance to achieve stringent RNP requirements. Alternatively, GBAS could serve as the sole means to enable a curved approach. This option is described in this paper. The option which utilizes the GBAS functionality to broadcast desired (curved) flight paths, the Terminal Area Path (TAP) functionality was investigated in this work. For this, simulator trials were performed to evaluate different means of flying these procedures in terms of guidance displacement sensitivity and means of displaying deviation information. Based on the results of the simulator trials, flight trials were conducted. Results from flight trials are presented in this manuscript to show how this method for conducting curved approaches can be applied.

curved approaches, noise abatement, navigation performance, ground based augmentation system, terminal area path

I. INTRODUCTION

Curved approaches have been a topic in aviation for quite some time. The first implementations had the goal to facilitate approaches in mountainous areas as curved approaches provide procedural means to avoid adverse terrain [1]. In the last years, especially in Europe, curved approaches were identified as means to reduce the noise impact of approaching air traffic as they enable aircraft to steer clear of densely populated areas in order to reduce the perceived noise there [2].

When referring to a curved approach, it is assumed that the approaching aircraft is guided along a desired flight path that contains different segments consisting of straight and curved legs. To be able to conduct such a curved approach, the aircraft has to (1) be guided (i.e., guidance signals must be available), (2) be able to follow the desired flight path with a given accuracy and, in the case of Global Navigation Satellite Systems (GNSS) based curved approaches, the aircraft has to (3) determine and monitor its current position with high integrity and precision. In other words an approaching aircraft has to stay below a Total System Error (TSE) which consists of the two major components Navigation System Error (NSE) and Flight Technical Error (FTE).

Curved approaches may be laterally guided only (non-precision approaches), laterally and vertically guided with degraded vertical precision (approach with vertical guidance) or laterally and vertically guided with full precision (precision approaches according to ICAO Annex 10 [3]). While the first two options are already implemented at a few locations in today's commercial aviation, precision curved approach procedures are still under development and investigation.

An example for a laterally guided approach is the so called "Canarsie Approach" at New York airport (JFK). The approach is a visual approach guided by approach lights (see also [4]). An option to conduct precision curved approaches is the use of a Microwave Landing System (MLS). In this case, the aircraft determines its position relative to the microwave transmitters of a ground station. The on-board receiver calculates the deviations from the desired flight path and the guidance signals are displayed. As MLS stations and on-board receivers are not standard equipment in today's aircraft, satellite navigation is

the primary means of navigation to conduct curved approach procedures.

Presently, only a few avionics systems or landing aids are able to provide guidance for curved approach procedures. Current curved approach procedures that provide vertical guidance are categorized as Required Navigation Performance Authorization Required (RNP AR) approaches. The following sections summarize background and requirements of these approaches with respect to navigation, procedure design, aircraft equipment and aircraft operations.

The lateral position source in all cases is GNSS. The on-board GNSS position solution of an approaching aircraft may be augmented (e.g., by a hybridization with INS systems or by differential GNSS systems) or may be a stand-alone solution. Currently, in the case of non-precision approaches and one class of approaches with vertical guidance (called Baro-VNAV or APV Baro), the source for the vertical position is a barometric altimeter. In addition, the vertical position in the case of another class of approaches with vertical guidance (called APV-I, APV-II or APV SBAS) and precision approaches is an augmented GNSS position. The augmentation of the position solution can be realized by space based or ground based systems.

As approaches with vertical guidance as well as precision approaches may enhance the situational awareness of pilots and reduce the risk of controlled flight into terrain, states are encouraged to implement approaches with vertical guidance as primary approaches or as backup for ILS and MLS precision approaches (see [5]). Therefore, in this work we focused on curved approaches with lateral and vertical guidance. For conventional (before GNSS was heavily utilized in aviation) approach procedures, an instrument approach in aviation was supposed to be conducted as a stabilized approach. This means, that the aircraft is fully configured (flaps and gear extended) at approach speed and no more major flight path changes are required (see also [6]) below at least 1000ft (if in instrument meteorological conditions, 500ft if in visual meteorological conditions) above ground. While this is reduced to 500ft even in instrument meteorological conditions during special GNSS based approaches (described in the next section), it is assumed that any curved segment must be completed before the aircraft reaches 1000ft above ground on its descent trajectory during the curved approaches considered in this work. With this design primitive the developed approaches are considered to be usable by a larger range of users.

II. NAVIGATION REQUIREMENTS

Curved approaches with vertical guidance are part of the performance based navigation (PBN) concept [7] defined by the International Civil Aviation Organization (ICAO). Within this concept, a new leg type, the *Radius-to-Fix or RF leg* defines a circular segment along a trajectory in terminal airspace maintaining a constant distance from a reference point for which track guidance is assured (see Figure 1)

For connecting different en-route segments, the fixed radius transition with radii of 15 or 22.5NM is used [8] instead. The RF leg is the core element of curved approaches, which are more accurately described as approach procedures

incorporating an RF leg. The performance based navigation does not specify the navigation sensor and flight control system with which to achieve the desired performance but rather gives high level requirements to comply with. However, it is envisioned that satellite navigation (either stand-alone or augmented) coupled with inertial sensors will be the navigation source for the majority of PBN compliant aircraft.

A. Required Navigation Performance

Required Navigation Performance (RNP) defines an implementation of the PBN concept. In general, RNP is always specified according to the achievable navigation accuracy of the aircraft, i.e. RNP 0.3 means that the aircraft position is within 0.3NM of the desired track during 95% of the time. This accuracy value only applies to the cross track position of the aircraft. Vertical guidance during RNP operations is achieved using barometric vertical navigation (Baro-VNAV). Thus, an approach procedure using RNP is classified as non-precision approach. Standard RNP requirements do not include a necessity for RF legs.
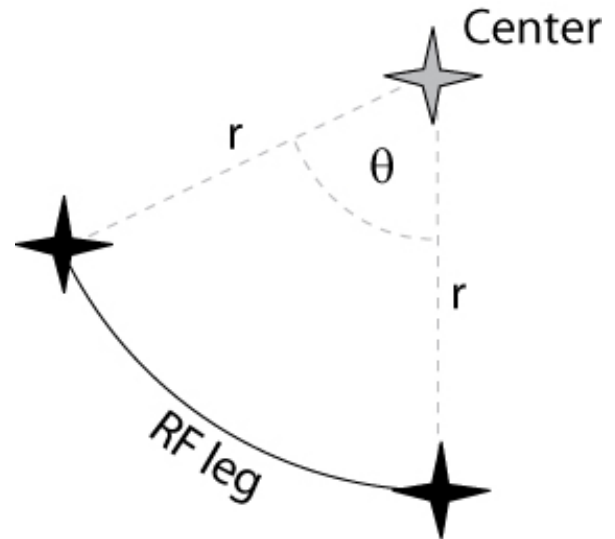

Figure 1. RF-Leg with defining horizontal elements turn radius r, center, arc angle θ, start and end points of the leg.

RNP approach procedures incorporating RF legs (curved approaches) require special operator approval and are thus called RNP AR APCH (authorization required approach). The FAA implementation of RNP AR is called RNP SAAAR (special aircraft and aircrew authorization required [9]). With RNP AR APCH, the procedure can incorporate RF legs as far as down to 500ft above ground level (AGL) and the final approach point may be within a curved segment. Detailed guidelines on how to implement RNP AR APCH can be found in [10].

A newly emerging concept called *advanced RNP* [11], to be placed in between RNP and RNP AR will permit RF legs during an approach, but not beyond the final approach fix and before the final phase of a missed approach.

B. Ground Based Augmentation System

The Ground Based Augmentation System (GBAS), called the Local Area Augmentation System (LAAS) in the United States, provides locally valid corrections and integrity information for GNSS to the user. The augmented position solution fulfills increased accuracy and time-to-alarm requirements and can be used for precision approaches. Besides the approach service, a GBAS station can also provide a differentially corrected positioning service (DCPS) for a user in the vicinity of the airport. DCPS could serve to enhance the RNP capabilities on-board of approaching aircraft.

The standards include the possibility to broadcast terminal area paths (TAPs) to provide precision guidance to aircraft maneuvering in the terminal area [12]. A recent update of [13], however, has removed the calculation of vertical integrity limits from the DCPS. This creates a gap between the [12] and [13] which needs to be addressed in a future update.

The TAPs include provisions for ARIN424 leg types, among them also RF legs. Since the differentially corrected position is accurate to a few decimeters in all three dimensions, precision guidance is also available on a TAP and hence enables precision curved approaches. Since the standards are still ambiguous, no commercially available GBAS ground station is capable of transmitting TAPs and only an experimental Multi Mode Receiver (MMR) manufactured by Funkwerk Avionics is able receive TAP data blocks broadcasted via the GBAS VHF data link.

Moreover, current autopilots require angular input for deviations from a desired flight path during a precision approach in order to steer the aircraft on flight paths which are assumed to be straight final approach segments only. Since the DCPS output used for TAPs is naturally rectangular and the path is also curved, an adaptation of the autopilot could be required for TAP usage. To avoid extensive adaptions of existing avionics systems the output of the on-board receiver are transformed to behave angular. This transformation was investigated during simulator trials in this work. The TAP functionality provides the adaption of sensitivity values for every TAP leg. This has an influence of the behavior of the displayed deviation signals in the cockpit. Different values were used in the simulator trials and the most practical one was selected for flight tests.

III. PROCEDURE DESIGN

Following, currently available design guidelines for curved RNP AR approaches are summarized. Moreover, the role of GBAS to support curved approaches is discussed. General guidelines for the construction of various precision and non-precision approach procedures are available through [6]. Regarding current procedures, the guidelines state that the allowed track angle change from intermediate to final approach is limited to 30° while the final approach needs to be designed as a straight segment. The construction of curved approaches exceeding turn angles of 30° or containing more complex trajectories is hence not covered by [6]. Nevertheless, it is possible to design curved approaches utilizing the RNP AR APCH concept. As precision curved approaches should provide at least the accuracy of RNP AR approaches, the design criteria

for them are used as a foundation of the TAP based approaches in this work.

A. Design of curved approaches based on RNPAR APCH

The design principles for RNP AR APCH approaches are given trough [9] and main aspects characterizing the procedure design are summarized in the following paragraphs. RNP AR APCH as currently defined utilizes Baro-VNAV for the vertical guidance. The obstacle clearance that needs to be maintained depends upon the approach segment. While for the initial approach a Minimum Obstacle Clearance (MOC) of 300m (984ft) is required, a reduction to 150m (492ft) is feasible for the intermediate approach. For the final approach, Vertical Error Budgets (VEB) are defined to take into account errors that arise through barometric altitude determination. Further information concerning the VEB is given in [9].

Lateral protection areas are defined as being 2xRNP, which means that a distance of 2xRNP needs to be maintained from obstacles in the horizontal plane. RNP values can be defined within the ranges given in Table 1.

TABLE I.   RNP VALUES RNP AR APCH [9]

Approach segment	RNP value [NM]		
	Maximum	*Standard*	*Minimum*
Initial	1.0	1.0	0.1
Intermediate	1.0	1.0	0.1
Final	0.5	0.3	0.1

For the design of curved RNP AR APCH segments, two waypoint types are available: Fly-by turns and Radius-to-Fix turns. Radius-to-Fix turns were introduced in an earlier section of this paper. A fly-by turn waypoint marks the intersection of two segments and is not overflown. The turn is calculated individually by the aircraft and the over ground tracks are hence dependent of environmental conditions and airspeeds.

As Radius-to-Fix turns are supported by the current GBAS TAP data format and have the advantage of defining a consistent over ground trajectory, RF-turns are seen as the primary means for the construction of curved approaches in this work.

The turn radii are determined based on a speed v which is calculated from the True Airspeed (TAS) of the fastest aircraft that is intended to fly the procedure plus an additional, altitude-dependent tailwind component that is given in [9]. By limiting the maximum bank angle to 20° above 500ft AGL and knowing the maximum TAS values of approaching traffic, a minimum turn radius can be calculated. Specific formulas for the calculation are also available through [9].

For the vertical trajectory design, applicable descent gradients are summarized in Table 2. Initial and intermediate approaches are to be defined with the goal of providing an optimized glide path angle. Maximum descent gradients for the final approach depend on the aircraft speed categories that are subject to the approach speeds at the threshold.

TABLE II. DESCENT GARDIENTS RNP AR APCH [9]

Approach segment	Speed category	Descent gradient
Initial		Std. 2.4°; Max. 4.7°
Intermediate		Std. 2.4°; Max. 4.7°
Final	CAT B (91-120 kts)	Max. 4.2°
	CAT C (121-140 kts)	Max. 3.6°
	CAT D (141-165 kts)	Max. 3.1°

Concerning the length limitations and recommendations for the approach segments, it is stated for the final approach that the length must be sufficient to allow a stabilization of the aircraft on its final approach tracks before reaching the Obstacle Clearance Altitudes/Heights (OCA/H). The decision altitude/height should, in most cases, be no smaller than 295ft [9].

B. Design of curved approaches based on GBAS

Besides RNP AR APCH, GBAS is capable of providing precision guidance for curved approaches, both in the vertical and in the horizontal plane. An advanced GBAS approach consists of TAP waypoints (straight Track-to-Fix and curved Radius-to-Fix waypoints being most important) and terminates with a straight Final Approach Segment (FAS). For the example depicted in Figure 2, waypoints 1-6 are part of the TAP while the segment from waypoint 6 to the threshold is part of the FAS which is "ILS-look-alike" [12].
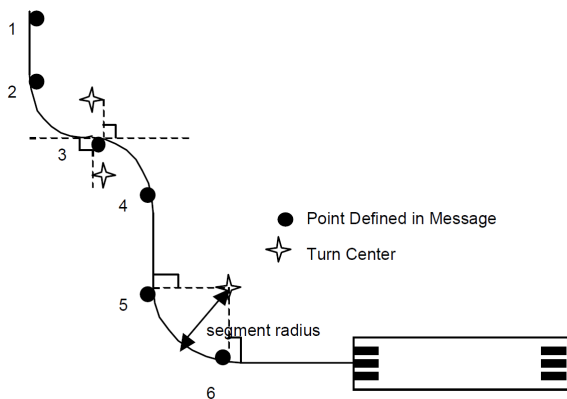

Figure 2. Example of a curved approach based on GBAS [12]

As GBAS TAP is defined at the very elementary level of a data format, design recommendations are not available yet. Thus, it can be suggested to apply RNP AR APCH design guidelines for the time being. Except Fly-by turns, GBAS TAP supports the same waypoint types as RNP AR APCH. As far as the vertical guidance is concerned, a specific altitude can be assigned to every waypoint, enabling the construction of arbitrarily vertical profiles. The descent angle is simply given by the distance between two waypoints and their differences in altitude. However, due to the satellite based altitude measurement, the concept of vertical error budgets is not applicable and minimum obstacle clearances can be reduced.

IV. OPERATIONAL GUIDELINES

To be allowed to conduct a curved approach that is vertically guided and currently has the most stringent requirements (RNP AR APCH), the aircraft has to be certified against the applicable accuracy and integrity requirements and the aircrew has to be especially trained and certified. Additionally, the approach has to be certified in terms of a flight safety assessment (see also [5]).

For RNP AR, the desired approach is selected by the aircrew from a database stored in the Flight Management System (FMS). For GBAS, the TAP data is uplinked through the VHF data broadcast messages. The transition from the en-route to the approach phase is initiated by the FMS itself or by activation of the cockpit crew. Usually, the pilots rely on the information provided on the Primary Flight Display (PFD) and the Navigation Display (ND). In current implementations the aircraft's air data information (attitude, speed, and altitude) is shown on the PFD. The position and navigation information is shown on the ND. The realization of the display of the approach information during RNP AR depends on the aircraft type and manufacturer. Examples are given in Figure 3 and Figure 4. The common denominator is that lateral and vertical deviation information is shown on one of the displays mentioned and that there is some information provided regarding the actual navigation performance as this is a requirement for RNP approaches. Usually, the actual navigation performance is shown as a boxed area around the lateral and vertical deviation scale. If the actual navigation performance is worse than the required navigation performance or if the deviation excessively outruns the actual navigation performance box, the approach has to be discontinued and a go around has to be initiated.
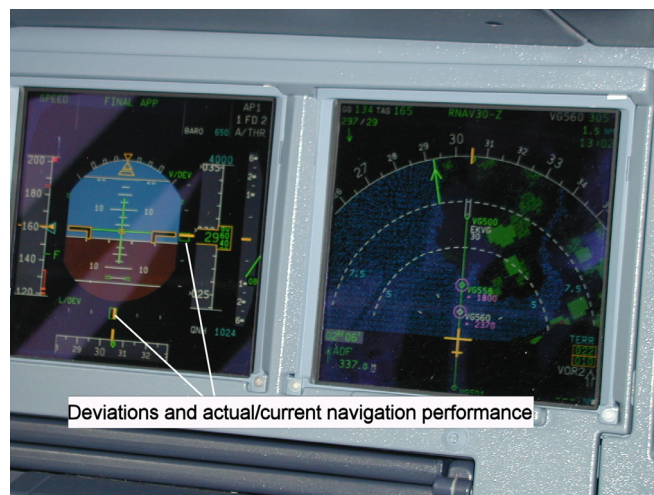

Figure 3. Example of display information during curved RNP approach in an A319 [14]

In the case of a Baro-VNAV approach the lateral deviations are calculated based on the (augmented) GNSS position on board of the approaching aircraft and the vertical deviations are calculated based on the barometric altimeter. Therefore, the correct altimeter setting has to be assured. In addition the barometric altimeter is temperature dependent and therefore the

on-board system has to calculate the temperature correction. If unable, the approach may only be conducted in a certain temperature range. For a precision curved approach or an APV SBAS approach the lateral and vertical deviations are calculated based on an augmented GNSS position.
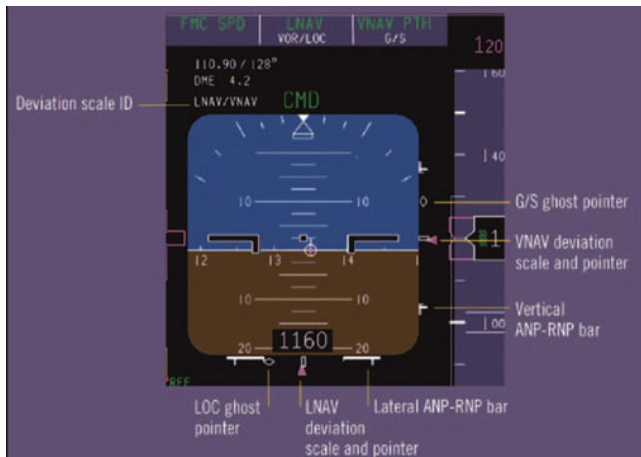

Figure 4.   Example of display information during curved RNP approach in an B737 [15]

For a precision curved approach using the TAP functionality, the desired flight path is selected by the crew via a five digit channel number. This tunes the on-board receiver to the desired approach path and would lead to an output of the deviations from this flight path. It is also imaginable that the tuning is done automatically by the FMS that holds the pre-loaded flight plan. Another option can be that after the desired approach path was selected the transmitted waypoints of a TAP are loaded into the flight management system and then the aircraft conducts a RNP AR approach based on these waypoints. This approach does not differ from a standard RNP AR approach and hence does not reduce the requirements, in terms of crew training and certification, for conducting such approach.

Therefore, we tried to develop a precision curved approach that has less stringent requirements regarding the equipment of an aircraft. For the curved approach procedures described in this work, only a capable MMR that calculates the deviations and actual navigation performance is required. In addition the interface to the aircraft would have to be slightly modified. Depending on the choice of displaying the information further adaptions will be required.

As mentioned before, in current implementations the lateral and vertical deviations are displayed in conjunction with the actual navigation performance in the PFD. Depending on how the approach is flown (automatically or manually), different accuracies can be achieved. If a curved approach is conducted manually, usually a flight director is used. For a B737 different accuracies were demonstrated in this setup (see [16]). The range of values was 0.41NM to 0.1NM depending on the flight phase and the equipment of the aircraft. These values were used as a baseline for the investigation of the developed approaches in this work.

Curved Approaches or RNP AR were originally intended for airports in mountainous terrain. Therefore, examples for curved approaches due to terrain are much older and more frequent in number than those for noise abatement.

The first RNP AR approach (actually the approach whose design helped define RNP AR) was Juneau, Alaska. Here, mountains near the airport prevent a straight-in approach. The approach minimum of the conventional approach was such that the airport was unreachable during one third of the year due to low ceilings leaving just the maritime supply route to deliver goods to Juneau. The RNP AR approach leads towards runway 26 of Juneau along a valley with a course offset by more than 35° from the runway heading. The final turn onto the extended centerline is conducted at 1.6NM from the runway threshold, which means at a height of roughly 660 feet above threshold. This approach helped tremendously in lowering the minimum at the airfield and thus to increase the accessibility of this airport throughout the year.

While the original purpose of RNP AR was to provide instrument approaches in mountainous terrain, the great potential for noise-abating procedures has been recognized. Some examples for noise-abating approach procedures in Sweden were given in [2]. In the course of the project HETEREX, funded by the German ministry of economics, DLR developed some exemplary noise abating RNP AR procedures for the airport of Nuremberg, Germany (see Figure 5). Nuremberg is not located in a mountainous area but populated areas are located about 4 NM from the threshold of runway 28 directly under the track of the straight-in ILS approach. Here, the specifications of RNP AR enabled the design of several possible solutions to circumnavigate the settlements and serve runway 28 with an instrument approach that does not overfly any populated areas below a height of 3000 ft. These solutions were described in detail in [17] and are examples developed by DLR to show the potential of RNP AR for noise-abatement.

Figure 5.   Example RNP AR to Nuremberg, Germany compared to ILS straight-in

V.   CURVED PRECISION APPROACHES

To be able to conduct research in the area of GBAS based approaches, the Institute of Flight Guidance of the German Aerospace Center is operating an experimental GBAS ground station at the airport Braunschweig-Wolfsburg (EDVE). The station is manufactured by Thales Air Systems and was installed in 2009 at the research airport (see also [18]). It is able to broadcast the standard GBAS Approach Service Type C

(GAST-C) signal with the well-known final approach segments. This is equivalent to an ILS category I (CAT I) implementation. In addition, it is able to transmit Terminal Area Path (TAP) data. This allows the design of curved segments within the reference flight paths.

A. TAP Design

Two different TAPs were designed for the investigations. They are referred to as TAP A (Figure 6) and TAP B (Figure 7). TAP A is laterally the same as the existing RNAV approach at Braunschweig-Wolfsburg airport. It consists of two straight segments, a curved segment with a track angle change of 89° and a final approach segment. In contrast to the existing approach, it has a continuous decent slope of 3°.
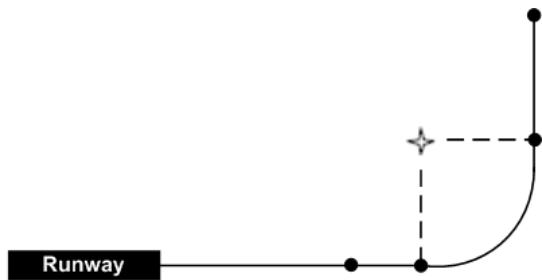
Figure 6. Lateral Layout of TAP A

TAP B consists of two straight segments, two curved segments with track angle changes of 30° and -30° and the final approach segment. Vertically it also has a continuous decent profile of 3°.

Figure 7. Lateral Layout of TAP B

The two TAPs were used in simulation trials and in flight trials with an Airbus A320. Different forms of indicating the desired flight path was used: "raw data", "flight director" and "tunnel-in-the-sky" display. These different display setups will be described below.

B. Simulator Trials

In preparation for flight trials, a fix-based generic cockpit simulator was used to investigate curved precision approaches based on GBAS. Therefore, a Multi-Mode Receiver (MMR) simulator was integrated in the existing (simulated) avionics architecture. The simulated MMR is able to calculate deviations based on the (true) simulator position. The positioning part of a real MMR is neglected here. Basically, the simulated MMR serves as a deviations calculator that is tuned from the cockpit and is able to receive a preloaded set of TAP and FAS data. The cockpit simulator is equipped with six freely programmable displays. During the simulator trials, different parameters of the curved precision approaches were varied and different means of presenting the guidance

information were investigated. In first investigations, the two curved approaches were conducted manually. The deviation signals were shown as ILS-Look-Alike signals. The pilots only had the diamond shaped deviation symbols to steer the aircraft along the curved approach. This display setup is referred to as "raw data" (see Figure 8).
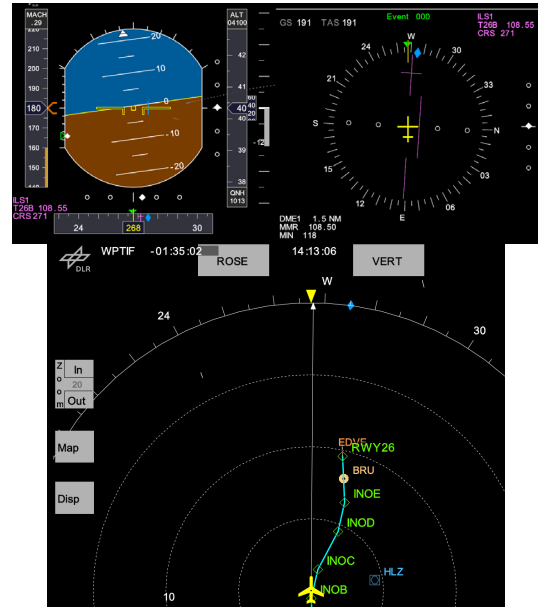

Figure 8. Display layout for raw data approaches

Normally, during conventional straight-in approaches, the runway direction is fixed as the final part of the approach is aligned with the runway track and the runway is not moving. The runway direction is either selected by the pilots or loaded from a database according to the flight plan. It is indicated on a horizontal situation indicator (see magenta line in the top right display of Figure 8) or on a navigation display. The indication of the runway direction is useful for the pilots as they can adapt the magnitude of the required course changes due to the deviations to the actual and the desired track of the aircraft.

For the setup presented in this work, the "runway direction" was continuously altered by the simulated MMR during a curved segment. It is was to the true track of a straight leg or to the tangent of the present position projected on the fixed radius turn. Therefore, the indication is rotating during a curved leg. This was supposed to help the pilots with the estimation of the required bank angle change during a curved leg. This display setup is referred to as "raw data" as no flight director or turn anticipation were displayed during the curved approaches. Figure 8 shows the displays used in the trials.

The display layout described was used for a simulator study with several pilots. The pilots conducted the two approaches manually. The main variable investigated in these trials was the displacement sensitivity: The TAP functionality allows the adaption of the deviation sensitivity for each TAP leg. This means that the value of the lateral or vertical deviation at which full scale deflection is indicated is adjustable. Different values were investigated while evaluating the TSE accuracy performance. It was found that the manual flight path following

performance is dependent on the displacement sensitivity values as well as on the design of the approach procedure. Some results of the manual approaches are shown in the following figures (see also [19]). Figure 9. and Figure 10. show the standard deviation (1 σ values) of the deviations for the two different TAPs. The different curves represent the different sensitivity values (value of the lateral or vertical deviation that is required to lead to Full Scale Deflection (FSD); the lateral values are: 80m (common CAT I sensitivity at runway threshold), 185m (0.1NM, RNP 0.1 sensitivity) and 555m (0.3NM, RNP 0.3 sensitivity)).

Figure 9. shows the standard deviation at a given distance from the runway threshold of all lateral deviations observed during manual approaches of type TAP A. The differently colored curves address the different sensitivity values.
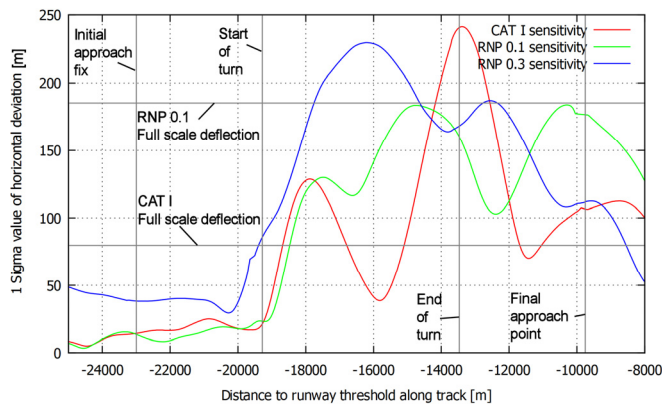

Figure 9.   Standard deviations of lateral deviations with different displacement sensitivities for TAP A

The horizontal lines indicate full scale deflection of the lateral deviation for a given sensitivity value and the vertical lines show the borders of the different TAP legs. It can be seen that for TAP A pilots were barely able to maintain RNP0.1 accuracy during manual flight according to raw data. It can be seen here, that a lateral displacement sensitivity value of 185m (RNP 0.1) yields a good amount of accuracy while staying below full scale deflection most of the time.
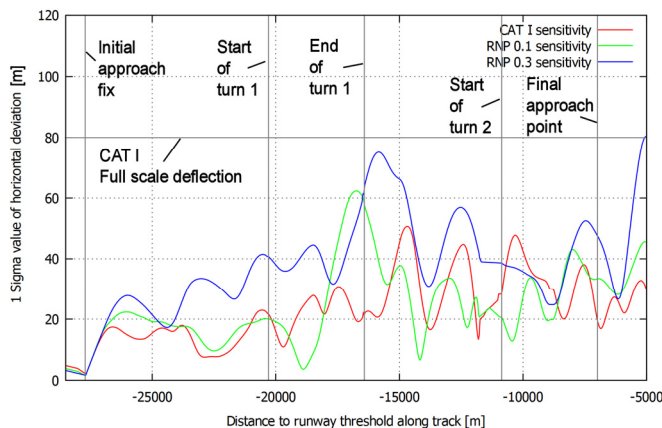

Figure 10. Standard deviations of lateral deviations with different displacement sensitivities for TAP B

Figure 10. shows the same information for TAP B. It can be seen that in this case the pilots were able to maintain the most stringent accuracy requirements for a precision approach (CAT I at threshold). Corresponding results were observed for vertical deviations.

In conclusion, it was found in the simulator trials that a medium sensitivity can be used to achieve RNP 0.1 performance for the two tested curved approach procedures. Therefore, the displacement values equivalent to RNP 0.1 procedures were used in the following flight trials. This corresponds to a lateral displacement sensitivity value of 185m and a vertical displacement sensitivity value of 15.24m

High sensitivity values were not recommended by the pilots as they state that such parameter setting leads to a reduction of situational awareness and a high workload. This is because with high sensitivity values, in indicated full scale deflection is reached very easily. This leads to strong correctional maneuvers by the pilots. In addition, while full scale deflection is indicated the pilots can not estimate how big the actual deviation really is. This leads to overshoots while trying to recapture the desired flight path.

In addition, two other display setups were tested in the simulator for the subsequent flight trials: a flight director signal and a "tunnel-in-the-sky" display. The flight director is dependent on the state of the aircraft, the deviation signals and the calculated runway direction. With this setup, medium sensitivity values could be used to achieve acceptable performance. This setup was appreciated by all pilots. As another means of displaying the necessary information, a "tunnel-in-the-sky" display was used. It was developed for a Head Up Display (HUD) and uses HUD symbology. In this work, it was used as a head down display. Next to the required aircraft state information, the deviation information was displayed. In addition, a reference trajectory was displayed. It was laterally limited by two "walls". The width of the walls was set to 0.1NM (according to RNP 0.1). With this setup the best results were obtained as this display allows turn anticipation and increases the situational awareness.

C. Flight Trials

After the TAP procedures were investigated in the simulator, flight trials were conducted. Therefore, the ATRA, an Airbus A320 flight test bed, operated by the German Aerospace Center was slightly modified. To be able to fully compare the observed results (regarding observed deviations from the desired flight path) from the simulator trials with the ones from the flight trials, the MMR simulator (deviations calculator) was used for the calculation of the deviations during the flight trials as well. Different GNSS based positions (from different receivers installed in the cabin) can be used as input for the MMR simulator and the deviations from the selected TAP are being output for the generation of the displays in the cockpit.

The generated displays were shown on a foldable experimental cockpit display was integrated into the cockpit on the first officer's side. The freely programmable displays that were already used in the simulator trials were shown on the experimental cockpit display. Three different display setups

were used. In the first one, a Primary Flight Display (PFD), a horizontal Situation indicator (HSI) and a map display were shown to the experimental pilot (see Figure 8.). In this setup, only raw data i.e. the angular deviations in terms of diamond-shaped symbols was provided to the experimental pilot.
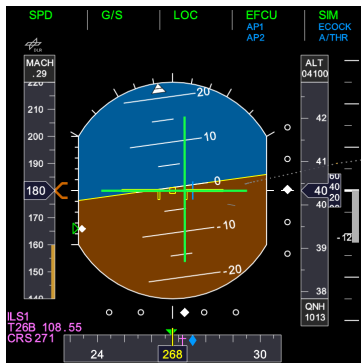

Figure 11. PFD with flight director engaged (green bars)

Identical displays were used in the second setup. But here, additionally a flight director was shown in the PFD. Figure 11. shows the PFD with the flight director (green bars) activated. This setup help the pilots to estimate the required corrections to stay on the desired flight path and a higher path following accuracy could be achieved.

For the third setup, the "tunnel-in-the-sky"-view was used. This display architecture was extensively investigated in the past and provided very good applicability for advanced approach procedures (see also [20] for an example for helicopters) Figure 12. shows the display information that was provided to the pilots. It can be seen that the display allows good turn anticipation as the flight path can be seen beforehand.
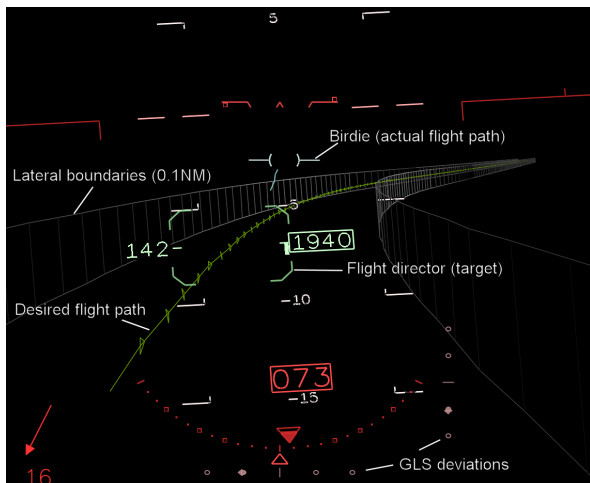

Figure 12. : Layout of "tunnel-in-the-sky" display

Some results of the trials are shown in the following figures. As stated before, the values for the displacement sensitivity were kept constant in the flight trials and only the different display layouts were investigated.

Figure 13. shows the lateral deviations (upper figure) and the vertical deviations (lower figure) observed during the manual flight of TAP A. The red curve indicates the deviation while flying according to raw data. It can be seen that the lateral CAT I accuracy requirement is violated (80m). In addition, the capture of the "localizer" is difficult when flying according to raw data in and after the curved leg. The green lines represent the deviations during manual flight according to flight director. It can be seen that the aircraft was laterally within a +/- 185m corridor all of the time. The blue lines represent the deviations observed during flight according to the tunnel display. It can be seen that the pilots were able to steer the aircraft very precisely. The vertical lines represent the borders of the different TAP segments and the horizontal lines show the limits for the different approach types.

The vertical deviations show a similar behavior for all the different display setups. The pilots were (barely) able to keep the deviations smaller than 50ft (15.24m). Still, while flying according to flight director or "tunnel-in-the-sky", the vertical deviations are steadier and the pilots stated the subjective situational awareness was greater.
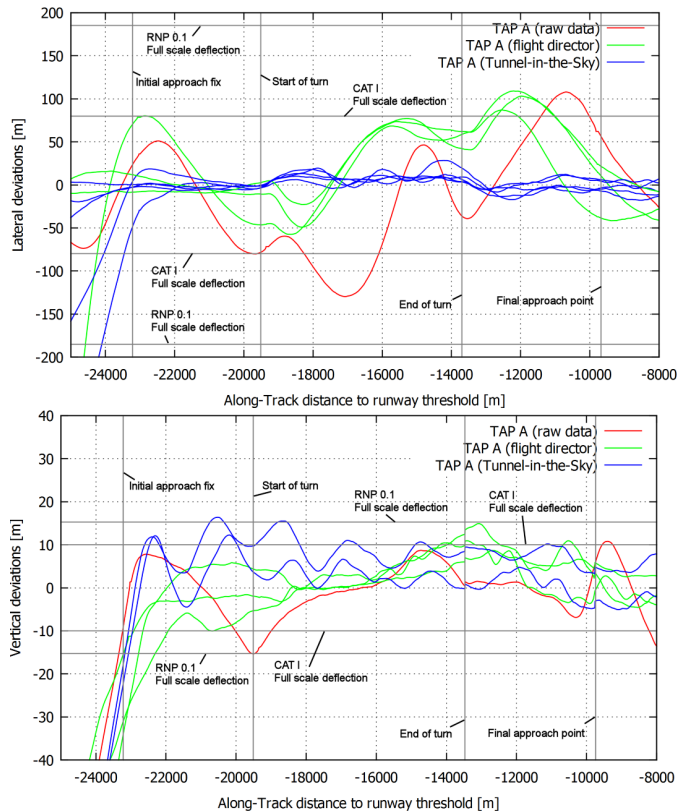

Figure 13. Lateral (a) and vertical (b) deviations with different display means during manual flight of TAP A

Similar results were obtained during manual flight of TAP B. Figure 14. shows the lateral (upper figure) and vertical (lower figure) deviations during the approach. It can be seen that the flight path following accuracy was very high during TAP B especially during approaches according to flight director and "tunnel-in-the-sky" display. The approaches

according to raw data were not as accurate but still more accurate that during the approaches with TAP A due to the lateral design with smaller track changes. This confirms the results obtained in the simulator.

Figure 14. (lower figure) shows the vertical deviations during TAP B. It can be seen that the vertical deviations remain within 15m (50ft) while flights according to flight director. This is even true for the continuous 3° slope during the turn. The deviations exceed 15m (50ft) during the approach according to raw data in Figure 14. The deviations during flight according to "tunnel-in-the-sky" display behave similar to the deviations according to flight director.
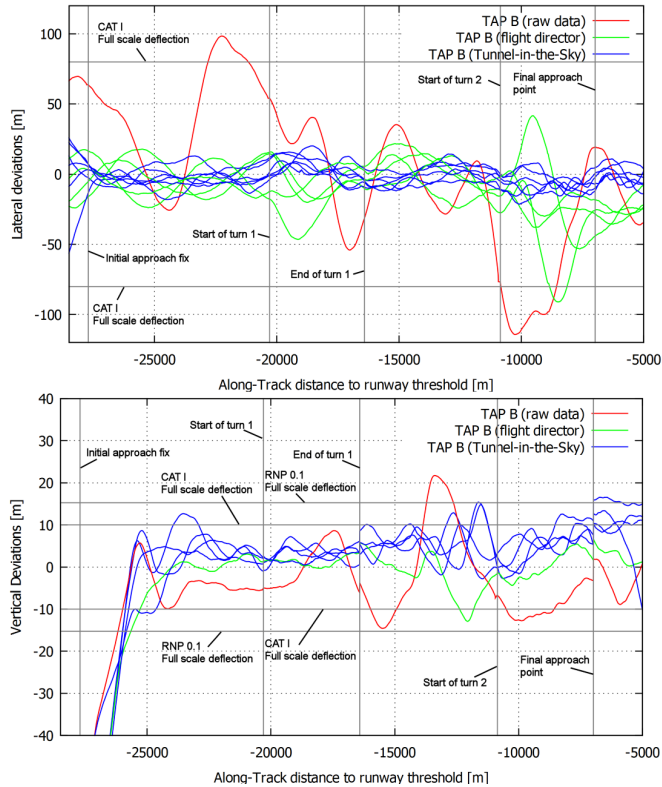

Figure 14. : Lateral (a) and vertical (b) deviations with different display means during manual flight of TAP B

In conclusion, it can be stated that a flight director or a "tunnel-in-the-sky" can be used to conduct precision curved approaches. The achieved accuracy is fully compliant with the requirements for RNP 0.1 approaches and the display setup was rated fully acceptable by the pilots. As the deviation information is only dependent on the MMR (i.e. the output of deviations and the runway direction for the flight director) installed on-board the aircraft, the requirements for aircraft equipment could be reduced for conducting RNP approaches with this setup. A modification of the display systems could enable manual precision curved approaches based on GBAS solely relying on the transmissions of a ground station and one on-board receiver with the proper display information.

VI. IMPACT OF CURVED APPROACHES ON ATM

From an ATM perspective, the initial validation trials with precision curved approach procedures based on GBAS TAP functionality in simulator and flight trials may be summarized in the form of result statements comprising serious complexity:

- Manually operated precision curved approach procedures are feasible but will require additional pilot support by means of flight director guidance information or different means of displaying information. The standard operation mode for such procedures will be utilizing aircraft automation. Still, the proposed setup ensures predictable flight paths for approaching aircraft.

- Trajectory-based aircraft operation as well as full datalink functionality represent essential operational premises for the conduction of curved approaches. These features are central items of the SESAR and NextGen programme definitions.

- The complex definition of curved approach procedures which include an efficient vertical profile and a flexible horizontal route setup demand data-base driven construction, either onboard for the pilot crew and on ground for the ATM-controller crew. The FMS functionality includes such features already. However, conformity between onboard and ATM equipment needs to be guaranteed to avoid incidents and accidents within the terminal area. Here, the advantage of a GBAS with pre-defined and steadily broadcasted desired flight paths can play an important role in future developments.

Under such premises the final validation of operation concept, automation mode conditions and technical equipment supervision represents a serious challenge [21]. A variety of emergency conditions with respect to the focus areas mentioned above have to be considered from the cockpit view and from an ATM perspective. Operational consequences for the individual aircraft as well as all other traffic (e.g., time based approach sequencing and low visibility procedures as mentioned in [22]) represent substantial issues for on-going research.

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