ADVANCED RNP TO ILS AUTOLAND APPROACHES FOR OPTIMAL BENEFITS FROM PBN: FLIGHT TESTING PROCEDURES WITH AN A320

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Extended Abstract

We report on the the performance of our Airbus 320 during novel advanced required navigation performance (RNP) procedures which contain a fixed radius turn that delivers the aircraft onto a short ILS precision final. The three main areas of interest of the flight trials were the performance of the autoland capability, vertical path following during the RNP part of the procedure and lateral path following during the transition from RNP to localizer guidance. Today, precise area navigation systems have become more common in aircraft ranging from a small single engine piston airplane through helicopters and large jet transports. If these systems also provide continuous monitoring and display of the navigation accuracy they can qualify for operations under the required navigation performance (RNP) concept. Most recently, the aviation community recognized the potential for exploiting additional benefits from these systems and introduced the Performance Based Navigation (PBN) foundation through ICAO Doc 9613 [14] for new kinds of en-route, departure and approach procedures. RNP is part of the PBN concept. Within the PBN concept exists the possibility to incorporate turns with a precise ground track into departure, en-route, arrival and approach procedures. These turns are called fixed radius transitions and are coded as radius-to-fix (RF) path terminators in the ARINC 424 standard They offer the advantage of repeatable ground tracks during the turn and thus more freedom for the procedure designer when route planning in dense traffic, high terrain or obstacle rich environments.Moreover, socio-economic factors can be included - such as circumnavigating noise sensitive areas with guaranteed track keeping performance precluding stray aircraft. Whilst offering these benefits such advanced RNP approach operations are still non-precision procedures and automatic landings cannot be performed after their successful completion.

Hence, to enable automatic landings and to extract maximum benefits from RNP operations, they must transition into a precision final approach segment provided by the Instrument Landing System (ILS) so that the guidance loops for flare and land modes of the auto flight guidance system can activate. This is often called RNP to ILS (or RNP2ILS). Naturally, the same considerations would apply to the GPS Landing System as well. Since traditional operations involving autoland are straight-in approaches, the behavior of the auto flight control system during maneuvers that involve a curved intermediate approach segment terminating at the final approach fix (FAF) is not known. In this study we investigated (a) the performance of the autoland capability (b) the vertical path during the entire approach and (c) the lateral path following during localizer capture.

For the trials, we designed five instrument approaches to Braunschweig-Wolfsburg airport during which a RF curve terminates at the ILS intercept point at different heights.Each approach starts at an designated initial approach fix with a straight segment. The straight segment is followed by a radius-to-fix curve ending at the final approach fix, where the aircraft is fully established and centered on the localizer and glidepath of the ILS. We constructed the procedure such that the altitude constraints at initial, intermediate and final approach fix describe a continuous vertical path with minus two degree inclination.

The chosen heights for the final approach fix were 550ft, 750ft, 1000ft, 1500ft and 2000ft and the approach names are ILS x, where x in {S,T,U,V,W}, respectively. The ILS at Braunschweig-Wolfsburg airport has a standard glide path angle of 3 degrees so that the aircraft intercepts the ILS glide path from below. Each approach had two different initial approach fixes which corresponded to a track angle change of 90 degrees and 180 degrees during the constant radius turn-to-final. Additionally, when beginning the approach from the 90 degree track offset, a 2 degree vertical path angle was included in the ARINC 424 code of the initial and intermediate approach segments.
The procedure coding was conformal to the latest issue of ICAO PANS OPS [15], [16], but is not yet supported by the newest ARINC 424 [6] database standard and the packing software used by the database suppliers. Therefore it was necessary to designate the FAF as final approach course fix (FACF) and to insert a artificial and unused final approach fix on the extended runway centerline further downstream in the approach.
For the trials, we used DLR's own Advanced Technology Research Aircraft (ATRA), an Airbus A320 MSN659 with flight test instrumentation and a FMS 2. The approaches were entirely flown using the auto flight guidance in managed mode and with auto-thrust activated. The approach mode was armed either at the FAF or before the initial approach fix.

During no approach did the aircraft respect the intended initial vertical path of a continuous descent at 2 degrees downwards, but performed a descent with thrust at idle until reaching the next altitude constraint ("dive and drive"). This behavior repeated itself during all RNP segments before the ILS final. When the approach mode button was depressed at the FAF, the aircraft respected the entire lateral path guidance of the RNP part with a lateral total system error of less than 20m. When the approach mode was armed earlier, the autopilot established the aircraft on an intercept heading as soon as the course deviation indicator became alive. This resulted in a dogleg and a violation of the RNP corridor. When the approach mode button was depressed at the FAF, the intercept mode caused a slight and short oscillation with a maximum amplitude of 2 degrees about the vertical axis before full capture was indicated in the primary flight display. Finally, automatic landing was possible from all heights,
We show supporting evidence that RNP2ILS approaches can be safely flown all the way to an automatic landing using the flight management guidance computer and the auto flight control system. In order to fly the desired path with vertical path angle during the RNP initial and intermediate approach, a separate mode (such as LNAV/VNAV) different from the singular approach mode would need to be implemented in the aircraft. Additionally, airlines and other operators currently apply stabilization criteria following which the aircraft must be established on a straight final with the correct sink rate at 1000ft above aerodrome level in order to continue the approach. For landings in low visibility conditions, more stringent criteria are often applied. An operational implementation of RNP2ILS approaches with a curved final intercept would require a rephrasing of the criteria to include a concept such as RNP established.

1 Introduction

Conventional airways are defined through the connection of ground-based radio navigation aids, most commonly the Very High Frequency Omnidirectional Radio Range (VOR) and distance measuring equipment (DME). Due to their fixed location in space, this limits the number of available routes to the network that is formed by these beacons. Naturally, such a network will always be less efficient that the direct great circle connection between origin and destination. With the advent of Global Navigation Satellite Systems (GNSS), their global availability plus the subsequent approval of most states to use GNSS as primary means of navigation for all phases of flight, the opportunity for a more dynamic route planning and free route airspace have become available to the aviation community. Compared to conventional area navigation (RNAV) based on lines of position from VOR/DME stations, satellite navigation provides much a higher accuracy and availability. Moreover, it allows monitoring of the position solution through receiver autonomous integrity monitoring techniques [18]. In fact, certification of a GNSS navigation device for navigation under instrument flight rules requires continuous integrity monitoring to ensure the proper navigation performance. Moreover, besides the most commonly used NAVSTAR GPS [3], other GNSS such as GLONASS, GALILEO and Beidou exist or are in the process of achieving full orbital constellations. To increase coverage, some countries have established regional satellite navigation systems (Indian Regional Navigation Satellite System IRNSS and the Japanese Quasi Zenith Satellite System QZSS) that complement other GNSS. Augmentations Systems based on differential corrections provide higher accuracy and integrity in a local area (Ground Based Augmentation System GBAS ([9],[5],[1],[12]) or a specific region (Satellite Based Augmentation System SBAS, [8], [4],[2]).

Giving credit to the multitude of combination of position sources including hybridization of different technologies (like inertial navigation aided GNSS receivers) the International Civil Aviation Organization (ICAO) introduced the Performance-based Navigation (PBN) framework, according to which requirements are set for a specific airspace or procedure rather than on the equipment used for it. As long as the aircraft can fulfill these requirements on it is unimportant in which way the compliance is achieved. The relevant ICAO DOC9613 [14] specifies the requirements applying to the Total System Error (TSE) of the aircrafts path following capabilities. The TSE consists of the three components Flight Technical Error (FTE), Navigation Sensor Error (NSE) and Path Definition Error (PDE) which are additive [13]

One current implementation of PBN is called Required Navigation Performance (RNP. [17]) and usually specified with a numerical value expressing 95% of the aircraft lateral total system accuracy requirement in nautical miles. For example, RNP 5 means that the aircraft must be certified to maintain a track within 5 miles to the left and right during 95% of the time. Usually, the pilot is provided with a course deviation indicator (CDI) which shows the rectilinear cross track deviations from the desired track. For the vertical component the aircraft uses a barometric altimeter to determine its height above a designated pressure surface. The vertical TSE is not covered under RNP, but altimeter NSE accuracy requirements are specified. RNP can be used for aircraft instrument approaches to guide the aircraft to a safe landing on a runway. When used in this manner, the RNP begins with 1nm at the beginning of the approach and scales down to 0.3 nm on the final approach. At all times, cross track deviations are measured perpendicular to the desired course. Nevertheless an RNP approach (abbreviated RNP APCH) is a non-precision approach, meaning that the actual landing must be performed manually by the pilot.

To fly an RNP APCH, the aircraft must be equipped with a suitable and current navigation database in the ARINC424 [[6]]. This standard defines so called “path terminators”, i.e. point in space and how to get there. For example, the track-to-fix path terminator contains a ground track value and a location to reach (also called “fix”) on this track. The document governing air navigation procedure design [cite PANS OPS, vol 2, III-2-5-1] suggests to use only a certain subset of path terminators for RNP approaches, namely Initial Fix (IF), Track to Fix (TF), Radius to Fix (RF) and Mandatory Hold (HM) in order to avoid discontinuities in the lateral approach path. Further details on the coding and an overview of all leg types can be found in [6]. As an extension to the RNP concept, the recent issue of [14] introduces the possibility to fly curved segments with a predefined track angle change and curve radius during an instrument approach, summarized under the advanced RNP concept. Before the advent of advanced RNP, only straight segments were definable in a navigation database. Since an aircraft cannot make abrupt course changes, the transitioning between two straight segments was not well defined. This lead to a different ground track for each aircraft type /flight management system (FMS) and wind vector combinations. The new leg type to enable precise path following during the curved segments is the previously mentioned Radius-to-Fix (RF). It begins at a previous fix, follows a circle with a predefined radius and center and ends at the beginning of the next segment. Exit track angle of the RF must be the same as the one of the following leg and entry track angle the one of the preceding leg in order to avoid discontinuities in path steering.

On the contrary, a precision approach requires angular guidance in the lateral and vertical direction to the runway in the shape of a funnel. It must be referenced to geoidal altitude. This means that as the aircraft approaches the runway, deviations become more sensitive to lateral and vertical motion and a higher accuracy is achieved the closer vehicle gets to the runway. Modern transport aircraft can perform automatic landings from such a precision approach, even in conditions without outside visibility from the cockpit (i.e. in dense fog or precipitation). Three such precision approach systems are available on the market to airport operators: the microwave landing system MLS, the GPS Landing System GLS and, most commonly used, the instrument landing system ILS. Before intercepting the final precision approach cone, the aircraft usually navigates in reference to the directional gyro, possibly supported by radar vectors from an air traffic controller, and at fixed barometric altitudes.

Now, in order to optimize approach procedures it lies at hand to combine a final precision approach segment with RNP feeder, initial and intermediate approach segments. Transitions between track angle changes should be made utilizing RF transitions. Often, terrain constraints and noise abatement require the final approach segment on the xLS to be as short as possible with limited space and time to track the straight in final approach course. Hence, we are especially interested in the case where the RF curve delivers the aircraft directly onto the precision approach. This means at the end of the curved segment, the aircraft is centered on localizer and glideslope and can commence its guided descent.

Previous studies mainly investigated issues of track keeping performance and FTE. [e.g. [10],[19]]. Emphasis was put especially on the altitude performance, i.e. the transition from guidance by the altimeter to vertical guidance provided by the glide slope beam and the ability to deliver the aircraft laterally onto the localizer. The altitude performance was considered especially critical since departures from the standard atmosphere temperature gradients lead to altitude errors. For example, on a warm day air density is lower and therefore the true altitude is higher than the indicated altitude. A procedure designed such that an exact match is achieved between RNP vertical path and xLS glide path in a standard atmosphere will now deliver the aircraft above the glide slope center beam. This may cause, in extreme cases, the autopilot to be unable to capture the vertical path due to its design limits. Laterally, depending on the autopilot and point of approach mode activation, doglegging during localizer intercept was shown to be an important issue for obstacle protection in the transition region between RNP and xLs.

The Single European Sky ATM Research Project (SESAR), work package 9.9 delivered a top level RNP to xLS functional requirements[21], architecture [20] and concept of operations [22]. The SESAR concept of operations contains recommendations for procedure design, one of those being that for automatic landings, a minimum final approach segment of 5Nautical Miles (NM) would be required due to “current autland laws technical constraints (mainly the integrator settling times)”. Moreover, it also envisions a final approach segment of less than 3NM and a xLS joining as low as 500ft for future operations. The Sesar ConOps also reports on a set of simulator validation exercises with the shortest final approach segment being 3nm, the outcome of which is positive, but significant differences were found between aircraft types. Some more details of these simulations can be found in [19]. Unfortunately, none of the SESAR RNP2xlS documents are available to the public. Results of [19] are published as [10] and [11] which conclude that for all simulated aircraft a direct transition from the curved segment is possible without the need for straight intermediate segment. The Performance based Rulemaking Committee (PARC) of the Federal Aviation Administration of the United States of America published RNP2XLS recommendations in 2014 [7] requiring a segment shallower than the glide path of the xLS of at least 1NM length and a maximum track angle change of the curved segment ending at the final approach course fix to be 180 degrees or less. Here in this study we flight test RNP 2 ILS approaches. The approach mode of the autopilot could be armed upon reaching the final approach point with immediate transition to active mode. Alternatively, the mode could be armed before with the expected negative consequence of a large dogleg deviation from the prescribed track increasing the flight technical error. While also determining FTE of the A320 D-ATRA owned by DLR besides the items of the previous simulator studies, we focus on additional points of interest. Moreover, even though automatic landings are one of the most safety critical certifications in aviation, little is known outside the manufacturer about the limits of such a system. We intent to primarily look at the altitude above the aerodrome at which the RF leg can deliver the aircraft on an ILS beam and automatic landings are still possible. Secondly, we try to fly the approach as a continuous descent approach using altitude constraints and vertical path angles coded in the database of the flight management system as part of the ARINC424 path terminators. Different combinations of constrains at waypoints and vertical path angles have potential to lead to vastly different behavior of the FTE.

2 Procedure Design

An instrument approach procedure describes the last phase of a flight and is defined as the trajectory an aircraft should follow from the Initial Approach Fix (IAF) to the decision altitude or missed approach point. It is composed of initial, intermediate and final approach and, if necessary, the missed approach segments. The initial approach is the segment from the IAF to the Intermediate Fix (IF). Here, the aircraft departs the first navigation aid or fix to begin the procedure intended to conclude with a landing. The intermediate approach is placed between IF and Final Approach Fix (FAF) or Final Approach Point FAP. Here, initial course alignment towards the final approach course and configuration of the aircraft for landing should be achieved. The final approach as the last part of the approach before either a landing or a missed approach procedure is performed. It is located between the FAF or FAP and the decision altitude for precision approaches or the missed approach point for non-precision approaches. Final course alignment and descent for landing make up the key indicators of the final approach segment

Lastly, the missed approach segment needs to be executed if the conditions for a successful landing are not fulfilled and returns the aircraft, usually climbing back to a safe altitude, to the terminal area from where it can divert to another suitable airport or try the approach a second time. Often, the word “fix” is used in aircraft procedures. While nowadays it generally describes a way point, the name originates from a time where a vehicles position was fixed by means off intersecting lines of position.

In order to be able to test experimental procedures, the approach paths must be coded ARINC 424 conformal and added to the navigation database of the FMS of the ATRA test aircraft. The ARINC 424 format standardizes the manner in which navigation data is stored and exchanged in airborne navigation systems. Each approach contains a series of waypoints that are defined by latitude and longitude and end at the threshold of the corresponding runway. A waypoint is denoted by a five-digit/letter identifier and can be part of multiple routes and procedures. The role of a waypoint in a particular navigation application, i.e. the leg type that leads to the waypoint, is denoted by a path terminator. An approach can also feature multiple IAFs in order to provide a more flexible access to the procedure.

Here, we coded a set of five experimental RNP to ILS approaches was designed for runway 26 of Braunschweig-Wolfsburg airport as ILS precision approach procedures. Each approach includes a RF leg terminating on the ILS intercept point at different heights between 550 and 2,000 feet above ground level, resulting in a final approach length between 1.73 and 6.28 nautical miles. The individual approaches are named ILS S through ILS W and feature greater ILS intercept heights with ascending alphabetical order. Details on intercept heights and length of the final approach segment can be found in Figure 1. Each approach includes two initial approach fixes (IAF) that are connected to the entry point of the RF leg using a TF leg. The IAFs are placed such as to result in a track angle change in the RF leg of either 90 or 180 degrees. During the RNP part of the approach, i.e. up to the ILS intercept point, the vertical profile is designed to feature a constant descent with a flight path angle of minus two degrees starting at the IAF. The approaches ILS S through ILS V start in an altitude of 4,000 feet above sea level, whereas ILS W starts in 5,000 feet above sea level in order to provide a straight leg with a length sufficient for alignment prior to the entry point of the RF leg. An overview of the approach design is shown in Figure 1 in a manner similar to the approach charts presented to the pilots.

The five-digit waypoint identifiers were chosen so as to allow a clear identification of both the approach and the individual path that the waypoint belongs to. They are composed of two alphabetical and three numeric characters identifying the approach. The first alphabetical character is the designator of the approach {S,..,W}, the second character describes the placement in the waypoint sequence and the three digits signify the track angle change during the RF leg.

It is notable that the ARINC 424 standard in its current version does not foresee the possibility an RF leg terminating directly on the ILS intercept point. Quality assurance tools of the database coder require a straight segment before the designated intercept point. This is a legacy issue as [PANS OPS] requires a 2 nm straight segment following a final approach course fix for each ILS approach. As a workaround we called the FAP a final approach course fix and designated a separate and unused point on the final approach course as xFAP0. The arming and intercept of the ILS is performed in the autopilot and independent of the FMS waypoint sequencing. This means that the FMS will automatically sequence to the next waypoint upon overflying of each xFAP0 whilst aircraft guidance is provided by the ILS. In case of RNP terminating in a GLS approach, neither [6] nor [15], [16] contains this restriction.

PANS-OPS, Volume 2, Part III, Section 2.4.1.4 defines additional criteria for RF legs that end at the Final Approach Point (FAP) or Final Approach Fix (FAF) for non-RNP AR procedures: In order to not exceed a track angle change of 45 degrees within an along-track distance of two nautical miles before the FAP, the minimum turn radius is restricted to 2.55 nautical miles. Following this ICAO guideline, we set the turn radius for the RF leg in the experimental approaches to 2.6 NM.

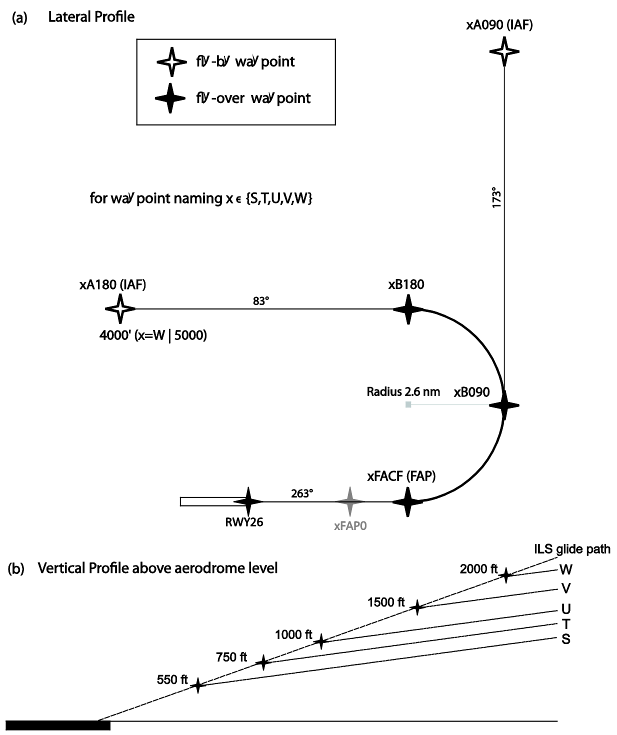

Figure 1 Approach Design

Furthermore, we added altitude constraints to the approach paths. As shown in Figure 2 (a) and (c), we coded the approaches containing a 180 degree track angle change having an “AT” altitude constraint at the initial approach waypoint xA180 and at xFACF. No design vertical path angle is included in the navigation database. The approaches with a 90 degree track angle change also contain these constraints as well as additionally an “AT or ABOVE” constraint at the beginning of the curve at waypoints xB090 as well as vertical path angles for all legs. Approaches are designed to follow a -2° descent angle before the ILS glide path intercept and then the standard ILS vertical path angle of -3°. From a previous simulator test, we expect the an Airbus A320 to follow a dive-and-drive behavior when following altitude constraints as illustrated in Figure 2(b). This means upon passing one constraint, the autothrust would perform an idle descent down to the next constraint altitude, where it would set continuous thrust to maintain that altitude until crossing the point with the constraint. Descent rate is dependent on initial aircraft energy conditions and flap settings but limited to -500ft/min by flight guidance computer logic.

In order to perform automatic landings from a precision approach, the autopilot and other involved systems of the aircraft is required to meet certain criteria set in [ICAO DOC 9365, CS-AWO and CS25] .A low visibility automatic landing according to CAT3 b must always be fail operational, i.e. two autopilots running in parallel so that a single failure does not cause a catastrophic event [EU OPS SPA.LVO.100 & AMC]. The aircraft manufacturer states all necessary operational conditions in the Flight Crew Operations Manual (FCOM), for example such as landing gear down, flaps full, glide slope angle within a certain range and others specific to the aircraft.

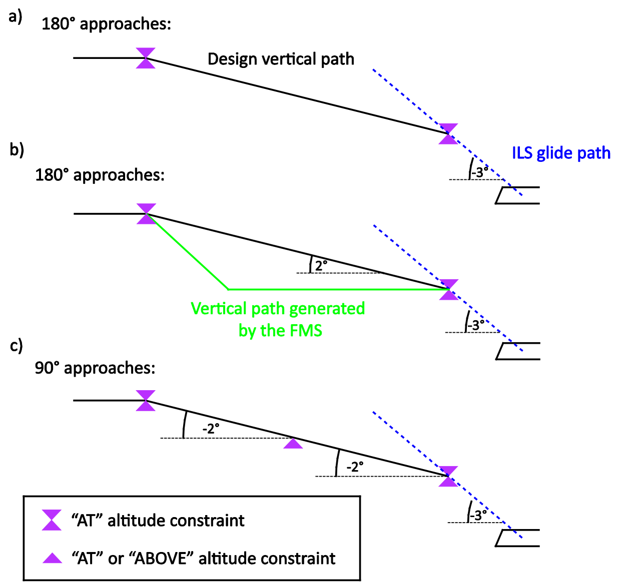

Figure 2 Vertical path coding with and without flight path angle. Design vertical path and „dive and drive” behavior of the aircraft

3 Flight Test Setup

DLR’s experimental Airbus A320 is equipped with the current Thales FMS2 and a basic Flight Test Instrumentation (FTI). The FTI provides ARINC429 data acquisition from the avionics as well as additional sensors such as precise high quality GNSS receivers and data storage as well as real time visualization of this data to the flight test engineer. It consists of 6

CRONOS data acquisition units from IMC (http://www.imc-berlin.com/applications/aerospace/) , three controlling computers and 7 display screens for two engineer workstations. From the FTI a custom IENA data stream can be provided to further experimental stations if needed. More details can be found in [ATRA FTI Documentation]. All data is recorded at a rate of 20Hz.

For the RNP to ILS experiments, we used the FTI to record the relevant ARINC429 data including position, autopilot modes, ILS data, cross track error, altitude and time. The entire experiments were flown using the OEM automatic flight guidance system in managed mode with only gear , flaps and approach mode arming performed by the pilots.

In order to perform automatic landings with the A320, both autopilots need to be engaged after the approach mode is armed. The automatic flight system will then perform the necessary self-checks and determine its performance. The result will be displayed on the Flight Mode Annunciator (FMA) as either “CAT 2”, “CAT 3 SINGLE” or “CAT 3 DUAL. At a sufficient low altitude, the mode will switch to LAND mode. At this point, the autopilot can only be disengaged by performing a go-around.

Unfortunately, no information about performance and control laws of the avionics used in the ATRA is available from the manufacturers. It is therefore not possible to draw conclusions about the actual capabilities of the ATRA regarding RNP to ILS transition in combination with an automatic landing.

In total we flew 16 approaches on 4 days, the first approach on the return flight from a different experiment. The main experiments were conducted on July 20, 21 and 23 2015 at Braunschweig-Wolfsburg airport in visual meteorological conditions. An overview of all approaches is shown Table 1. For each ILS intercept altitude from Figure 1 we intended to fly one approach with the 180° track angle change, one with 90° track angle change and the approach mode armed at waypoint xA090 and one with the approach mode armed when glide slope and localizer indicators are centered. However, beginning with ILS U 90° (Approach 3), arming the approach mode at the IAF caused the autopilot to lock onto the first side lobe of the localizer signal and the aircraft wanting to track towards the runway in approximately 45° relative angle. The approach mode was subsequently canceled and the aircraft was flown in heading mode back to the desired track. Since all other approach tracks with a lower intercept height are located even closer to the localizer antenna, we also expected side lobe capture and substituted them according to Table 3. Approach #5 was aborted by the pilots because the A320 indicated the previously mentioned dive-and-drive behavior down to 550ft above aerodrome elevation. Since the terrain surrounding Braunschweig airport is slightly higher, this would have led to prolonged low level flight with high thrust which is not very comfortable for the flight crew.

During approach #13, VFR traffic unknown to ATC caused a TCAS Resolution Avisory which prompted the pilots to temporarily level off in order to maintain altitude separation with respect to the intruder.

Except for the ILS S 180 all approaches were completed with an ILS capture on the RF Leg and subsequent automatic landings.The experimental pilots corrected interuptions as the ones caused by the side lobe and the TCAS alert using selected autopilot modes and steered the ATRA back on the desired path afterwards.

We expect the aircraft in managed mode to go through a certain sequence of automatic pilot mode transition during the RNP2ILS approaches. The auto flight system distinguishes lateral and vertical modes separately. For the vertical, we would begin in altitude hold mode and then ideally transition to the geometric path descend mode till the xFACF, where the aircraft transitions to glide slope capture and then glide slope tracking. When autoland is active, the landing finishes with flare mode. In sequence this would be ALT->DES->G/S* ->G/S ->FLARE. Laterally, we begin in navigation mode, followed by localizer capture, localizer track and land mode: NAV->LOC*->LOC->LAND

Approach No.	Date	Approach
1	16 July 2015	ILS W 90°
2	20 July 2015	ILS V 180°
3	20 July 2015	ILS U 90°
4	20 July 2015	ILS T 90°
5	20 July 2015	ILS S 180°
6	20 July 2015	ILS W 90°
7	21 July 2015	ILS V 90°
8	21 July 2015	ILS U 180°
9	21 July 2015	ILS T 90°
10	23 July 2015	ILS W 180°
11	23 July 2015	ILS T 90°
12	23 July 2015	ILS S 90°
13	23 July 2015	ILS V 90°
14	23 July 2015	ILS U 90°
15	23 July 2015	ILS V 180°
16	23 July 2015	ILS S 90°

Table 1: Flight test procedure for RNP to ILS approaches at Braunschweig-Wolfsburg airport

4 Results

4.1 Lateral and Vertical Path Following

The one sigma scatter of of the cross track flight technical error for each approach well below 185,2m (or RNP0.1). There is no evidence of a difference in lateral track behaviors. The approaches with 90° TAC were flown with the approach mode armed at the initial approach fix and with approach mode arming and immediate activation at the final approach point located at the xFACF. When the approach mode was armed early (see Figure 5), the autopilot enters localizer capture mode and flies at constant heading. This results in a straight segment where the aircraft should still follow the desired curved path.

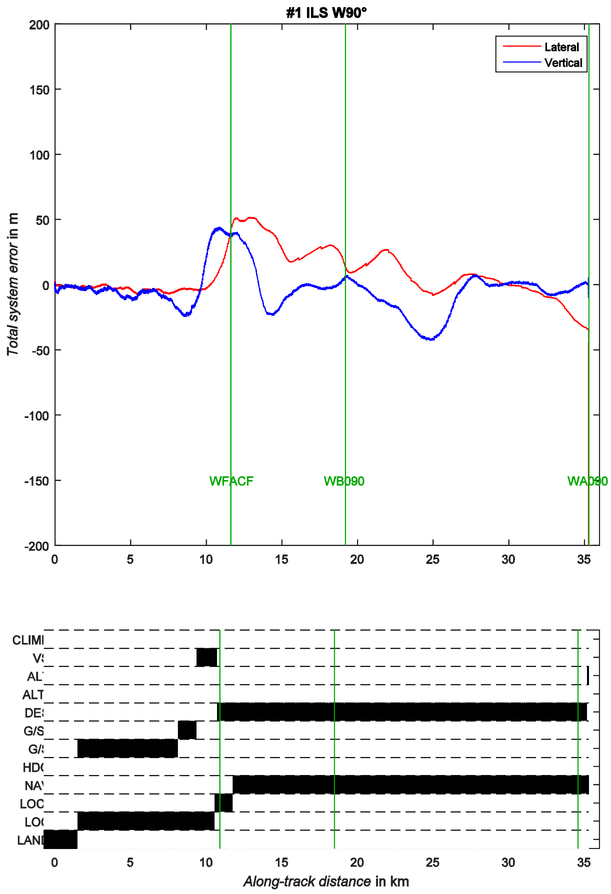

Figure 3 ILS W90 from 16 July 2015. The top panel shows lateral and vertical flight technical error, the bottom panel indicates autopilot modes active during the approach. Green lines mark the approach waypoints. The aircraft arrived slightly high at WFACF which was corrected by the pilot using VS mode

It is notable, however that only once the RNP0.1 corridor was violated and at all times the aircraft remained within RNP0.3 (555,6m) of the track centerline. Comparing the lateral flight technical error (FTE) in Figure 3 and Figure 5 we can see that the error caused by early activation of the approach mode is only of the order of 50m and thus well within the RNP0.3 corridor (and even RNP0.1), the highest accuracy that is currently implemented for RNP operations.

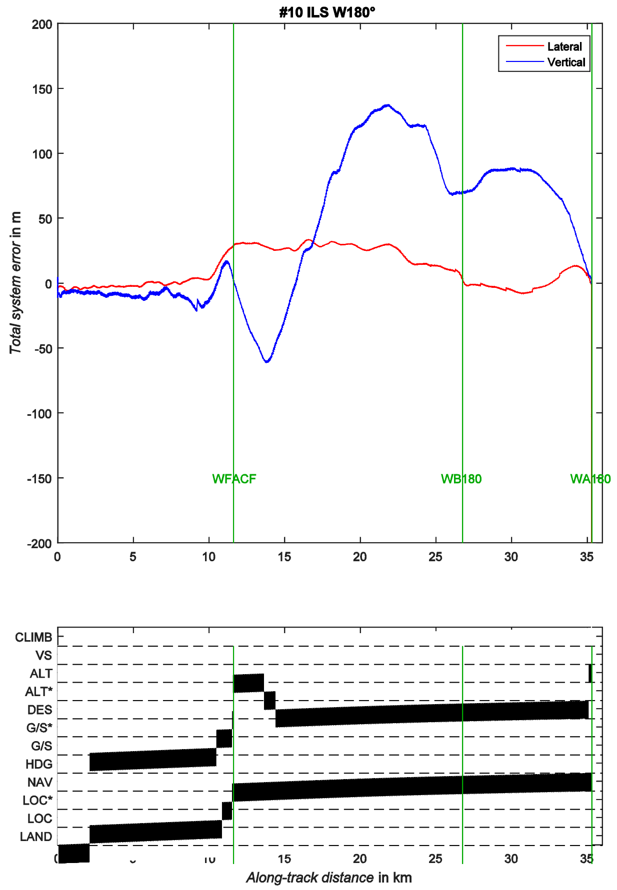

Figure 4 ILS W180 from 23 July 2015. The top panel shows lateral and vertical flight technical error, the bottom panel indicates autopilot modes active during the approach. Green lines mark the approach waypoints. The dive and drive mode is visible in the vertical modes from kilometer 12 to 15 and in the vertical FTE variation between WFCAF and WB180.

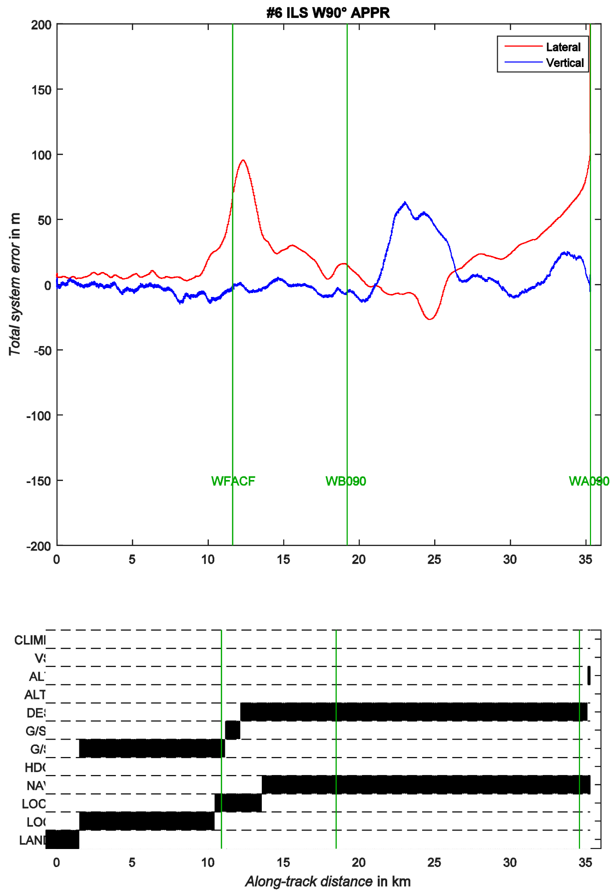

Figure 5 ILS W90 from 20 July 2015 with the approach mode armed at WA090. The top panel shows lateral and vertical flight technical error, the bottom panel indicates autopilot modes active during the approach. Green lines mark the approach waypoints. The cross track error spike slightly before WFACF is caused by early intercept of the localizer.

4.2 Mode Transitions

Figure 3 through Figure 5 show lateral and vertical flight technical error during the three different ILS W approaches and flight management guidance mode transitions over the along-track distance from the runway threshold. Individual segments are separated by vertical green lines. In Figure 13, the aircraft performed a continuous descent but arrived slightly high above the glide path at WFACF. The experimental pilot used the V/S selected mode for a short descent and then engaged the approach mode. At this point, the FTE analysis shows an vertical error close to zero. Upon capture of the ILS glide path beam, the vertical error is approximately constant at 45m. The reason for the high arrival was most likely a surface temperature 15°C above the international standard atmosphere at Braunschweig airport.

Figure 4 illustrates nicely the dive and drive behavior that was previously mentioned. Between WA180 and WFCAF the aircraft performs a descent down to the next constraint altitude at WFACF in DES mode, and then maintains this altitude until passing the WFACF. Here, for a brief moment the FMS reselects DES mode to proceed to the next constraint altitude. However, now the flight crew selected approach mode on the FCU and the autopilot locked onto the ILS signals.

Lastly, in Figure 5 we show one approach where the Approach mode of the autopilot was already armed at the initial approach fix. Lateral and vertical mode transitions are the same as in Figure 3 (without the selected V/S mode). However, localizer capture occurs earlier causing the aircraft to deviate laterally from the designed path at the order of 100m. This is the expected dog-legging behavior. However, the deviation is small compared to a potentially required RNP of 0.3NM (555,6m) laterally.

Here, we chose to show the data from the RNP to ILS W approaches in Figure 3 through Figure 5 as a representative example for all series of approaches performed in this flight test. The V,U,T and S approached are qualitative similar with only a lower intercept height and this a smaller distance from the xFACF to the runway

4.3 ILS Intercept Analysis and automatic landing

The elapsed time between approach mode arming and full tracking of localizer and glide slope for each one of the 16 approaches was between 13.8 and 22.1s when depressing the approach mode button at xFACF. Time is obviously much longer for those approaches that were flown with arming the mode at the initial approach fix (3,6,13,15). Approach 3 is an exception, where, the approach mode was cancelled by the pilots due to an inadvertent capture of a side lobe of the localizer beam. In 7 out of 12 cases, when the approach button was depressed when localizer and glideslope were approximately centered, the localizer was tracked after about 13.8s, the glide slope in 8 out of 13 cases after 18.9 seconds. Since the data was recorded at 20Hz, the measurement uncertainty is in the order of 0.05s.

In all 16 cases when automatic landings were performed, the LAND mode engaged between 316 and 381 feet radar altitude. This is in agreement wih [A320 FCOM] which describes the land mode as “Common mode engaged below 400 ft RA during an automatic ILS approach.” During approach 11 and 12, the aircraft was less than half a dot (0.075°) above the glide path. This may have impacted the guidance loops of the autoland system to need additional time to converge. Thus, the LAND mode activated lower as the aircraft descended on the glide path. Even during the ILS S approaches, where SFACF , the final approach point, is located only 550 feet AAL, the LAND mode engaged at 316ft radar altitude and 363 ft radar altitude, indicating quick convergence of the guidance loops in the auto pilot computer

5. Mode Transitions

We found that technologically flying an RNP to ILS approach with automatic landings is very feasible, even with ILS intercept heights as low as 550ft AAL. In order to perform a continuous and stable descent with the A320 auto flight guidance, it is very important to set constraints and vertical path angles as the trajectory computation prefers a dive and drive path outside the final approach segment. Here, we tested only am approach path devoid of constraints at the intermediate fix and vertical path angle in comparison with an approach including both constraints and vertical path angle in all ARINC424 path terminators. It is imaginable that an intermediate coding approach with only VPA or only constraints at waypoints could have the same effect.

Also, we could only flight test one aircraft type. As indicated by [DeSmedt2015], different aircraft/autopilot combinations behave vastly different. However, this study was conducted using simulators. In preparation for the RNP2ILS flight trials, we tested all approaches in an A320 Full Flight Simulator at TFC Käufer in Essen, Germany. Here, for the ILS S approaches, the LAND mode only activated at 180ft radar altitude compared to 316 and 363 in the real airplane. Therefore care needs to be taken when comparing simulator results to the real aircraft.

Finally, the Pilots were comfortable with ILS intercept heights down to 1000ft AAL. The ILS

T and S approaches (with intercept heights of 550 ft AAL and 750ft AAL) appeared to them subjectively less safe since the aircraft was not aligned with the final approach and the runway in sight straight ahead until very late during the approach.

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