RNP TO PRECISION APPROACH TRANSITION FLIGHT SIMULATIONS

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Abstract

EUROCONTROL, in collaboration with the Technical University of Berlin and under the SESAR [1] work programme, has conducted an experiment investigating the behavior of 6 different aircraft types when performing a transition from a curved RNP procedure to a precision final approach (using an ILS, GLS or more generically an xLS landing system). Basic procedures were coded in ARINC 424 format whereby a Radius-To-Fix (RF) leg connected directly to the localizer/glideslope intercept point of a 3, 6 or 9 NM final segment. A set of alternative procedures were designed as well, which contained a short intercept leg with a defined intercept angle between the end of the RF and the final segment. To test the influence of navigation position errors on the xLS transition, lateral biases with various magnitudes up to 0.3 NM and in either northern or southern direction were introduced in the procedures (with the final approach course aligned to the east). The procedures were flown using RF capable certified full motion flight crew training simulators.

Significant differences were observed in the capture capability of the localizer. In a category of aircraft it is not possible to transition from LNAV to LOC mode directly. Therefore a crew procedure is required, switching to heading mode near the end of the RF leg for some aircraft. All aircraft types were able to perform a simultaneous localizer and glideslope capture. In most of the scenarios, the aircraft was able to transition from a 2 degree barometric slope along the RNP procedure to a 3 degree glideslope at the capture point. In 95% of the cases the aircraft needed an additional 500 feet to stabilize after the localizer/glideslope capture altitude. This suggests a minimum capture altitude of 1500ft, corresponding to a required minimum final segment length of 5 NM. The alternative procedures containing an intercept leg did not provide advantages over the procedures without intercept leg. It was concluded that successful transitions to a 5 NM minimum final segment length would work if the Total System Error along the RNP procedure would be below 0.16 NM. In this case, a straight intermediate segment between localizer and glideslope capture would not be required according to the test results.

Introduction

Required Navigation Performance (RNP) is a capability in an aircraft's navigation system that allows accurate tracking of a lateral route, departure or arrival procedure, within specified performance boundaries. A variety of RNP specifications exist today, as described in the ICAO Performance Based Navigation (PBN) Manual [1]. Among these specifications, Advanced RNP provides the option to use a specific path terminator, called Radius to Fix (RF), in the definition and execution of a procedure. Using the RF capability, as specified by current aviation standards [2], a curved path over ground with a defined constant radius can be flown between a defined start and end point. Aircraft equipped with this function will adjust the bank angle during the turn in function of groundspeed and turn radius to stay on track. Tracking performance of systems using the RF function was assessed in earlier work [3], which recommended the use of RF functionality as the preferred leg type to define turns in terminal area procedures. With an estimated current worldwide RF-capable aircraft equipage rate of well above 50% [4], standard instrument departure and arrival procedures (SIDs and STARs) requiring RF capability are gradually being implemented by certain states in Europe. Primary objectives are most often to concentrate tracks away from populated areas and therefore reduce noise. For example, results from a track keeping analysis, using track data gathered from a trial involving the use of RF on an area-navigation (RNAV) departure procedure at Schiphol airport in the Netherlands, are presented in [5].

[1] Single European Sky ATM Research

Problem Statement

A particular area of interest where the RF function can be used is for the transition from an RNP procedure to an xLS precision final approach procedure, where x refers either to ILS, MLS or GLS. This would allow operators to use the low minima associated with precision approaches while allowing procedure designers the opportunity to include a repeatable curved segment in the approach design. In addition this would allow the design of a repeatable vertical path, as the lateral path is unambiguously defined, which will enable an environmental friendly continuous descent operation.

Procedure design criteria have been proposed in the ICAO Instrument Flight Procedures Panel (IFPP) for the use of RF in the intermediate segment of an approach procedure using barometric vertical guidance (baro-VNAV) or an approach procedure using SBAS, allowing the RF to end directly at the Final Approach Fix (FAF) or Final Approach Point (FAP) on the runway centerline axis. However, design criteria for the connection of an RF leg to an xLS precision final approach are not defined. It is not yet well understood what the performance limitations are of aircraft using the RF capability in a transition phase, switching from FMS based guidance along the RNP path to guidance generated by the Multi-Mode Receiver (MMR) during the xLS operation [6].

Current ICAO PANS-OPS procedure design criteria require that the intermediate approach segment of an xLS procedure shall be aligned with the final approach segment. The length of this intermediate approach segment should be sufficient to permit the aircraft to stabilize and establish on the final approach course prior to intercepting the glide path, taking into consideration the angle of interception with the final approach course. Minimum distances between final approach and glide path interception are 1.5 NM for final approach intercept angles up to 15 degrees and 2 NM for angles up to 30 degrees [7]. However, in case when the final approach course is intercepted from an RF leg, the intercept angle will be continuously reducing. Also the question could be asked why an intermediate segment aligned with the final approach course is still required for xLS procedures, while it is not for baro-VNAV and SBAS procedures. Another question is how the aircraft should vertically transition from the RNP to the xLS operation and whether a continuous descent operation is possible if a straight intermediate segment is required.

A topic that is currently also under discussion when considering RNP to xLS transitions, is what the minimum distance should be between the runway threshold and the point at which the RF leg intercepts the final approach course. A preliminary SESAR study (Project 9.9) and the FAA Performance-based Operations Aviation Rulemaking Committee (PARC) have produced proposals to calculate this distance in function of the final approach course Full Scale Deviation (FSD) and the aircraft's maximum cross track deviation along the RNP path [8] [9]. However the proposed formulas are not consistent and both assume that the aircraft's cross-track deviation equals the maximum value allowed by the RNP specification, leading to relatively large distances.

Purpose of the simulation

In order to formulate procedure design criteria for RNP to xLS transitions, the ICAO IFPP has highlighted the need for data collection [6]. This simulation was undertaken to support this data collection and to find answers to the following questions:

- What is the behaviour of current avionics when transitioning from RNP to xLS and are there any significant differences between various systems?
- Can all systems transition from LNAV to localiser/glideslope while flying the RF leg?
- What would be an acceptable distance to threshold to capture the final approach course from an RF leg, taking into account expected navigation precision?
- Is a straight intermediate segment required between the end of the RF leg and the glide path intercept point?
- Can an RNP to xLS procedure be designed to facilitate a continuous descent operation?
- Are there any operational requirements for flight crew to perform the transition?

A set of procedures were designed consisting of RNP to xLS transitions using RF legs with various radii and various final approach segments lengths. These procedures were coded in aircraft databases and implemented in 6 different certified flight crew training simulators. The procedures were flown under both normal conditions and under conditions, in which small navigation errors were introduced in the scenarios to test their influence on the final approach intercept capability of the avionics. The scenario development and test facilities are described further below.

Scenario Development

Procedure Design

Three basic procedures were developed consisting of an ILS final approach segment with lengths of 3, 6 and 9 NM, connected directly to an RF leg with radii of respectively 1.5, 2.3 and 2.8 NM. The total track change along this RF leg was 180 degrees. The end of the RF leg was aligned with the final approach course and was coinciding with the glide path intercept point. Therefore a straight segment between the end of the RF leg and the glide path intercept point was absent. The RF leg was bounded by two altitude constraints: one at the end of the RF leg, equal to glide path intercept altitude and one at the start of the RF leg such that a 2 degree vertical path was created along the RF leg. This allowed a transition in the vertical dimension from a 2 degree barometric path to a 3 degree geometric glide path at the end of the RF and start of the final approach segment. The radii where calculated in function of a maximum allowed bank angle of 25 degrees and a maximum design groundspeed. The maximum design groundspeed was a function of a speed constraint at the start of the RF leg and a design wind. Design winds were chosen as proposed in [6]. The speed constraints at the start of the RF leg were for the procedures with a 3, 6 and 9 NM final approach segment respectively, 180, 200 and 220 KIAS. The three basic procedures are displayed in red on Figure 1.

Similarly, three alternative procedures were developed using the same basic principles as for the basic procedures, except the fact that an intermediate segment was created between the RF leg and the final approach course. However, this intermediate segment (further called intercept leg) was not aligned with the final approach course but instead intercepted the final approach course with an angle of 20 to 30 degrees. The length of the intermediate segment varied between 1 and 2 NM. Speed constraints and turn radii were the same as in the basic procedures. Both ends of the intercept leg as well as the start point of the RF leg contained altitude constraints which created a 2 degree barometric path over the whole length of the RNP path between the start of the turn and the glide path intercept. The idea behind these alternative procedures was to allow a comparison of the basic procedures with a situation whereby the aircraft intercepts the final approach segment with a defined intercept angle but without the need to have a straight intermediate segment between final approach and glide path intercept. The alternative procedures are indicated in blue on Figure 1.

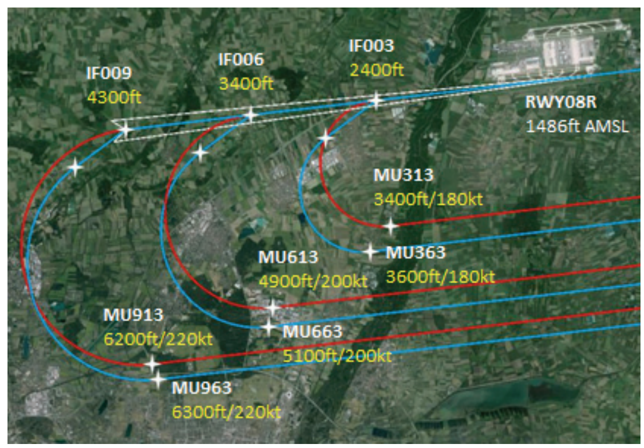

Figure 1. Overview of Basic Procedures (red) and Alternative Procedures (blue)

For all procedures, an arrival runway 08R was created at a custom airport called EDZA, with characteristics based on Munich Airport, Germany. The three basic STAR procedures were called MUNI3A, MUNI6A and MUNI9A in which 3, 6 or 9 refers to the distance to the threshold at which the RF leg ends and connects to a 3, 6 or 9 NM final procedure, called respectively I08R3, I08R6 and I08R9. The alternative STAR procedures were named similarly as the basic procedures expect that the last letter A was replaced with a letter ranging from B to G, referring to a particular combination of intercept angle and leg distance of the intercept leg. Table 1 lists the three final approach procedures with respectively 3, 6 and 9 NM lengths, which each connect to one of the seven STARs listed in Table 2. This leads to a total combination of 21 procedures.

Finally, the 21 procedures were designed for 11 different airports, called EDZA, EDZB up to EDZK, with each airport (and its corresponding arrival runway 08R) having a slightly displaced location from the basic airport EDZA. The magnitude and direction in which each airport was offset from EDZA are indicated in Table 3. These offsets were created so that when an offset airport with corresponding procedure was loaded in the FMS while the actual localizer and glideslope remained fixed at their programmed locations in the simulator, a situation was created in which the aircraft had a simulated position error along the RNP path before transitioning to the xLS final approach.

Table 1. Approach Names with Corresponding Length of Final Segment and Procedure Name

Approach	Length of Final Segment (NM)	Value of x in Procedure Names Table 2
I08R3	3	3
I08R6	6	6
I08R9	9	9

Table 2. Procedure Names with Corresponding Intercept Angle and Leg Distance of Intercept Leg

Procedure Name	Intercept Angle (°)	Intercept Leg Distance (NM)
MUNIxA	0	0
MUNIxB	20	1
MUNIxC	20	1.5
MUNIxD	20	2
MUNIxE	30	1
MUNIxF	30	1.5
MUNIxG	30	2

Table 3. Airport Names with Corresponding Offsets from Reference Airport EDZA

Airport	Offset Magnitude (NM)	Offset Direction	Offset Value
EDZA	0	N/A	0
EDZB	0.03	south	0.03
EDZC	0.03	north	-0.03
EDZD	0.05	south	0.05
EDZE	0.05	north	-0.05
EDZF	0.1	south	0.1
EDZG	0.1	north	-0.1
EDZH	0.15	south	0.15
EDZI	0.15	north	-0.15
EDZJ	0.3	south	0.3
EDZK	0.3	north	-0.3

Database Coding

The procedures were coded in ARINC 424 format using the latest ARINC specification [10]. According to this specification, the coding of an ILS approach procedure requires a Final Approach Course Fix (FACF) which is defined as a fix located on the localizer centerline, 8 NM or less from the Final Approach Fix (FAF). All localizer based approach procedures must begin at the FACF.

To comply with this requirement, the arrival procedures defined in Table 2 and illustrated in Figure 1 were coded as Airport STAR (PE) records with the RF leg as the last path terminator ending at a fix named IF00x (with x either 3, 6 or 9 depending on the length of the final procedure). This same fix was the first point in the ILS approach record where it was defined as the FACF. The FAF was the next waypoint in the ILS approach record, located 2 NM downstream from the FACF. The glideslope intercept altitude was set equal to altitude constraint at point IF00x and was above the glideslope crossing altitude defined at the FAF.

Complete ARINC 424 files containing the coded procedures were sent to Honeywell, GE Aviation and Universal Avionics, who converted the files into loadable databases.

Test Facilities

The simulators used in the test series were six full motion flight simulators operated by Lufthansa Flight Training and Swiss Aviation Training. They all have the highest certification standard called JAR-STD 1A Level D which is normally used for flight crew training. More in particular, the following aircraft simulator types were used:

- Boeing B737-300
- Boeing B777-200
- Airbus A320-200
- Airbus A340-300
- Embraer E190
- Bombardier Q400

The flight characteristics of the simulators correspond to existing reference aircraft to ensure a realistic behavior of the whole aircraft system. The simulators were equipped with original avionics, including the original Flight Management System (FMS). Custom databases containing the full set of designed procedures were provided by Honeywell, GE Aviation and Universal Avionics and loaded in the corresponding FMSs of the simulators. The simulators were equipped with a motion system with six degrees of freedom and a 180 degree wide visual system. An example of the exterior and interior of the simulators is provided in Figures 2 and 3.

An additional Data Gathering Utility (DGU) was installed on the simulation host computer. The DGU is able to create log files of the simulation state as stored in the system memory. It scans a specified set of up to 200 parameters at regular intervals (up to 60 Hz) and writes the values into a file for subsequent evaluation. This type of data recording was available for 3 of the 6 simulator types. High-definition video recordings of the Primary Flight Display (PFD) and the Navigation Display (ND) were made for each scenario during the tests in all 6 simulator types.

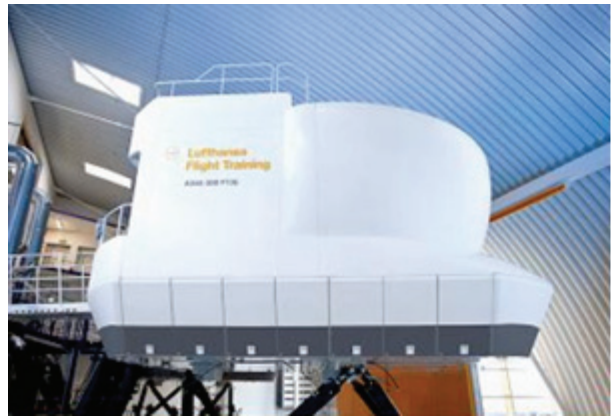

Figure 2. Exterior of the Airbus A340 Full Flight Crew Training Simulator Used in the Tests

Figure 3. Interior of the Airbus A340 Full Flight Crew Training Simulator Used in the Tests

Discussion of Results

The purpose of the tests was not to compare performance of individual aircraft with each other. Therefore in the discussion of the results, the aircraft types will be further indicated as A/C 1, A/C 2 up to A/C 6, whereby the number corresponding to a particular aircraft type was randomly chosen.

The complete list of scenarios flown in the 6 aircraft simulators are presented in the Scenario Table in the Appendix. The first 9 columns in this table list the aircraft number (A/C), the scenario number (SCN), the selected airport from Table 3 (Airport), the selected STAR from Table 2 (STAR), the inserted wind in the simulator (Wind), the length of the final approach segment (Final), the intercept angle (Leg) and the length (Dist) of the intercept leg if applicable and the bias corresponding to the simulated navigation error (Bias in NM with + sign corresponding to a bias to the south and a - sign corresponding to a bias to the north).

The last 5 columns in the Scenario Table in the Appendix provide the results that were obtained and are labeled as follows:

- Intercpt: indicates whether there was an automatic transition from LNAV to LOC mode in the guidance system of the aircraft after arming the approach mode (yes) or whether there was no transition from LNAV to LOC mode (no).
- H to LOC (Height to LOC): indicates the altitude difference in feet between the altitude at which the LOC mode engaged and the localizer/glideslope intercept altitude defined in the procedure.
- H to G/S (Height to G/S): indicates the altitude difference in feet between the altitude at which the G/S mode engaged and the localizer/glideslope intercept altitude defined in the procedure.
- H to Stab (Height to Stabilize): indicates the altitude difference in feet between the altitude at which the aircraft was stable and the localizer/glideslope intercept altitude defined in the procedure.
- Comment: provides more information for some particular scenarios.

Winds in the simulator were chosen in function of the sign of the bias in the procedures, creating the most unfavorable combined effect of bias and wind on the aircraft. For example, for procedures offset to the north, wind was from the south at 25 knots which resulted in a crosswind condition that pushed the aircraft further north. For procedures offset to the south, wind was from the north at 25 knots, pushing the aircraft further south. Temperature was set for all scenarios at ISA + 15. The latter caused the aircraft to be slightly high on the desired RNP path making the glideslope intercept more challenging.

Data was analyzed using the data recordings from 3 of the 6 flight simulators as well as the video recordings of the Primary Flight Display and Navigation Display of all aircraft.

Localizer Full Scale Deviation (FSD)

In the subsequent paragraph, the lateral intercept performance will be discussed and it will often be related to the position where the RNP path terminates and whether this is in or out the Full Scale Deviation (FSD) of the localizer. The latter depends on the displacement sensitivity of the localizer which is defined in [11]. Except for short runways, displacement sensitivity is such that the nominal sector width equals 210m (700ft) at the ILS reference datum (for our purposes the runway threshold). Assuming a sector width of 0 at the localizer reference point and a sector width of 105m either side of the localizer abeam the runway threshold, this allows determining the angular width θ of the LOC area bounded by 1 FSD starting from the localizer reference point. In our case this yields 2.41 degrees, with the distance between localizer reference point and the threshold, d_{loc} = 4981m. The lateral distance from the localizer centerline y corresponding to 1 FSD can be calculated from the distance to threshold x, the distance between the threshold and the localizer reference point d_{loc} and the angular +/- 1 FSD localizer sector width θ, as follows:

$$y = (x + d_{loc}) \cdot \tan(0.5 \cdot \theta) \qquad (1)$$

Lateral Intercept Capability

The first observation that could be made from the collected data and from experiences during the simulations is that there is a great variability in how different systems perform the intercept of the localizer and in how they cope with position errors while transitioning from the RNP path to the xLS procedure. The following four main categories of systems behaviors could be distinguished:

- Systems which could not transition from LNAV to LOC mode directly. In these aircraft, LOC mode could only be engaged from heading mode. That means that to make the operation work, the pilot needed to engage HDG at some moment on the RF turn which caused the aircraft to roll wings level, before the approach mode could be armed.
- Systems which only captured the localizer (after arming the approach mode) if the aircraft track crossed the localizer

centerline or if the aircraft's position was sufficiently close to the localizer centerline when completing the RF turn (deviation < 1 dot).

- Systems which captured the localizer if the aircraft track crossed the localizer course or if the final position of the aircraft after the RF turn was within the localizer Full Scale Deviation (FSD).
- Systems which captured the localizer independently of the position of the aircraft at the end of the RF turn, due to the fact that the aircraft rolled out automatically on an intercept track to the localizer at the end of the RF turn, while still in LNAV mode. The latter occurred if the aircraft was still outside of the LOC FSD when completing the RF turn and thus undershooting the localizer. The intercept track varied, depending on the aircraft type between 20 and 30 degrees.

Figures 4, 5 and 6 provide an overview of the horizontal tracks, vertical profiles and bank angles in function of distance to go, for the 3 aircraft types for which data recording was available (A/C 1, A/C 2 and A/C 3) and for the scenarios without intercept leg. First of all, it needs to be mentioned that the splay of tracks along the RF leg in Figures 4, 5 and 6 is intentional. They are caused by the lateral biases which were deliberately introduced in the procedures to test the capabilities of the different aircraft to transition from an RNP path with an assumed navigation performance to an xLS procedure. Track keeping performance along RF legs was not the scope of this project as it has been researched already in earlier work [3][5]. In general, flight technical errors corresponding to the procedure programmed in the FMS, which were observed during the tests, were well below 0.1 NM (and in most cases even below 0.05 NM)

The difference in behavior between the different aircraft types is clearly visible in the horizontal tracks in Figures 4, 5 and 6. Figure 4 indicates that for the scenarios with a high positive bias, causing the RNP path to undershoot the localizer and end outside the LOC FSD, A/C 1 did not intercept the localizer but instead flew parallel to it. For intercepts at 3 NM with 0.15 NM biases, LOC mode did engage in A/C 1 but the convergence to localizer centerline was so slow that the aircraft actually never aligned with the runway centerline before it was over the threshold. Horizontal tracks for A/C 2 and A/C 3 in Figures 5 and 6 clearly indicate that for similar scenarios with high positive biases (causing the aircraft to undershoot the localizer), the aircraft corrected the situation by rolling out on a fixed track with an intercept angle of either 20 or 30 degrees towards the localizer. For the procedures with negative biases, causing the RF leg to terminate north of the localizer, the bank angle profiles in all three Figures 4, 5 and 6 indicate that the aircraft increased bank up to 30 degrees when performing the intercept. In many cases, especially for A/C 1 and A/C 3, this still caused an overshoot of the localizer, although the aircraft remained within the LOC FSD. In the latter case, the 30 degree positive bank was succeeded by a negative bank angle of 5 to 10 degrees to correct the overshoot. Finally the horizontal tracks in Figure 5 indicate that A/C 2 had some difficulty with intercepting the localizer at 3 NM from the threshold without overshooting the localizer significantly. The tracks are temporarily outside the LOC FSD and negative bank angles of up to 15 degrees are observed within 3 NM from the threshold to re-intercept the localizer from the opposite side.

Close-ups of the horizontal tracks of the three different aircraft types intercepting the localizer at 6 NM from the threshold are provided, for the +/- 0.15 NM biases in Figure 7 and for the +/- 0.30 NM biases in Figure 8. Figures 7 and 8 also display the reference track that the aircraft should have flown in the absence of position errors. Finally, the column labeled "Intercpt" in the Scenario Table in the Appendix is graphically presented in Figure 9 for all six aircraft types. The green or red symbols for each aircraft type indicate whether or not there was an automatic transition from LNAV to LOC for the procedures without intercept leg, depending on the distance at which the RNP path intercepted the localizer (3, 6 or 9 NM) and the lateral bias applied in the scenarios. Also the LOC FSD is displayed in Figure 9. All the dots within the LOC FSD in Figure 9 relate to scenarios in which the RNP path, taking into account the lateral bias, ended at the indicated distance to the threshold within the LOC FSD. In summary, Figure 9 provides a clear overview of the findings discussed above.

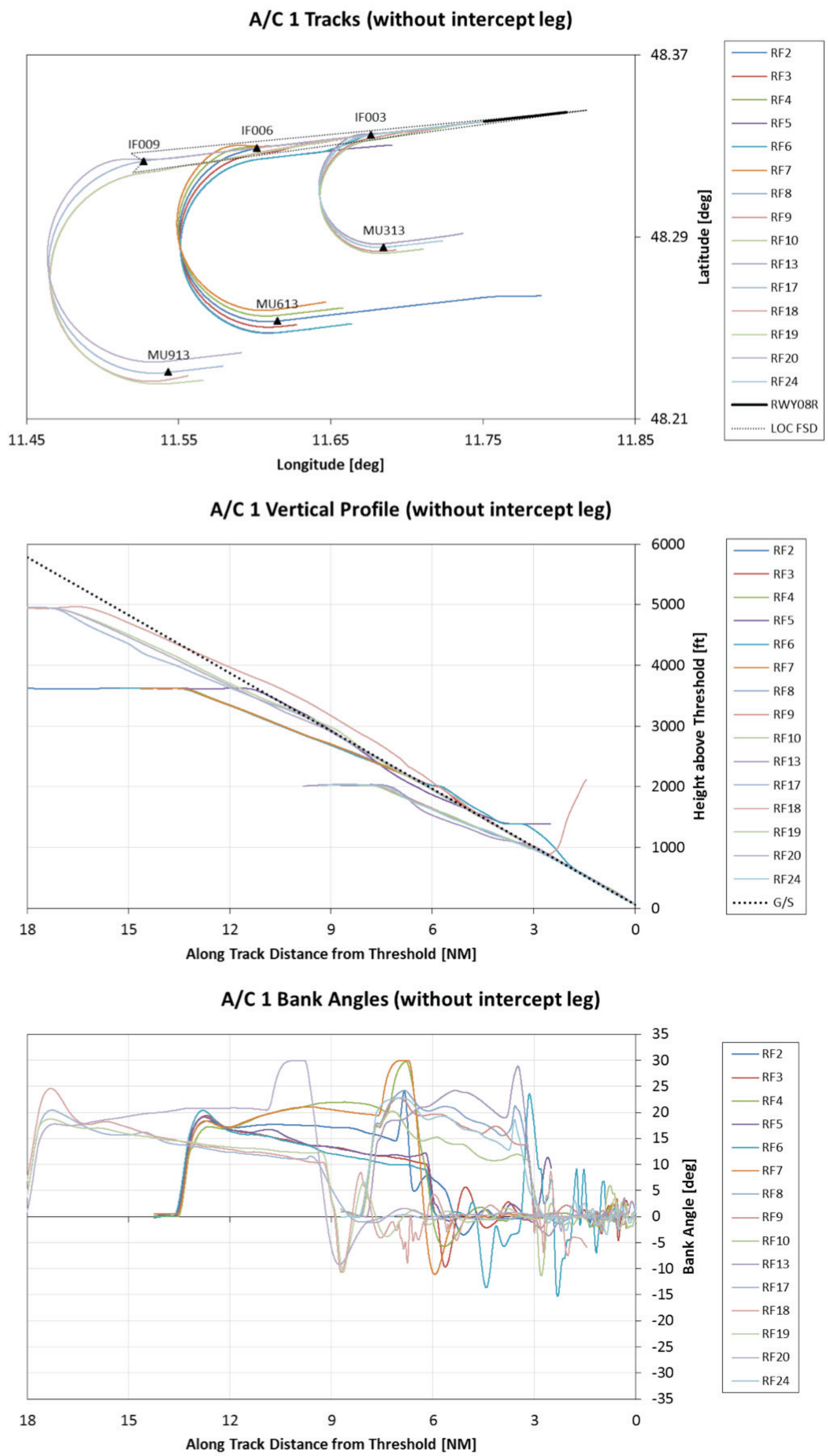

Figure 4. A/C 1 Tracks, Vertical Profiles and Bank Angles (Scenarios without Intercept Leg)

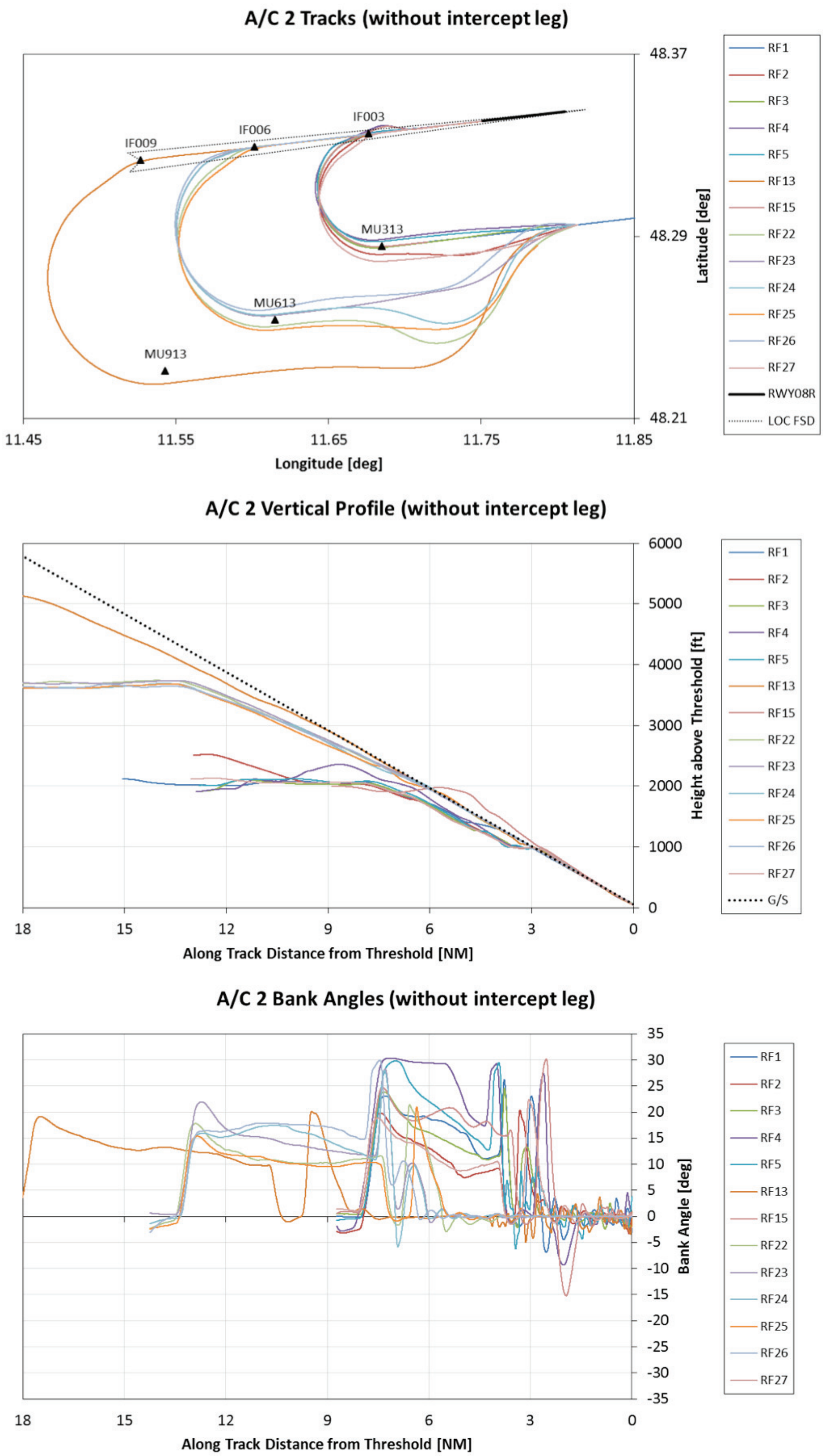

Figure 5. A/C 2 Tracks, Vertical Profiles and Bank Angles (Scenarios without Intercept Leg)

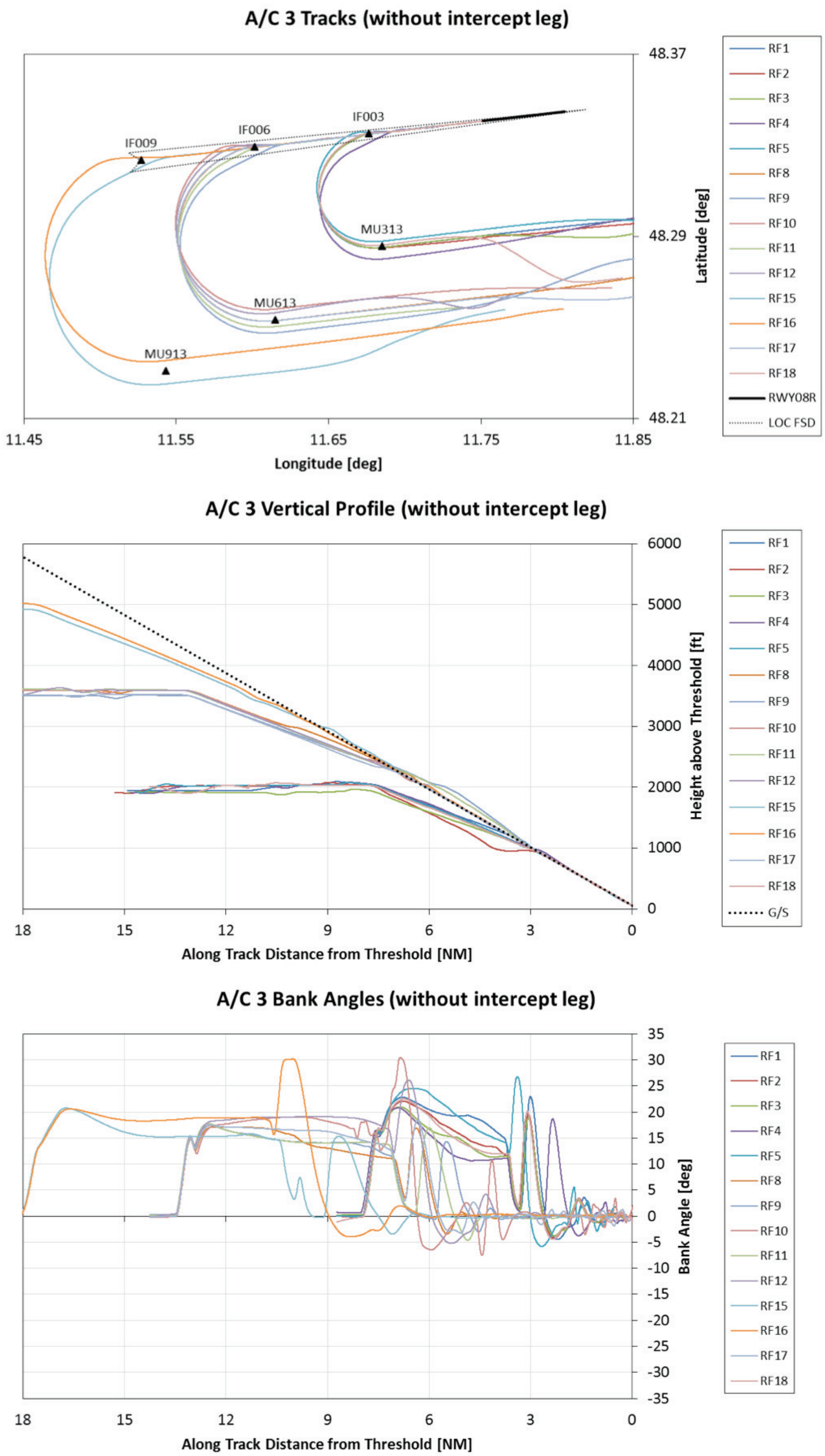

Figure 6. A/C 3 Tracks, Vertical Profiles and Bank Angles (Scenarios without Intercept Leg)

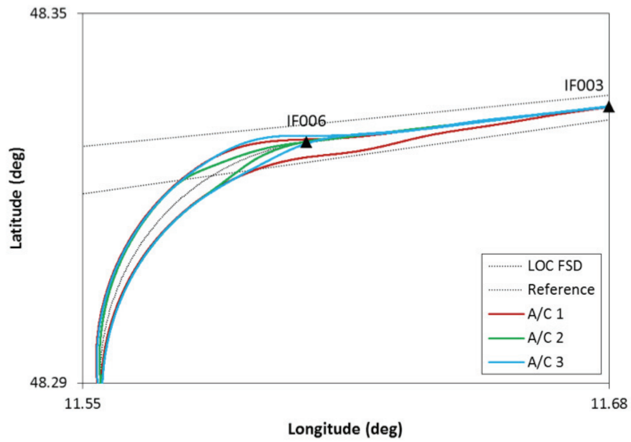

Figure 7. Close-up of Tracks near Transition for Procedures with 6 NM Final and +/- 0.15 NM Bias

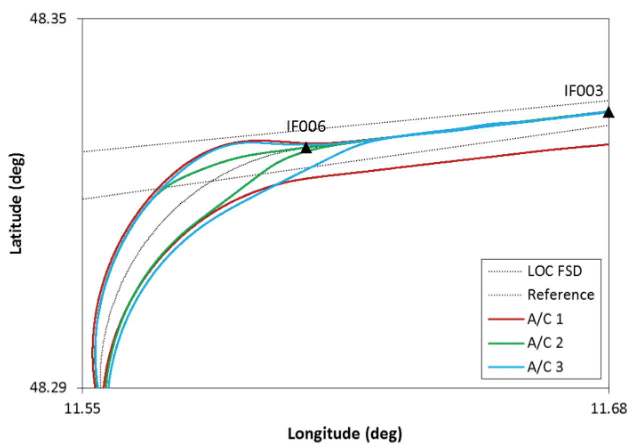

Figure 8. Close-up of Tracks near Transition for Procedures with 6 NM Final and +/- 0.30 NM Bias

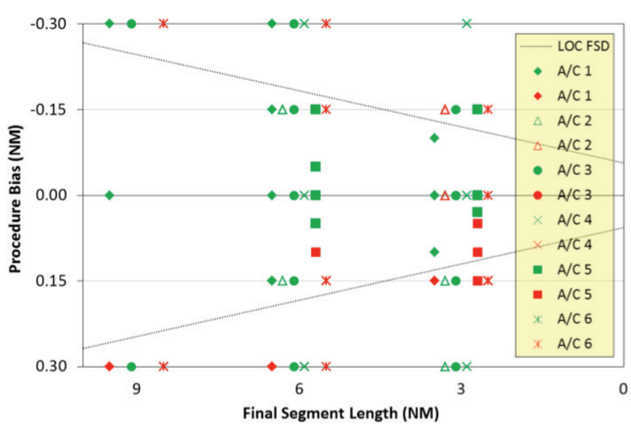

Figure 9. Automatic LNAV to LOC Transition (green) or No Automatic Transition (red) Versus Lateral Bias and Final Length

Vertical Intercept Capability

The vertical profiles in Figures 4, 5 and 6 are more complicated to analyze. If the scenarios in Figure 4 for which the aircraft had trouble intercepting the localizer are ignored, it can be seen that the vertical profiles of the remaining scenarios are quite consistent. They transition from a 2 degree vertical angle along the RNP procedure to a 3 degree angle when the glideslope is intercepted. This is also the case for nearly all scenarios flown with A/C 3, as indicated in Figure 6. Some clear deviations (drift above glideslope) can be observed in the vertical profiles of A/C 2 in Figure 5, which are due to pilot error while engaging VNAV. Apart from that it can be seen that at 6 NM, the vertical profiles intercept the glideslope from a 2 degree descent angle whereas at 3 NM they contain a short level-off before intercepting the glideslope. The reason for this is currently unknown. However, in general it was found that vertical navigation (as well as speed management) in the intermediate approach flight phase still requires a lot of manual input from the pilot.

Glideslope capture only occurred after or simultaneously with the localizer capture. In all six aircraft types LOC and G/S modes could activate simultaneously depending on the relative position of the aircraft to the localizer and glideslope. Capture of the glideslope usually only occurred if the aircraft's vertical position was relatively close to the glideslope centerline (deviation within half a dot) or depending on the aircraft type, when the vertical path was converging at a sufficient rate towards the glideslope centerline.

To get a better idea about the vertical capture performance and the interaction between lateral and vertical capture, the columns H to LOC and H to G/S in the Scenario Table in the Appendix are color coded. The two columns are shaded in green if they both contain values above -50 feet and if the difference between the values of both columns is less than 50 feet. This is the case when both localizer and glideslope captures occur within an altitude difference of 50ft and at not more than 50ft below the localizer/glideslope capture altitude defined in the procedure. The condition was found to be true for 70 out of the 120 scenarios listed in the table. The H to LOC as well as the H to G/S columns are shaded in red whenever they contain a value less than -50 feet. This is the case when the capture occurred more than 50 feet below the procedure defined altitude. For the localizer capture, 24 of such cases could be found. In 18 of those 24 cases, the table indicates that there were capture problems. The remaining 6 cases are for scenarios with an intercept leg, which surprisingly seemed to make the capture more challenging. For the scenarios without intercept leg, when no capture problems were observed, localizer capture was always above the procedure defined altitude. The H to G/S column is shaded in red for 34 scenarios. Out of these 34 cases, 19 scenarios experienced lateral capture problems, while 7 of the 34 scenarios contained an intercept leg. The remaining 8 scenarios without intercept leg, in which the G/S was captured 50 feet or more below the procedure defined altitude, are cases in which the aircraft drifted above the glideslope before or during localizer capture. In these cases the pilot had to take corrective action, engaging a vertical speed mode, to capture the glideslope from above.

Stabilized Approach

Airline procedures require the aircraft to be stabilized above a given height, most commonly 1000ft above ground in instrument flight conditions. Otherwise, the approach should be discontinued and a go around initiated. Therefore it is interesting to investigate, for the various scenarios and final approach segment lengths, how long it took after localizer and glideslope capture for the aircraft to meet a stable condition. The Column labeled H to Stab (Height to Stabilize) in the Scenario Table in the Appendix indicates the altitude difference in feet between the altitude at which the aircraft was stable and the localizer/glideslope intercept altitude defined the procedure. The conditions to determine whether the aircraft was stable for the H to Stab parameter were defined as both LOC and G/S modes engaged and deviations within one dot, aircraft track converging to its final state and within 5 degrees of the LOC course, no excessive rate of descent and speed corresponding to the distance to threshold and aircraft configuration.

Figure 10 indicates the height to stabilize versus the lateral navigation bias. Red (resp. blue and green) dots represent the procedure with a 3 NM (resp. 6 and 9 NM) final segment. For some of the tests, the aircraft did not capture the localizer or the capture was considered as not operationally acceptable. These runs are circled. Note that the lateral navigation bias in Figure 10 is expressed as the corresponding angular bias from the localizer centerline (in units of 1 LOC FSD) at the procedure defined localizer/glideslope capture point. In the configuration used in the tests, one full scale deviation bias means a 0.12 NM lateral bias for a 3 NM final procedure whereas it means a 0.18 NM lateral bias for a 6 NM final procedure. Figure 10 indicates that the length of the final segment does not really impact the height to stabilize or the localizer capture behavior of the aircraft. For each final segment length, there were 3 cases for which localizer capture was absent or not satisfactory. The mean and 95% values are indicated for different lateral navigation bias intervals, being respectively [-3,-1], [-1,1] and [1,3] FSD. To compute these values, the circled points indicating capture problems have been disregarded. Figure 10 also indicates that the 95% boundary of the height to stabilize increases with the lateral navigation bias. When the bias is negative, the path is offset towards the north and so the aircraft will cross the localizer centerline before the end of the RF turn and can initiate the capture from a higher altitude. In the opposite case, when the bias is positive, the offset is towards the south and the aircraft will terminate the RF turn without crossing the localizer centerline. This causes the aircraft to converge to the localizer at a lower altitude.

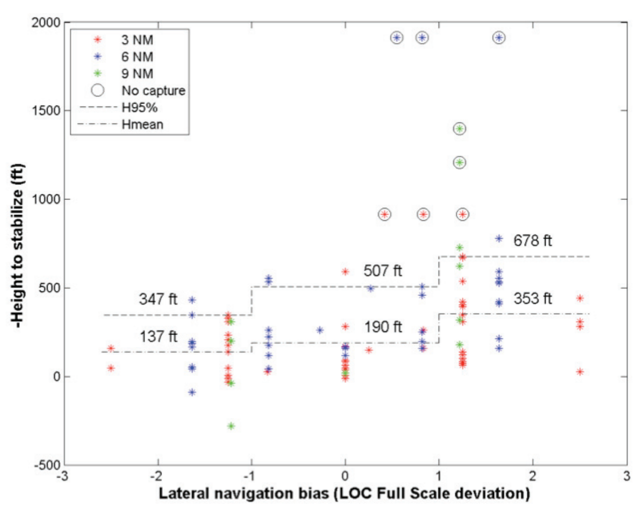

Figure 10. Height to Stabilize Versus Lateral Bias and Final Length (3, 6, 9 NM)

Figure 11 indicates the height to stabilize versus the aircraft type, for the 3 different categories of lateral biases. The green plots (resp. blue and red) represent the bias lower than -1 FSD (resp. between -1 and 1 FSD and higher than 1 FSD). Again, the scenarios for which the capture was not operationally acceptable are circled. The mean and 95% boundary of the height to stabilize have been computed for each aircraft type, disregarding the circled points. Figure 11 indicates that the height needed by the aircraft to stabilize varied significantly between different aircraft.

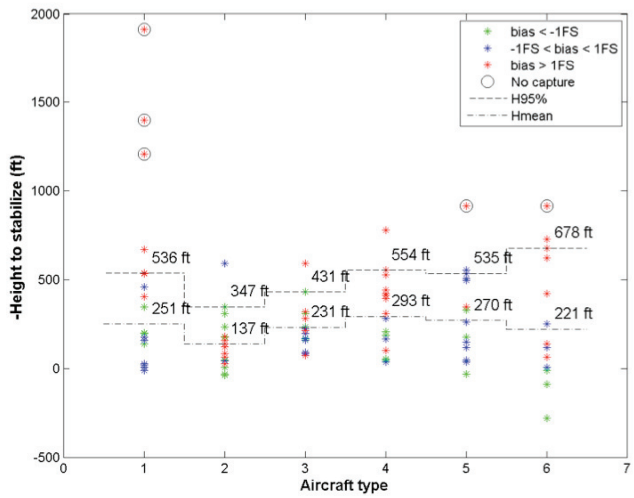

Figure 11. Height to Stabilize Versus Lateral Bias and Aircraft Number

Finally, Figure 12 represents the cumulative distribution of height to stabilize for all aircraft types and final segment lengths and depending on the 3 categories of biases: bias < 1 FSD, - 1 FSD < bias < 1 FSD and bias > 1 FSD. When only considering the cases in which the RNP path ended within +/- 1 FSD of the localizer, in 95% of the cases the height to stabilize was below 507 feet, independently of the length of the final segment.

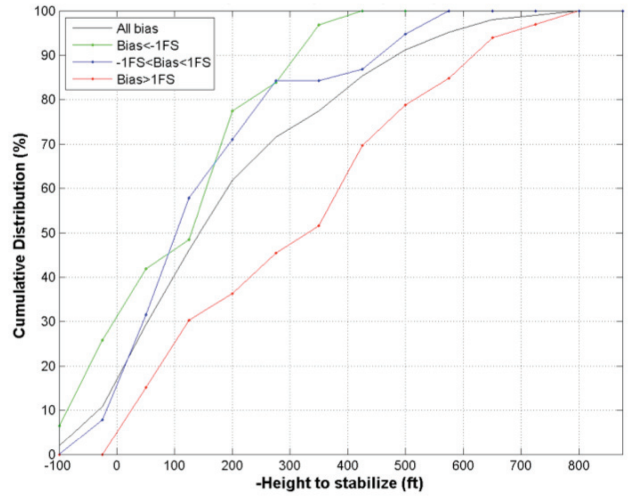

Figure 12. Cumulative Distribution of Height to Stabilize in Function of Lateral Bias

Influence of Intercept Leg

Initially it was expected that the procedures with an intercept leg (MUNIxB to MUNIxG) would facilitate the intercept because of the fact that the aircraft could capture the localizer in a more conventional way, from a defined intercept angle. In addition it was considered that for aircraft that could not transition from LNAV to LOC mode directly, an intercept leg would allow the crew more time to engage heading mode after which the approach mode could be armed. When analyzing the data though, it was found that the intercept leg did not always create a more favorable situation for the aircraft to capture the localizer. Figure 13 illustrates the horizontal tracks of A/C 1 and A/C 3 intercepting the localizer at 6 NM from the threshold after flying a MUNI3F procedure containing an intercept leg with intercept angle of 30 degrees and with +/- 0.30 NM lateral navigation biases. If Figure 13 is compared with Figure 8, it can be seen that the aircraft intercepts the localizer at a position further beyond the procedure defined intercept point IF006. Theoretically this can be explained as follows: if a procedure intercepts a localizer at an angle α, a lateral bias y perpendicular to the localizer will cause the biased procedure to cross the localizer at a distance equal to y / tan(α) beyond the intercept point of the non-biased procedure. In Figure 13, A/C 3 intercepts the localizer even further beyond IF006 in case of a 0.30 NM bias because the crew did not engage heading mode. This caused the aircraft to automatically select a 20 degree intercept track to the localizer instead of remaining on the intercept leg of the procedure. A similar situation was observed for aircraft types in which the crew selected a heading equal to the track of the intercept leg, after which the crosswind pushed the aircraft to the right of this track.

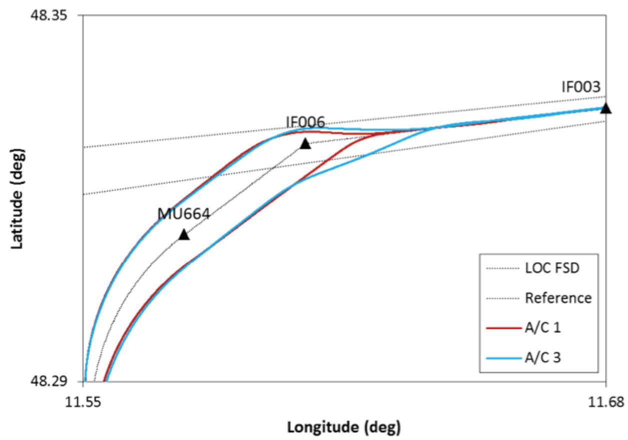

Figure 13. Close-up of Tracks near Transition for Procedures with 6 NM Final, Intercept Leg and +/- 0.30 NM Bias

Figure 14 represents the height to stabilize versus the lateral navigation bias for two different cases: the red plots represent the procedures with an intercept leg while the blue plots represent the procedures without intercept leg. Again, the scenarios for which the capture was not operationally acceptable are circled. The procedures with intercept leg contained fewer cases without localizer capture, because the crew most often engaged heading mode while on the intercept leg. However, Figure 14 does not show a height to stabilize reduction for the procedures using and intercept leg.

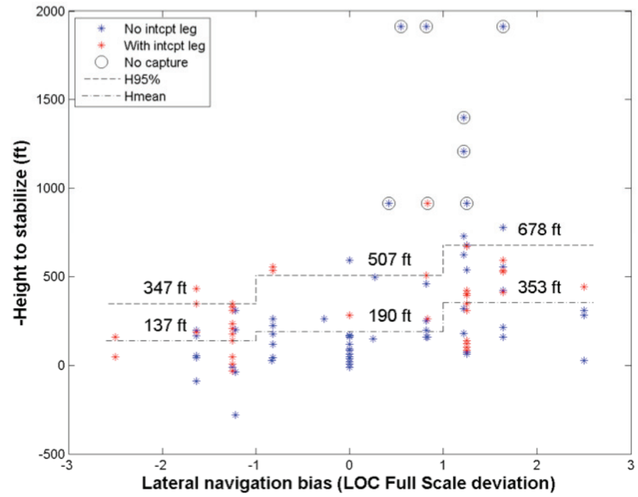

Figure 14. Height to Stabilize Versus Lateral Bias and Existence of Intercept Leg

Obstacle Assessment

Obstacle assessment criteria for the precision approach segment are defined in [7]. The precision segment starts at the Final Approach Point (FAP), that is, the intersection of the nominal glide path and the minimum altitude specified for the preceding segment. In our procedures this would be the localizer/glideslope intercept point IF00x (with x either 3, 6 or 9). Basic ILS surfaces as well as more stringent Obstacle Assessment Surfaces (OAS) are defined for obstacle assessment. The basic ILS surfaces consist in the approach area of a vertical slope of 2% (transitioning into 2.5% when more than 3060m before the threshold) with a lateral splay of 15% starting near the runway threshold. The OAS surfaces consist in the approach area of a vertical slope (called the "W" slope) with a nominal 2.85% gradient. In addition they consist of 2 lateral slopes on either side of the localizer centerline (called "X" slopes). The "X" slopes are such that at 3 NM before the threshold and at 1000ft, the nearest obstacle could be at a lateral distance of 920m (0.5 NM) from the localizer centerline. A detailed comparison of the recorded data versus the obstacle surfaces has not been performed. However, if the scenarios with capture problems are ignored and considering the criteria briefly summarized above, it can be expected that the splay of horizontal tracks and vertical profiles in Figures 4, 5 and 6 are well within the obstacle protection areas.

Conclusions and recommendations

Tests have been performed investigating the behavior of 6 different aircraft types when performing a transition from a curved RNP procedure to an xLS final approach. Basic procedures were coded in ARINC 424 format whereby a Radius-To-Fix (RF) leg connected directly to the localizer/glideslope intercept point of a 3, 6 or 9 NM final segment. A set of alternative procedures were designed as well, which contained a short intercept leg with a defined intercept angle between the end of the RF and the final segment. To test the influence of navigation position errors on the xLS transition, lateral biases with various magnitudes up to 0.3 NM and in either northern or southern direction were introduced in the procedures (with the final approach course aligned to the east). The procedures were flown using RF capable, certified, full motion flight crew training simulators.

Significant differences were observed in the intercept capability of the localizer. In a category of aircraft it is not possible to transition from LNAV to LOC mode directly. An intermediate step is required whereby the crew needs to engage heading near the end of the RF leg, before arming the approach mode. In other aircraft types, the aircraft position along the RNP procedure (including the simulated biases) needed to end within the Full Scale Deviation or for some aircraft even closer to the localizer centerline, to be able to capture the localizer. A third set of aircraft performed an automatic track correction at the end of the RF leg when the RNP path did not sufficiently converge to the localizer. Expect for the captures at 3 NM, in general, procedures with simulated navigation errors causing the RNP path to undershoot the localizer caused more difficulty than procedures overshooting the localizer. This is because when overshooting the localizer, the aircraft started the correction (by increasing the bank angle) earlier and at a higher altitude than when undershooting.

In most of the scenarios, the aircraft transitioned well from a defined 2 degree barometric slope along the RNP path to the 3 degree glideslope. In some situations, some aircraft performed a short level-off just before the glideslope intercept. All aircraft types were able to perform a simultaneous localizer and glideslope capture. A simultaneous capture occurred in 70 out of the 120 scenarios. In some situations, especially for the procedures with a high positive bias undershooting the localizer, corrective action was required by the crew to intercept the glideslope. This consisted of engaging a vertical speed mode and initiating the descent below the capture altitude as soon as the localizer was alive and sometimes capturing the glideslope slightly from above.

The altitude difference between the observed altitude at which the aircraft was in a stable approach condition and the localizer/glideslope capture altitude as defined in the procedure, was determined for each scenario. This parameter was called “height to stabilize”. It was found that if scenarios with capture problems were excluded, 95% of the scenarios required a height to stabilize of less than 507 feet. Scenarios in which the glideslope was captured slightly from above are included in this result. The height to stabilize of 507 feet is required to allow localizer and glideslope indications to become within half a dot of deviation and the aircraft track to become fully aligned with the runway centerline. This demonstrates that a final length of 3NM is too short for an RNP to xLS transition to be operationally acceptable. Airline procedures require commonly that the aircraft is stable at 1000ft above ground. Considering a height to stabilize of 507 feet, this would mean that the capture point of the localizer/glideslope has to be at least at 1500ft, which corresponds to about 5 NM from the threshold.

The procedures with intercept leg did not provide noticeable benefits in the ability for the aircraft and flight crew to capture the localizer. On the contrary, they made the situation worse for the procedures with a lateral bias undershooting the localizer. The lateral bias combined with the fixed intercept angle, crosswind and aircraft capture behavior resulted in localizer captures further beyond the procedure defined capture point in a majority of cases. Due to the absence of a 2 NM straight intermediate segment, this caused more problems to capture the glideslope than for the procedures without intercept leg.

In summary, a procedure with a simultaneous capture of localizer and glideslope from an RF leg, at a minimum distance of 5 NM to the threshold seemed to work well. A formula was proposed which calculates the lateral distance to the localizer centerline at which localizer deviation is full scale, in function of distance to threshold. It is highly recommended that the RNP path, taking into account possible navigation errors, terminates within this lateral distance. In the configuration used for the tests, this lateral distance would be 0.16 NM for a 5 NM final procedure. In case of a 12 NM final procedure, the lateral distance would be 0.31 NM. Within this lateral distance, localizer deviation will be in view to the pilots who can then ensure the aircraft establishes well on the glideslope. Note that 0.16 NM and 0.31 NM would approximate half, respectively the whole allowed Total System Error (TSE) of an RNP 0.3 procedure. It could be argued that with modern avionics, actual TSE is most often relatively low, which could justify a capture at 5NM with a maximum allowed TSE of 0.16 NM.

Under the conditions above, the tests indicate that localizer/glideslope captures from an RF leg can be performed without the need of a 2 NM intermediate segment. One requirement though is that for certain aircraft types the crew needs to select heading mode near the end of the RF leg, before arming the approach mode. Otherwise the aircraft might not capture the localizer.

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Disclaimer

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Appendix: Scenario Table

A/C	SCN	Airport	STAR	Wind	Final	Leg	Dist	Bias	Intercept	H to LOC	H to G/S	H to Stab	Comment
A/C 1	RF2	EDZA	6A	0/0	6			0	yes	240	240	-157	
	RF3	EDZH	6A	352/25	6			0.15	yes	-10	-10	-460	
	RF4	EDZI	6A	172/25	6			-0.15	yes	300	300	-176	
	RF5	EDZJ	6A	352/25	6			0.3	no	-1914	-1914	-1914	no intercept
	RF6	EDZJ	6A	352/25	6			0.3	no	-600	-1150	-1914	no intercept, engaged HDG to intercept
	RF7	EDZK	6A	172/25	6			-0.3	yes	340	340	-195	
	RF8	EDZA	3A	0/0	3			0	yes	160	140	-7	
	RF9	EDZF	3A	0/0	3			0.1	yes	70	20	-158	
	RF10	EDZH	3A	352/25	3			0.15	no	10	10	-536	very slow loc convergence
	RF11	EDZH	3F	352/25	3	30	1.5	0.15	no	-90	-90	-668	very slow loc convergence
	RF12	EDZH	3F	352/25	3	30	1.5	0.15	yes	-40	-40	-404	AP disconnected
	RF13	EDZG	3A	172/25	3			-0.1	yes	140	100	-26	
	RF15	EDZJ	6A	352/25	6			0.3	no	-600	-840	-1914	no intercept, engaged HDG, no data
	RF17	EDZA	9A	352/25	9			0	yes	170	170	-20	
	RF18	EDZJ	9A	352/25	9			0.3	no	210	-1010	-1208	very slow loc convergence, above G/S
	RF19	EDZJ	9A	352/25	9			0.3	no	10	10	-1397	very slow loc convergence
	RF20	EDZK	9A	172/25	9			-0.3	yes	400	30	-200	
	RF21	EDZJ	6F	352/25	6	30	1.5	0.3	yes	-10	-480	-535	HDG selected
	RF22	EDZK	6F	172/25	6	30	1.5	-0.3	yes	220	220	-346	HDG selected
	RF23	EDZI	3F	172/25	3	30	1.5	-0.15	yes	140	120	-139	HDG selected
	RF24	EDZA	3A	0/0	3			0	yes	N/A	N/A	N/A	cockpit video for presentation
	RF25	EDZA	3A	0/0	3			0	yes	N/A	N/A	N/A	cockpit video for presentation
A/C 2	RF1	EDZA	3A	0/0	3			0	yes	280	280	-158	
	RF2	EDZH	3A	352/25	3			0.15	yes	0	0	-64	
	RF3	EDZA	3A	0/0	3			0	yes	150	0	-64	
	RF4	EDZI	3A	172/25	3			-0.15	yes	260	-20	-347	
	RF5	EDZI	3A	172/25	3			-0.15	yes	200	-20	-177	
	RF7	EDZI	3B	172/25	3	20	1	-0.15	yes	200	200	-234	
	RF9	EDZI	3G	172/25	3	30	2	-0.15	yes	40	40	31	
	RF10	EDZI	3B	172/25	3	20	1	-0.15	yes	200	200	-7	
	RF11	EDZI	3C	172/25	3	20	1.5	-0.15	yes	0	0	-45	
	RF12	EDZH	3C	352/25	3	20	1.5	0.15	yes	0	0	-139	
	RF13	EDZJ	9A	352/25	9			0.3	yes	40	40	-180	
	RF14	EDZK	9A	172/25	9			-0.3	yes	360	360	40	
	RF15	EDZA	3A	0/0	3			0	yes	440	-440	-593	VNAV engaged too late, above G/S
	RF16	EDZH	3E	352/25	3	30	1	0.15	yes	20	20	-121	
	RF18	EDZI	3E	172/25	3	30	1	-0.15	yes	140	140	-309	
	RF19	EDZH	3F	352/25	3	30	1.5	0.15	yes	-40	-40	-83	
	RF20	EDZI	3F	172/25	3	30	1.5	-0.15	yes	140	140	-347	
	RF21	EDZI	3G	172/25	3	30	2	-0.15	yes	20	20	-7	
	RF22	EDZH	6A	352/25	6			0.15	yes	80	80	-157	
	RF23	EDZI	6A	172/25	6			-0.15	yes	260	260	-44	
	RF24	EDZI	6A	172/25	6			-0.15	yes	220	220	-44	
	RF25	EDZJ	6A	352/25	6			0.3	yes	-20	-20	-157	
	RF26	EDZK	6A	172/25	6			-0.3	yes	380	380	-44	
	RF27	EDZJ	3A	352/25	3			0.3	yes	-20	-20	-26	
	RF28	EDZK	3G	172/25	3	30	2	-0.3	yes	180	-40	-158	
A/C 3	RF1	EDZA	3A	0/0	3			0	yes	150	150	-92	
	RF2	EDZA	3A	0/0	3			0	yes	-10	-10	-83	
	RF3	EDZH	3A	352/25	3			0.15	yes	80	20	-73	
	RF4	EDZJ	3A	352/25	3			0.3	yes	-50	-200	-281	
	RF5	EDZI	3A	172/25	3			-0.15	yes	N/A	N/A	N/A	no video available
	RF6	EDZH	3F	352/25	3	30	1.5	0.15	yes	N/A	N/A	N/A	no video available
	RF7	EDZI	3F	172/25	3	30	1.5	-0.15	yes	110	110	-234	
	RF8	EDZA	6A	0/0	6			0	yes	200	200	-157	
	RF9	EDZJ	6A	352/25	6			0.3	yes	20	-840	-214	above G/S (< 1 dot)
	RF10	EDZK	6A	172/25	6			-0.3	yes	340	340	-167	
	RF11	EDZH	6A	352/25	6			0.15	yes	140	-740	-195	above G/S (< 1 dot)
	RF12	EDZI	6A	172/25	6			-0.15	yes	250	250	-224	
	RF13	EDZJ	6F	352/25	6	30	1.5	0.3	yes	-100	-560	-592	above G/S

	RF14	EDZK	6F	172/25	6	30	1.5	-0.3	yes	200	200	-431	
	RF15	EDZJ	9A	352/25	9			0.3	yes	10	10	-320	
	RF16	EDZK	9A	172/25	9			-0.3	yes	400	400	-310	
	RF17	EDZA	6A	0/0	6			0	yes	160	160	-157	cockpit video for presentation
	RF18	EDZA	3A	0/0	3			0	yes	80	20	-168	cockpit video for presentation
A/C 4	RF1	EDZA	6A	0/0	6			0	yes	40	20	-167	
	RF2	EDZJ	6A	352/25	6			0.3	yes	200	-700	-781	above G/S
	RF3	EDZJ	6A	352/25	6			0.3	yes	0	-420	-554	above G/S
	RF4	EDZK	6A	172/25	6			-0.3	yes	450	340	-54	
	RF5	EDZJ	6F	352/25	6	30	1.5	0.3	yes	-80	-80	-412	
	RF6	EDZK	6F	172/25	6	30	1.5	-0.3	yes	260	260	-186	
	RF8	EDZJ	6F	352/25	6	30	1.5	0.3	yes	-180	-380	-526	
	RF10	EDZJ	3A	352/25	3			0.3	yes	0	-250	-309	above G/S
	RF11	EDZK	3A	172/25	3			-0.3	yes	320	320	-45	
	RF12	EDZK	3F	172/25	3	30	1.5	-0.3	yes	220	220	-45	
	RF13	EDZJ	3F	352/25	3	30	1.5	0.3	yes	-130	-220	-442	above G/S
	RF16	EDZH	3F	352/25	3	30	1.5	0.15	yes	-60	-60	-309	
	RF17	EDZH	3F	352/25	3	30	1.5	0.15	yes	0	0	-423	
	RF18	EDZH	3F	352/25	3	30	1.5	0.15	yes	0	0	-102	
	RF19	EDZH	3F	352/25	3	30	1.5	0.15	yes	0	0	-394	
	RF20	EDZI	3F	172/25	3	30	1.5	-0.15	yes	230	180	-206	
	RF21	EDZA	3F	0/0	3	30	1.5	0	yes	60	60	-281	
	RF22	EDZA	3A	0/0	3			0	yes	180	180	-36	cockpit video for presentation
	RF23	EDZA	3A	0/0	3			0	yes	N/A	N/A	N/A	cockpit video for presentation
	RF24	EDZA	3A	0/0	3			0	yes	N/A	N/A	N/A	cockpit video for presentation
A/C 5	RF1	EDZH	3A	352/25	3			0.15	no	-914	-914	-914	no intercept
	RF2	EDZF	3A	352/25	3			0.1	no	-914	-914	-914	no intercept
	RF3	EDZD	3A	352/25	3			0.05	no	-914	-914	-914	no intercept
	RF4	EDZB	3A	352/25	3			0.03	yes	-80	-80	-149	intercept when loc < 1 dot
	RF5	EDZD	3A	352/25	3			0.05	no	-914	-914	-914	no intercept
	RF6	EDZF	3E	352/25	3	30	1	0.1	no	-914	-914	-914	no intercept, aircraft kept in LNAV
	RF9	EDZH	3F	352/25	3	30	1.5	0.15	yes	-200	-200	-347	
	RF10	EDZF	3E	352/25	3	30	1	0.1	yes	-50	-50	-262	
	RF11	EDZF	6A	352/25	6			0.1	no	-1914	-1914	-1914	no intercept
	RF12	EDZD	6A	352/25	6			0.05	yes	-170	-170	-497	intercept when loc < 1 dot
	RF13	EDZH	6F	352/25	6	30	1.5	0.15	yes	-40	-40	-507	
	RF15	EDZI	6F	172/25	6	30	1.5	-0.15	yes	100	100	-535	
	RF16	EDZI	6G	172/25	6	30	2	-0.15	yes	120	120	-554	
	RF17	EDZE	6A	172/25	6			-0.05	yes	200	200	-261	
	RF18	EDZI	6A	172/25	6			-0.15	yes	230	230	-261	
	RF19	EDZI	3F	172/25	3	30	1.5	-0.15	yes	140	140	-328	
	RF20	EDZI	3F	0/0	3	30	1.5	-0.15	yes	110	110	-177	
	RF21	EDZA	6A	0/0	6			0	yes	20	20	-120	cockpit video for presentation
	RF22	EDZA	3A	0/0	3			0	yes	100	20	-45	cockpit video for presentation
	RF23	EDZA	3A	0/0	3			0	yes	80	30	-36	cockpit video for presentation
	RF24	EDZI	3A	172/25	3			-0.15	yes	300	300	31	
A/C 6	RF1-4	EDZA	3A	0/0	3			0	no	80	80	-7	
	RF7-2	EDZH	3A	352/25	3			0.15	no	-914	-914	-914	no intercept, aircraft kept in LNAV
	RF7-3	EDZH	3A	352/25	3			0.15	no	100	-180	-678	above G/S
	RF7-4	EDZH	3A	352/25	3			0.15	no	50	-40	-139	
	RF7-5	EDZH	3A	352/25	3			0.15	no	0	0	-64	
	RF8-1	EDZH	6A	352/25	6			0.15	no	-80	-80	-252	intercept when loc < 1 dot
	RF8-2	EDZH	6A	352/25	6			0.15	no	-1914	-1914	-1914	no intercept, aircraft kept in LNAV
	RF9-3	EDZI	3A	172/25	3			-0.15	no	260	260	12	
	RF10	EDZI	6A	172/25	6			-0.15	no	250	250	-120	
	RF13	EDZJ	6A	352/25	6			0.3	no	-300	-300	-422	intercept when loc < 1 dot
	RF14-1	EDZJ	9A	352/25	9			0.3	no	-400	-400	-727	intercept when loc < 1 dot
	RF14-2	EDZJ	9A	352/25	9			0.3	no	-400	-400	-623	intercept when loc < 1 dot
	RF15	EDZK	6A	172/25	6			-0.3	no	340	340	88	
	RF16	EDZK	9A	172/25	9			-0.3	no	520	520	280	