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INFORMATION PAPER

INSTRUMENT FLIGHT PROCEDURE PANEL

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Agenda Item X:
X.X:

Practical example of the benefits of an RNP-AR to LPV merge in mountainous areas

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SUMMARY

IFPP/15 WP1a-013 *Proposed evolution of RNP-AR concepts* reported first attempts to integrate an RNP AR approach with an LPV final segment. This paper presents a further attempt to merge an RNP AR approach with an LPV in a challenging environment and describes in some detail the results and the methodology used during the design process and the simulator assessment. Lastly, a number of changes needed to enable future implementations are suggested.

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1. INTRODUCTION

1.1 The rationale for the inclusion of FAS-DB-guided final approaches (SBAS or GBAS) into the RNP AR concept of operations was initially discussed in IFPP/15 WP1a-013, the main driver being the need for more robust and stable vertical navigation within the final segment. Whereas the vertical guidance of RNP AR approaches is still based on the barometric altimeter and thus, subject to its inherent error, local and wide area augmentation systems provide GNSS-based geometric altitude inputs to define the vertical path. Considering the better vertical performance of these systems, less constraining design criteria can be used leading to a lower OCH and to a system minimum of 200 ft above runway threshold if the corresponding service level is available. It seems therefore reasonable to think that combining the best of the two navigation technologies is the logical way forward to enable 3D instrument approach operations type B (a.k.a. precision approach operations) in demanding environments.

1.2 This integration can be particularly interesting for runway ends with difficult access due to challenging topography. The narrower protection areas of the RNP AR navigation specification can facilitate the access to the vicinity of the aerodrome and the connection to a GNSS-based ILS-like final approach. In case of a missed approach, the mode of navigation can likewise be reverted to RNP AR to guarantee a safe extraction in a complex terrain environment. This could increase the availability of many aerodromes with existing RNP AR approaches even in poorer visibility conditions than currently possible.

1.3 Salzburg Airport (LOWS) in Austria is one of those aerodromes with existing RNP AR approaches to runway 33 to counteract the effect of extensive alpine terrain in the surroundings. One of these procedures (RNP Z RWY 33 [AR]) facilitates an approach coming from the south following a valley, which is bordered on both sides by high mountains, and leads onto the final approach course in a double bend that consists of several curved legs (see Figure 1). The straight segment of the final is 1.5 NM long and like the initial and intermediate segment requires an RNP value of 0.3 to produce an OCH of 369 ft above runway threshold. This OCH can currently enable 3D approach operations type A with equal or higher DH. An additional minima line for RNP 0.1 was considered prior to the first publication but finally rejected due to the negligible reduction of the OCH and the lack of certified operators.

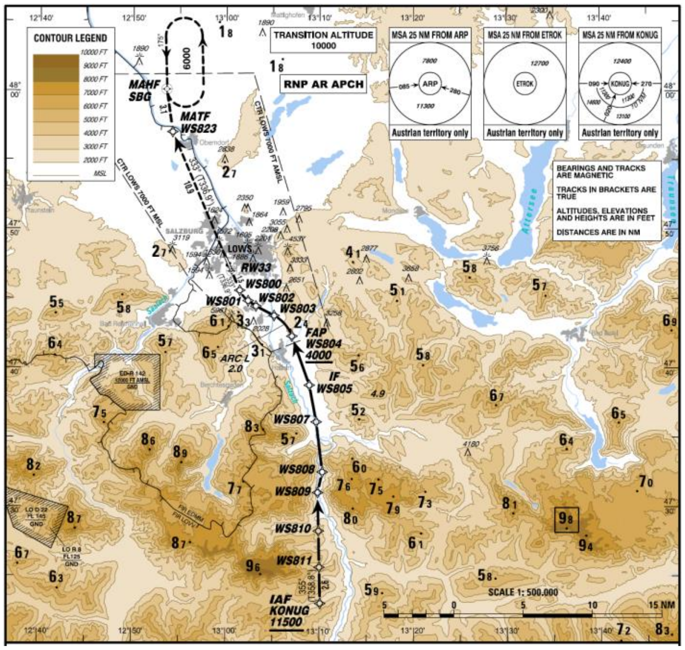

Figure 1. Current RNP Z RWY 33 [AR] in Salzburg, Austria.

1.4 The idea to replace the straight part of the final approach with a straight LPV segment while keeping the changes to the published RNP Z RWY 33 [AR] to a minimum came up during a joint research effort by the authors and led to the development of a Master thesis by Mr Richard Unkelbach. Much of the material presented here and further details can be found in the thesis *Design and Testing of RNP AR to SBAS LPV approaches into Salzburg Airport*, which was submitted to the Technical University of Berlin in 2022.

2. PROCEDURE CONSTRUCTION

2.1 For practical reasons we decide to design this test approach procedure for CAT D aircraft or lower. Specific minima lines for the other aircraft categories can be calculated through the same design process and only certain aircraft parameters such us maximum speeds, aircraft dimensions and height loss need to be adjusted. We also decide to design an SBAS CAT-I precision segment because of the better system minimum and availability of the service in Salzburg.

2.2 The straight final approach needs to be extended slightly compared to the existing RNP AR. We anyway opt for a short straight final below 3 NM because of terrain limitations. A GPA of 3.5º is required for the same reason.

2.3 The RF leg to the final approach course is not ending at the FAP but at the FACF to allow for sufficient capture distance between the lateral and vertical interception of the FAS guidance after switching from barometric to geometric vertical navigation. We apply here the new set of criteria introduced in Doc 8168 Vol II with Amendment 9. The distance of the capture segment, between FACF and FAP, is calculated for a given approach geometry and ISA temperature deviation as per Appendix D to Chapter I to avoid the interception of the LPV GS from above on hot days. A nearby massif (1973 m) south of the aerodrome significantly limits the length of the segment and therefore the maximum temperature deviation to ISA that can be accepted. Following an iterative calculation process and considering all the limitations we obtain a flat capture segment of only 0,27 NM length preceding a 2,25 NM short straight final with a FAP altitude of 2300 ft AMSL (889 ft above threshold elevation). For the maximum temperature deviation, we choose 25° C above ISA (ISA+25), which corresponds to about 37.2° C at aerodrome elevation. This value lies in the upper range of local heat records measured in recent decades. Under these conditions, the root sum square of the altimeter system and temperature-related height errors yields a total vertical navigation error for the LPV approach of roughly 100 ft. This error would cause the aircraft to intercept the GS right upon reaching the FACF after the last turn without considering any flight technical error.

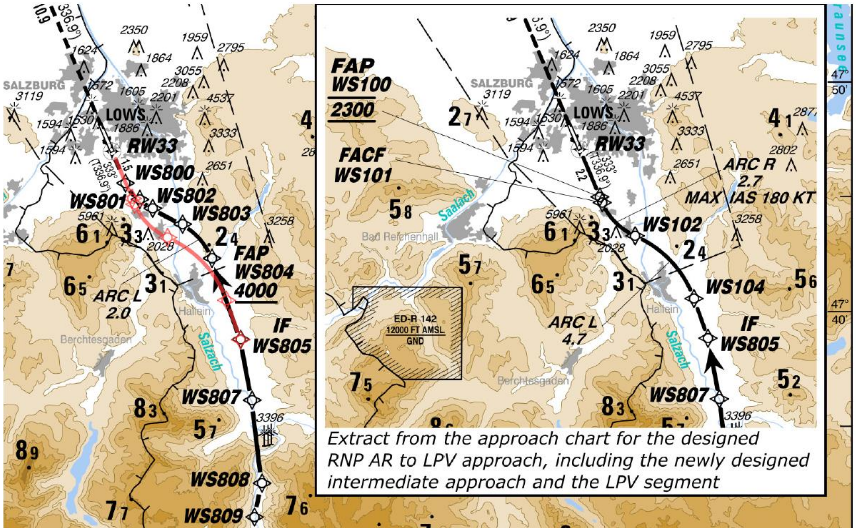

Figure 2. The new RNP AR to LPV approach is shown in the inset. The differences in the nominal track compared with the existing RNP AR approach are highlighted in red next to the inset.

2.4 Following the same design concept as the existing RNP AR approach, the connection between the current intermediate segment and the new final plus capture segment can be done through another double bend with two consecutive RF legs. We design this new connection with no deviations from standard RNP AR criteria and with minimum lateral and vertical changes to the existing procedure. The result is shown in Figure 2. The missed approach segment remains unmodified with its minimum 2.5 % climb gradient required.

3. PROTECTION AREAS AND OBSTACLE ASSESSMENT

3.1 The existing RNP AR approach requires RNP 0.3 in all approach segments. However, due to the proximity of the terrain in the intermediate and the final approach, we need more demanding containment requirements, and we select RNP 0.1 for these segments.

3.2 Even though the criterium to establish mountainous areas in Austria deviates from the one promulgated in PANS-OPS as of today, we decide to double the MOC for all segments except for the final and for the last RF leg of the intermediate leading to the FACF. During the RF turn to the final approach course the aircraft will already be flying at very low heights due to the shorter final approach segment. At these heights no atmospheric phenomena are expected to degrade the performance of the barometric altimeter beyond the standard tolerances.

3.3 For the blending of the RF leg protection areas based on RNP AR with the OAS system of the CAT I segment we apply the rules promulgated in 1.3.6.4 from Doc 8168 Vol II (p. II-1-1-7) with some adjustments and some considerations in mind. The rules dictate the CAT I segment to be bounded by the E”-D” line and the extension of the D-D” line before the point D”, there are no secondary areas. Since RNP AR does not use secondary areas either, we only consider merging with respect to the primary areas of the RF leg. The merging rules are different for the inside and the outside of the RF leg. The decisive factor in both cases is whether the respective primary area boundary before the FACF intersects with the respective extension of the D-D” line. In our case (see Figure 3), this happens for the inside of the RF leg but not for the outside.

3.4 On the inside, the extension of the D-D” line becomes the boundary of the primary area from the point of intersection, with the intermediate approach MOC having to be applied between the extended D-D” line and the D”-C” line (see Figure 3). Consequently, the protection areas are extended towards the inside of the turn.

3.5 For the outside of the RF leg, the primary area boundary must be extended in a 15-degree splay relative to the final approach course until it intersects the extended D-D” line (see Figure 3). Outside the D”-C” line, the intermediate approach MOC must be applied. In our case, though, the very short FAS and the narrow RF leg protection areas cause the 15-degree splay to intersect the D-D”-line before it is extended, cutting off parts of the Y surface.

3.6 At this stage it could well be argued that the reduced total system error with which the aircraft arrives at the FACF (i.e. within the RNP 0.1 corridor marked in green in Figure 3) makes it very unlikely for the aircraft to immediately drift toward the outside of the turn when switching to LPV guidance since it would already be more or less located on the final approach course. Nevertheless, we prefer to keep the blending method with the 15-degree splay on the in- and outside of the turn to account for potential drifts off the nominal track.

3.7 SBAS CAT I OAS systems have the Y and the Z surface curtailed to a constant semi-width of 0.95 NM (except for CAT H). Moreover, if the X surface has a semi-width of less than 0.95 NM at the FAP, a primary area with 0.95 NM semi-width must be applied between the FAP and any point where the OAS system reaches the same semi-width, i.e. the system is first curtailed and then artificially widened towards the FAP. This requirement is related to RNP approaches having an underlying performance of RNP 0.3 for the final approach, which corresponds to an RNP APCH protection area semi-width of 0.95 NM using the RNP APCH buffer value of 0.5 NM for the FAS. Although angular performance requirements apply for LPV, the RNP value of 0.3 is still coded for the final approach. When a missed approach is initiated, the FMS remains in NPA mode, meaning that the performance is then based on the coded RNP value (0.3). Bearing in mind that we can code a lower RNP value to achieve higher underlying performance and considering that the approach per se is already RNP AR with the highest possible performance of RNP 0.1 from the intermediate segment, the aircraft must also have the corresponding RNP AR capability and be certified accordingly. Consequently, we can require RNP 0.1 for the final and missed approach segments, too. Following the logic outlined for a standard SBAS CAT I OAS system, the higher underlying performance should allow us to limit the Y and the Z surfaces to the corresponding RNP AR protection area semi-width of 0.2 NM, while the X surface would have to have a semi-width of at least 0.2 NM at the FAP (see Figure 3).

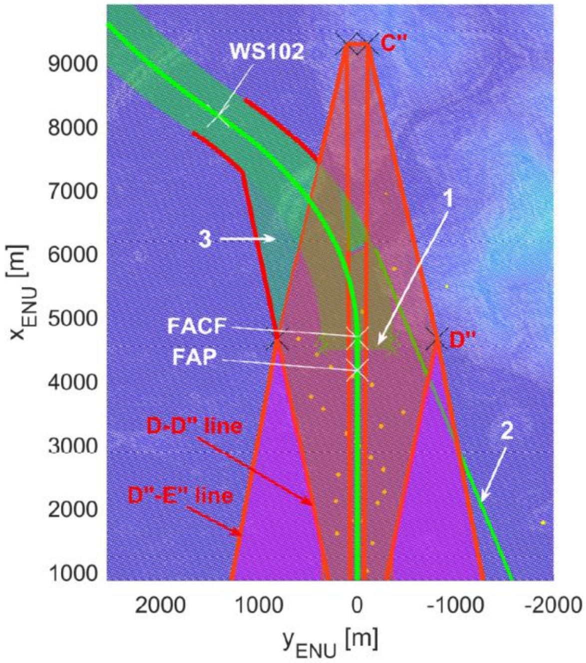

Figure 3. Blending of the intermediate segment with ILS CAT I OAS (no 0.95 NM corridor is considered). RNP 0.1 protection areas extended 1x ATT (0.1 NM) behind the FACF (1). Curtailing of the OAS on the outside of the turn (2). Extension of the primary protection on the inside of the turn (3)

3.8 The possibility of restricting the OAS system is a core advantage of the combination of RNP AR and LPV since one can now use the LPV surfaces, which take the better vertical performance into account, for the obstacle assessment without having to accept the significant OAS extension (excluding the X surface splay) compared to RNP AR. During the flight validation, however, it must be verified that the actual performance is RNP 0.1 and that the lateral deviations outside of LPV guidance are treated and presented to the pilots with respect to this requirement, as mandated by the RNP AR APCH specification. To guarantee RNP 0.1 performance, we can also think of an operational requirement for the pilot in command in addition to the coded RNP values: PANS-OPS foresees a transition to SBAS navigation least 2 NM before the FAF. In our case and as shown in Figure 3, however, this could lead to the aircraft cutting the remaining part of the turn after initiating the transition shortly after the initiation of the last RF leg, thereby leaving the RNP 0.1 corridor. We therefore require that the transition is not engaged until the remaining distance to the FACF equals 0.5 NM as shown on the navigation display (ND), which, including the ATT, should prevent the aircraft from leaving the RNP 0.1 corridor under LPV guidance with sufficient probability.

3.9 Once an appropriate shape for the OAS and the blending with the intermediate segment has been determined, the next step is the determination of the OCH following the standard process for 3D approach procedures and increasing the CAT D heigh loss margin (161 ft) in 24.15 ft owing to the GPA of 3.5º. The controlling obstacle for the whole procedure is an apron light pole 976 m behind and just 52 ft above the runway threshold, which results in an OCH of 218 ft. Compared to the existing RNP AR approach, that means a significant OCH reduction (-151 ft), which is achieved primarily because the control tower (located approximately 0.27 NM adjacent to the runway, 1336 m behind and 206 ft above the threshold) now falls out of the Y surface due to RNP 0.1. But even if it was covered by the OAS, the OCH would still drop to 306 ft (-63 ft).

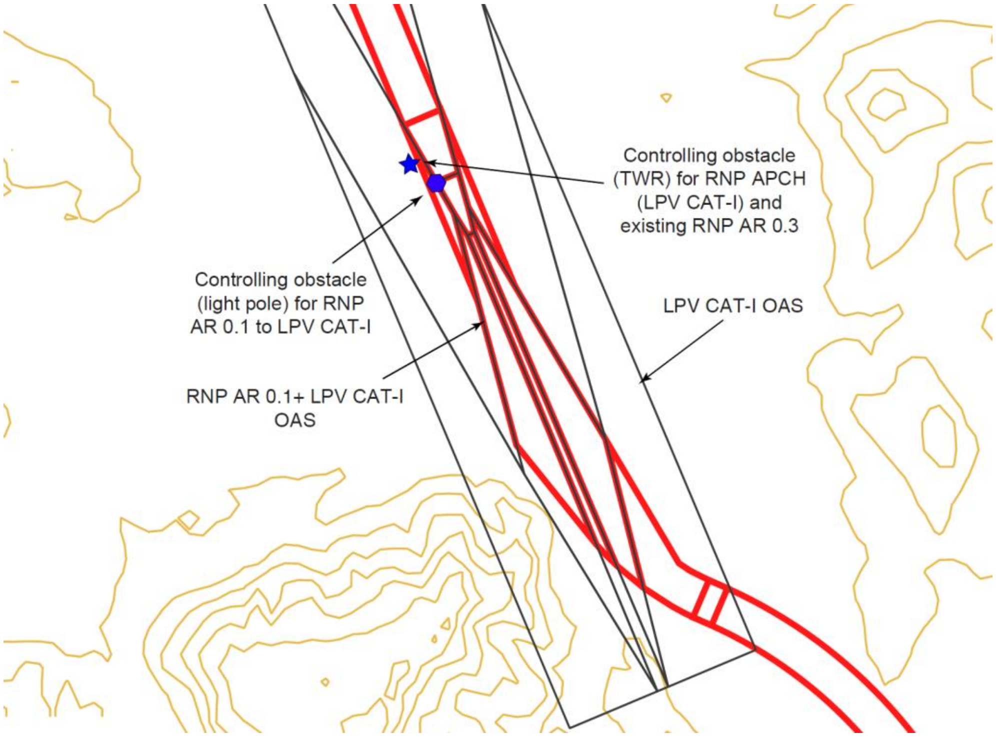

Figure 4. Depiction of the controlling obstacles and the OAS for LPV CAT-I and RNP-AR 0.1 to LPV CAT-I, respectively

3.10 Last but not least, it should be mentioned that the CAT I LPV segment ends when the Z surface reaches a semi-width of 0.95 NM if no turn is prescribed before. For RNP 0.1 performance, this value should be changed to 0.2 NM. Any obstacles located within the following straight missed approach are subject to a different criterion for ensuring obstacle clearance. After reviewing the rest of the segments of the approach we consider the obstacle assessment complete, and the approach protected against obstacles

4. **CODING**

4.1 Before testing the approach procedure in the simulator, we had it coded as part of a tailored navigation database that can be then loaded into the simulator’s FMS.

4.2 Even though VPA values are not usually coded outside of the FAS, we also calculate the VPA between the altitude restrictions at the waypoints throughout the intermediate approach to avoid dive-and-drive manoeuvres in managed mode to the extent possible.

4.3 Since the FACF altitude calculated to avoid the interception of the GS from above is the same altitude required to guarantee the required obstacle clearance for the RF leg, no altitude window can be coded but an “AT” constraint.

4.4 It is also important to note that the primary ARINC 424 record contains, for example, the RNP value required for the leg, but also two to three route qualifiers with one of them having to assume a certain value for RNP AR. The procedure data continuation record for the final approach sequence contains, among other things, the authorized levels of service. For RNP AR, that is the RNP value for the segment, whereas for LPV approaches it is “LPV” level of service. In addition, LPV requires a path point record (FAS DB) to be provided. Many Data Quality Requirements (DQRs) between coding providers and FMS manufacturers prevent the combination with RNP AR because the RNP AR qualifier cannot be combined with LPV as level of service. However, we do not necessarily need the qualifier because it only has a filter function and is used by the FMS processors to filter out RNP AR approaches from the database if the aircraft is not RNP AR certified.

4.5 Instead, we had the approach coded as advanced RNP (A-RNP) with a path point record provided and LPV as the approved level of service. A-RNP approaches normally require a fixed RNP value of 0.3 for the final approach while the value can be varied between 1 and 0.3 for the remaining segments. In our case, however, the DQRs with Honeywell as the A350 FMS manufacturer allowed the RNP values on the primary records to be selected lower than 0.3, which would not be the case for a standard RNP approach. In addition, A-RNP allows the combination with LPV.

4.6 A recent attempt to use the same coding for the Rockwell Collins FMS of an Airbus 220 failed because the coding requirements imposed by Rockwell Collins did not allow our implementation.

4.7 The chart, coding table as well as the FAS DB for the procedure can be found in the Appendix.

5. SIMULATOR ASSESSMENT

5.1 We performed a simulator assessment with the Airbus A350. The assessment took place on FT72, a Lufthansa Aviation Training A350-900 level D full flight simulator in Munich, Germany, in January 2022. As part of the assessment, the approach was tested under various wind and weather conditions that are summarized in Table 1.

5.2 …

Table 1 Simulator Assessment Scenarios

Run	Wind [° / kt]	Temperature	End of Scenario	Remarks
#1	NIL	ISA	Go-Around	Baseline
#2	All levels: 055/35	ISA	Go-Around	Turbulence: 50% Intended Wind (differences): 3000 ft: 109/50 1000 ft: 063/35
#3	3000 ft: 109/50 1000 ft: 109/50 Surface: 055/25	ISA-32	Touch-and-Go	Turbulence: 50% Intended Wind (differences): 1000 ft: 063/35
#4	All levels: 109/50	ISA+15	Go-Around	Turbulence: 50% Intended Wind (differences): 1000 ft: 243/35 Surface: 250/35
#5	All levels: 109/50	ISA+25	Approach only	Turbulence: 50% Intended Wind (differences): 1000 ft: 243/35 Surface: 250/35

5.3 *On-board representation of the approach*: The RNP values were correctly stored for all segments and displayed on the flight plan (F-PLN) page of the FMS, including RNP 0.1 for the final and the missed approach. On the ND, the leg RNP appeared except during the final approach under the localizer (LOC) guidance mode of the flight guidance system and during the initial go-around under the go-around track (GA TRK) mode. On the PFD, the RNP AR lateral and vertical deviation bars were displayed with the indication ”RNP AR” in green to the right below the artificial horizon. **Thus, the selected ARINC424 coding is sufficient despite the missing RNP AR qualifier for this particular FMS.**

5.4 On Airbus fly-by-wire aircraft, the landing system (LS) is used to display the angular deviations required for precision approaches in the form of magenta diamonds on the PFD. With LS activated, the RNP AR identifier on the PFD correctly switched to the satellite landing system (SLS) associated with LPV by Airbus, and the diamonds appeared immediately. However, these did not instantaneously replace the RNP AR deviation bars, which disappeared only upon crossing into the final approach under LPV guidance. Outside of this phase, both deviation bars overlapped both laterally and vertically when LS was active, which means that at no point during the approach under RNP AR guidance did the RNP AR deviation bars disappear. This represents the best possible fulfilment of the requirements of Doc9613 for both RNP AR and LPV.

5.5 Figure 5 shows the cross-track errors (XTEs) for all runs. Although strong wind and turbulence (e.g. run 5, magenta) caused larger XTEs than calm conditions (run 1, green), the maximum XTE equaled 42 m over all segments and flight phases. That is not even a quarter of the permissible two-sigma value of 182.5 m (0.1 NM) for RNP 0.1.

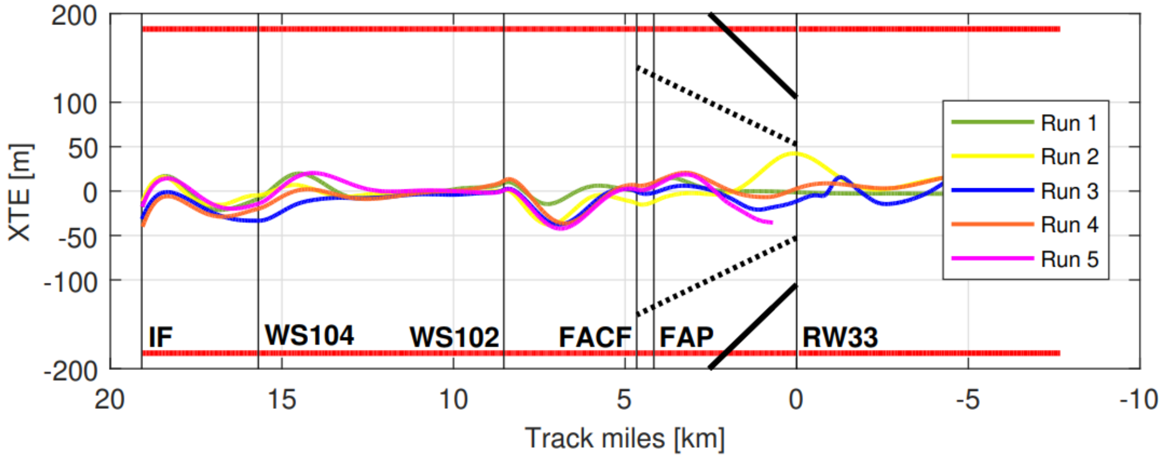

Figure 5 Cross-track error during the runs. For orientation, the lateral half and full scale LPV deflections are plotted as dotted and solid black lines, respectively. The RNP 0.1 TSE two-sigma value of ±182.5 m is plotted in red. The maximum XTE across all runs equaled less than 50 m, meaning that RNP 0.1 performance was achieved as required.

5.6 Figures 6 shows the cross-track errors vertical errors (VEs) for all runs. The results differ between low and high temperatures. Up to the FACF, the VE is relevant only in terms of the coded minimum heights, which were met in all cases. From the FACF on, deviations above (positive VE) as well as below (negative VE) the nominal path play a role. High temperatures were represented by ISA+15 (run 4, orange) and the ISA+25 (run 5, magenta) used for the approach design, each with wind. They led to higher true altitudes so that the VE remained positive. For ISA+25, we obtained significantly larger VEs of +81 m at the FACF and +43 m at the FAP. The VE with respect to LPV was about +52 m at the FACF and could not be reduced to zero afterwards, meaning that the LPV glide path was missed as it was intercepted from above. In these conditions, it is essential that the pilot sticks to the FMS computed vertical path. This was not the case for this run. The pilot’s insufficient configuration management led to the aircraft being continuously above the FMS trajectory which could not be recovered during the approach.

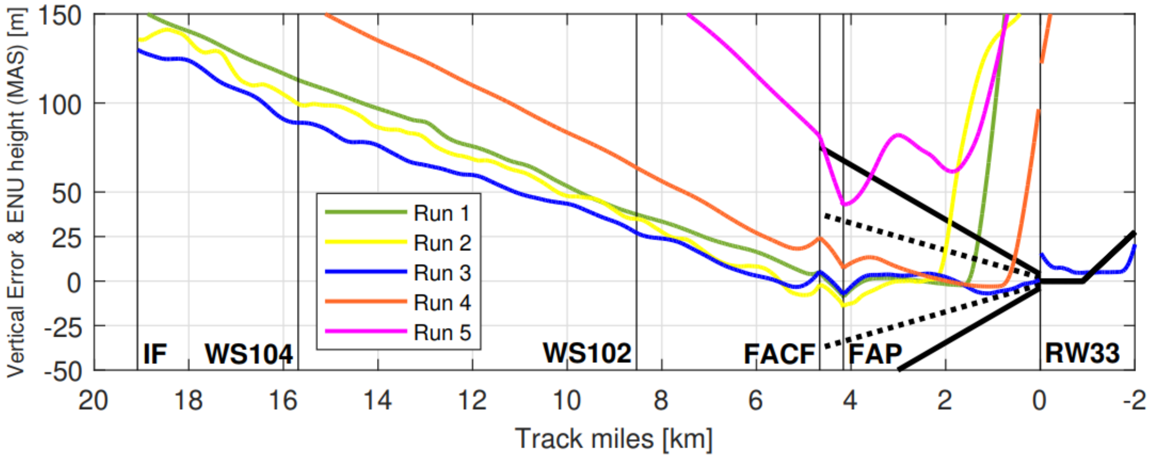

Figure 6 Vertical error during the scenarios. The vertical half- and full-scale LPV deflections are plotted in black and dotted black, respectively

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6. SUMMARY AND CONCLUSION

6.1 To avoid the limitations imposed by the surrounding mountainous terrain, we successfully developed an RNP AR (RNP 0.1) approach with an RF leg to intercept the final approach track, where a very short final segment driven by a FAS-DB (LPV) guides the aircraft to land on runway 33 at Salzburg airport. Thanks to this approach procedure the current lowest OCH (369 ft) for runway 33 could be reduced to 218 ft.

6.2 We restricted the width of the OAS based on performance assumptions (RNP 0.1 coded for all segments except for the initial). The blending of the intermediate segment with the OAS system is carried out by following the same basic rules applied today for RNP to xLS transitions (RNP APCH).

6.3 Since a coding of the procedure as RNP AR was not compatible with the inclusion of a path-point record for the final segment, we used A-RNP with the lower RNP values coded on all sequences to overcome this limitation.

6.4 Despite the coding as A-RNP, the approach was recognized and presented to the pilots as RNP AR, where the RNP AR deviation bricks could be overlaid with those of LPV on the PFD.

6.5 The cross-track error was kept well within RNP 0.1 performance during the simulation trial even in maximum wind and severe turbulence. The vertical error and the interception of the LPV glide path was generally smooth, with higher temperatures causing the margin to miss the glide path to decrease, as expected. For the maximum temperature assumed in the approach design (ISA+25), the glide path was missed due to pilot configuration errors.

6.6 Further assessments are needed to investigate whether the maximum temperature allowed for the approach needs to be limited even more in cases where no margin for error is given to the pilot. This is the case if the altitude constraint at the FACF is an “AT” altitude and not an altitude window. To avoid this, we recommend shortening the capture segment only as much as strictly necessary to ensure a safe transition to LPV guidance.

6.7 In case the coding standards for the navigation system database and DQRs are modified in the future in light of the planned changes to the A-RNP navigation specification (see IFPP/15 WP1a-002 *Updates to the A-RNP Navigation Specification and the RNP AR Navigation Specification*), the coding of a scalable RNP value in the final approach segment, as used for this experimental approach procedure, may no longer be possible.

6.8 In order to harmonize future implementations combining RNP AR and LPV finals and to increase the spectrum of FMSs that could correctly handle them without forcing a mismatch between the navigation specification used for the coding and the one used for the design, we propose the following actions:

- modification of the RNP AR navigation specification to include straight FAS-DB-guided final approaches
- revision of the route qualifiers policy in the ARINC standard 424 to ensure that path-point records containing the FAS-DB information can also be used for RNP AR approach procedures
- development of specific RNP AR to LPV CAT-I segment design rules based on proven principles applied in current criteria
- further evaluations by research institutions and the avionics industry to assess whether changes or improvements in the display of information to the pilot are required when flying these approaches.

7. ACTION BY THE WORKING GROUP

6.1 The group is invited to review and note the information provided.

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APPENDIX A
A1

Chart

APPENDIX A
A2

Coding table

APPENDIX A
A3

FAS DB