Design and Testing of a Vertically Guided High Precision Approach into Salzburg Airport

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The approach to landing on runway 33 of Salzburg Airport, Austria is severely impacted by mountainous terrain on the extended runway centerline. This renders all straight-in approaches but those based on Required Navigation Performance (RNP) Authorization Required (AR) impossible. Only the high navigation accuracy available under RNP AR minimizes the required obstacle protection areas sufficiently to be not penetrated by terrain. The combination of RNP AR and Localizer Performance with Vertical guidance (LPV) makes it furthermore possible to use a more precise angular guidance for the final approach. In Salzburg, this enables a reduction of the decision height from 368 ft to 218 ft above aerodrome level as critical terrain and obstacles now fall outside of the protection areas. A Level D full flight simulator test with an Airbus A350 showed that advanced RNP 0.1 coding is sufficient to achieve RNP 0.1 performance under all permitted environmental conditions.

I. Introduction

Required Navigation Performance (RNP) Authorization Required (AR) approaches are currently the only approach procedures to provide high navigation accuracy and the ability to use curved legs across all approach segments [1]. Compared to conventional approaches, this allows significantly smaller obstacle protection areas, constructed around the nominal approach path to ensure the required obstacle clearance, and allows more flexible procedure design. As a result, three-dimensional instrument approaches can also be offered at airfields where they were previously prevented by tight spatial constraints such as terrain, obstacles or airspaces close to the airfield [1]. RNP AR approaches are categorized by International Civil Aviation Organization (ICAO) as approaches with vertical guidance (APVs) together with approaches based on the RNP APCH specification. Both RNP AR and RNP APCH originate from the performance-based navigation (PBN) concept [2]. The main difference between both lies in the higher performance requirements associated with

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RNP AR that require the aircraft operator to show evidence of the necessary aircraft capability and sufficient crew training before obtaining authorization from the State regulatory authority to conduct such procedures. In return, greater flexibility in procedure design can be achieved due to improved navigation accuracy, integrity, and additional functionalities. For instance, RNP AR allows curved legs in the final approach and enables lateral accuracies (95 percent total system error, TSE) of 0.1 NM (expressed as RNP 0.1, 0.1 being the RNP value) in all approach segments, while RNP APCH only allows 0.3 NM in the final and 1 NM in the remaining approach segments (RNP 0.3 and RNP 1, respectively). As a result, the RNP AR obstacle protection areas are significantly smaller [3].

The RNP APCH specification includes different performance requirements for the final approach segment (FAS) depending on the guidance used. While Lateral Navigation/ Vertical Navigation (LNAV/VNAV) is based on rectilinear guidance, Localizer Performance with Vertical guidance (LPV) uses angular deviations from a center line and a glide path [2, pp. II-C-5-1ff.]. LPV approaches require the use of GNSS augmented by a space-based augmentation system (SBAS) for navigation during the final approach. They can also be flown as a Category (CAT) I precision approach (PA) with a minimum decision height (DH) of 200 ft above the landing threshold at which the pilots must decide whether to continue the approach or initiate a go-around. In contrast to LNAV/VNAV and RNP AR approaches, LPV does not require the aircraft to fly within a linear corridor but a cone that becomes narrower towards the runway so that the required navigation performance increases towards the runway as well. That is because guidance under LPV is based on SBAS and thus referenced to the ellipsoid geometry while LNAV/VNAV and RNP AR use, for instance, the less accurate and varying barometric altitude for vertical navigation [2, 4] Eventually, the navigation performance influences the obstacle assessment that determines the obstacle clearance height (OCH), i.e. the height down to which obstacle clearance can be provided during the final and the missed approach. The OCH, in turn, sets the lower threshold for the minimum DH [13, p. I-4-5-13]. That may give LPV approaches an advantage over RNP AR because the DH can - based on the improved vertical navigation accuracy - potentially be lowered, especially considering that the minimum DH for APVs is 250 ft rather than 200 ft [4]. However, this requires the obstacle assessment surfaces (OASs) to be used to determine the OCH (final and missed approach segments) and protection areas (remaining segments) to remain so small that no obstacles causing a higher DH are detected. At airports with tight spatial constraints, exactly that becomes a problem since only RNP AR allows sufficiently small areas.

Our goal is therefore to combine RNP AR approaches with LPV to compensate for the disadvantages of RNP AR within the final approach, realizing lower decision heights by means of LPV, without having to forego the higher RNP AR performance especially outside of the final approach segment. This could enable many airfields with existing RNP AR approaches to become available in even poorer visibility conditions, i.e., with even lower ceilings, than currently possible, thus becoming more independent of weather. Even though the number of large transport aircraft capable of flying LPV approaches is still very limited (e.g., some Airbus A220, A350, Embraer 175/195), it is expected to increase significantly in the near future [5]. That is supported by the continuously increasing number of published LPV approaches and the large number of planned procedures [6]. The U.S. Federal Aviation Administration already reported on advanced RNP procedures terminating in an LPV final approach segment at Friedman Memorial Airport [7]. Here, the intermediate approach was coded with an RNP value of 0.3 and the final approach was designed using APV criteria. However, the procedure was designed for a specific airline and not much information is publicly available. Through the combination of LPV with RNP AR, we expect to create a promising approach procedure that combines the best of both worlds - the accuracy of CAT I precision approaches (PAs) with the flexibility of RNP AR approaches - thus narrowing the remaining gap between PAs and APVs further.

This paper investigates this combination for Salzburg Airport, Austria. It has a single runway (RWY) 15/33 and is located southwest of the city directly on the northern edge of the Alps. While the approach to RWY 15, which is equipped with ILS, leads over the relatively flat foothills of the Alps, the extension of RWY 33 crosses steeply rising terrain south of the aerodrome. The terrain is, above all, characterized by the 1973 m high Untersberg, whose massif lies just over 3 NM away from the runway threshold (THR) and intersects the runway extended center line. There are currently two RNP AR approaches published for RWY 33 whereby only variant Z allows an approach coming from the south, flying through the mountains. As shown in Fig. 1, the approach follows the Salzach valley and leads onto the final approach course in a double bend that consists of several curved legs. These legs lead eastward past the Untersberg massif and end in the last part of the final approach, which is a 1.5 NM long, straight segment. The DH is at least 369 ft above threshold level [8, pp. LOWS AD2-1ff.]. In this paper, the existing final approach is replaced with a straight LPV segment that shall be incorporated in such way that changes to the existing approach layout are kept to a minimum. The approach shall then be coded for a navigation database that is used for a simulator assessment of the approach procedure with an Airbus A350.

So far, the combination of RNP AR and LPV is neither practiced nor foreseen by ICAO procedure design documents, therefore, comprehensible procedure design rules must first be established. The design rules for RNP AR APCH are described in ICAO document 9905: Required Navigation Performance Authorization Required Procedure Design Manual [3], while the rules for RNP APCH (including LPV) are described in ICAO Document 8168, Volume II: Procedures for Air Navigation Services Aircraft Operations (PANS-OPS), Construction of Visual and Instrument Flight Procedures [13]. Detailed system and training requirements for both specifications, as well as implementation guidance, can be found in the PBN Manual (ICAO document 9613) [2].

II. Procedure Construction

A. General approach to combine RNP AR with RNP-to-LPV minima

For both RNP AR and RNP APCH, the required lateral accuracy accuracy is expressed as RNP X, where X is the TSE in NM that must be achieved at least 95 percent of the flight time. RNP AR allows values from RNP 1 to as low as

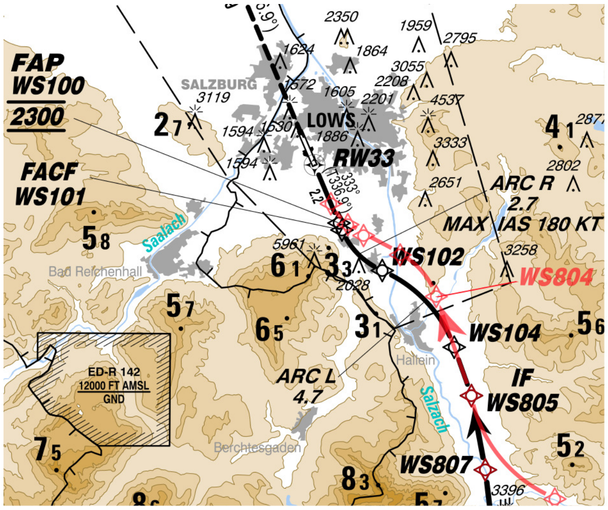

Fig. 1 Extract from the approach chart made for our designed approach with the existing RNP Z RWY 33 (AR) approach being printed in red.

RNP 0.1 in all approach segments [3]. Instrument approaches are protected against obstacles down to the OCH by two kinds of protection areas called primary and secondary areas. RNP AR only uses primary areas, which have a semi-width equal to 2x RNP value of the respective approach segment, i.e., between 0.2 NM and 2 NM. For the obstacle assessment of LPV approaches, the FAS and the initial and intermediate phases of the missed approach are considered as one segment, which is referred to as the LPV segment [13, p. III-3-5-1].

Current design criteria provide guidance to develop RNP approaches with an LPV final segment [13]. Our approach is therefore to apply the existing rules to the maximum extent possible, trying to extrapolate the rationale behind each rule to those cases not covered by the criteria. These cases are expected to arise mainly due to the narrower width of the RNP AR protection areas without buffers or secondary areas [3]. For the merging of the RF leg protection areas with the OAS system of the LPV segment, the rules from 1.3.6.4 of Ref. [13] have been applicable for standard RNP approaches since November 4, 2021, onwards [13, p. III-3-5-3]. The rules dictate that on the inside of the turn, the extension of the D-D" line must become the boundary of the primary area from the point of intersection. The minimum obstacle clearance (MOC), which is provided in the vertical direction, must be applied with the intermediate approach value of 150 m between the extended D-D" line and the D"-C" line. The affected area corresponds to surface 4 in Fig. 3. 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 Fig. 3, number 5). Outside the D"-C" line, the intermediate approach MOC must be applied. Here, unlike when merging an RF leg based on RNP APCH into SBAS OAS, the smaller width of the RF areas based on RNP AR can cause the 15-degree splay on the outside of the RF leg to intersect the D-D" line before its extension, cutting off parts of the OAS. 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 symmetrical RNP AR corridor marked in green in Fig.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 located close to the final approach course. Nevertheless, we prefer to keep applying the blending method with the 15-degree splay on the outside of the turn to account for potential drifts off the nominal track, even though these events are not expected under nominal conditions.

Another key aspect to combine RNP AR with an LPV final is the curtailing of parts of the SBAS OAS according to the underlying required navigation performance. The 0.95-NM corridor used to limit the SBAS OAS Y and Z surfaces is based on an underlying performance of RNP 0.3 for the final approach and corresponds to the RNP APCH protection area semi-width of 0.95 NM for RNP 0.3 using the RNP APCH buffer value of 0.5 NM for the FAS [13, p. III-1-2-7]. That is because the RNP value of 0.3 is still coded for the final approach even with angular performance requirements applying for LPV. When a missed approach is initiated - which is the reason for the curtailing given by Ref. [13] - the flight management system (FMS) remains in NPA mode, which is assumed to cause the performance to be based on the coded RNP value (0.3). At the earliest turning point of the procedure, the system reverts to RNP 1 with the LPV segment ending there at the latest [13, pp. III-3-3-2, III-3-5-7ff.]. For RNP AR, applying this rule regardless of the reduced containment areas without buffers may easily lead to an important loss of efficiency in obstacle-rich environments. This can be resolved by aiming for a higher performance in the final and the missed approach by coding lower RNP values for them. Since the approach per se is already an RNP AR approach with a given RNP value for the intermediate approach, the aircraft must also have the corresponding RNP AR capability and be certified accordingly. Consequently, a higher RNP value can be required for the final and missed approach segments, too. Following the logic outlined for a standard SBAS OAS system, the higher underlying performance should allow to limit the Y and the Z surface to the width of the corresponding RNP AR protection areas, while the X surface remains limited by the 15-degree splay from the outer RF leg protection area.

It is important to note that the curtailing of the OAS based on the underlying RNP can only be applied if it is guaranteed that the aircraft remains within the corresponding RNP AR corridor during the interception of the LPV segment. Moreover, the assumed improvement in navigation performance along the LPV segment yielded by coding lower RNP values must be verified during assessments to ensure that RNP AR performance requirements are indeed fulfilled.

B. Specific design considerations and process

For practical reasons, the proposed approach has been developed for aircraft of speed category D or lower, i.e., the indicated air speed (IAS) at threshold must not exceed 165 kt [3, p. 3-1]. Since Salzburg lies in the CAT 1 service area of the European GNSS Overlay System (EGNOS) [9], the final approach has been developed to the standards of this service, i.e. as a CAT I segment.

1. Initial placement of the Final Approach Point (FAP) and the Final Approach Capture Fix (FACF)

An SBAS CAT 1 segment is protected against obstacles and terrain by an OAS system consisting of a total of six sloping surfaces W, X, Y and Z as shown in Fig. 2. Each surface's geometry is described by the algebraic equation $z = Ax + By + C$ (with A, B and C being surface-specific constants) as explained in Ref. [13] or by a subset of the OAS end points C, D, E at threshold height as well as C", D" and E", each 300 m above threshold height. Both the constants and the end points must be obtained through the PANS-OPS OAS software based on a chosen approach and aircraft geometry [13, pp. III-3-5-3ff.]. While the intersection points and equations governing the slopes of the surfaces are the same for CAT I approaches based on ILS and those based on SBAS, the lateral dimensions of the OAS system and the termination of the precision segment are different for SBAS CAT I approaches. This difference has a direct impact on the obstacle assessment and is explained later in section II.B.3. The approach geometry is defined by the glide path angle (GPA), the reference datum height (RDH), the GNSS azimuth reference point (GARP)-landing threshold point (LTP) distance and the course width at threshold [10]. The last two parameters define the funnel describing the lateral FAS geometry, with the apex sitting at the GARP and the course width corresponding to the funnel width at the threshold (given by the LTP). The latter has been chosen to be the standard value of 210 m [13, p. II-1-1-13], with the position of the GARP 305 m behind the stop-end-of-runway (GARP-LTP distance = 2815 m) [8, pp. LOWS AD 2-13ff.]. The RDH corresponds to the glide path height above the LTP and is chosen to be 50 ft or 15 m, analogous to the existing RNP AR approach, leaving the GPA as the only variable. [13, pp. III-2-6-1ff.] The GPA has been set to 3.5° as the highest possible standard value because higher GPAs cause the OAS system to be more compact and narrower, which is desirable in view of the terrain situation. On the other hand, we can avoid any restrictions necessary for approaches with greater, i.e. non-standard, GPA [13, pp. III-3-5-6ff.]. As shown in Fig. 2, the resulting ILS CAT I surfaces (delineated by the bold red lines, number 1) do not intersect the terrain of the Untersberg massif but extend just past it. In both Figures 2 and 3, the height of the surrounding terrain with respect to the runway threshold is color-coded ranging from blue via turquoise to green with increasing height. Obstacles on the ground are marked with yellow dots (and lines in the case of the 3-D plot within Fig. 2).

To place the final approach point (FAP), i.e., the point where the final approach begins, within the OAS system, the basic idea is to extend the final approach slightly compared to the existing RNP AR approach as [13, p. I-4-5-1] requires a minimum FAS length of 3 NM for RNP APCH with LPV. The FAP shall be reached via a double bend departing from the existing leg from WS805 to WS804 (hereafter called WS804 leg), meaning that with a longer final approach the WS804 leg will have to be shortened (see Fig. 1). The double bend shall consist of curved segments in the form of Radius to Fix (RF) legs [2, p. II-C-App 1-1].

Since November 4, 2021, [13] grants the possibility of combining LPV with RF legs to the final approach course under RNP APCH. In this case, the RF legs must not end at the FAP but at an upstream waypoint, the Final Approach Capture Fix (FACF). The FACF must have a minimum distance to the FAP to ensure that the LPV glide path is never intercepted from above: In this case, an autopilot might not follow the profile and the approach would have to be aborted [13, pp. III-3-5-2ff.]. The threat mainly results from the change from barometric to ellipsoidal altitude, whose difference grows with larger temperature deviations from the international standard atmosphere (ISA) due to the temperature-related pressure altimeter error [11].

By default, the FACF is to be placed 1 NM ahead of the FAP at the same altitude [13, p. III-3-6-30]. However, due to its location on the final approach course, that would shift the proposed approach critically towards the terrain by the resulting extension to the south (see Figures 1 and 3). For this reason, the length L of the FACF - FAP segment has been minimized following the procedure described in Appendix D of Ref. [13], where the vertical displacement due to errors resulting from using barometric altitude can be approximated for a given approach geometry and ISA temperature deviation. The error at the FACF must then be smaller or equal to the difference between the LPV glide path altitude at the FACF and the true FACF altitude so that the glide path is not intersected from above. As the difference depends on L, L can be lowered until the difference is exactly equal to the calculated altitude error.

To define the approach geometry, we choose the vertical path angle (VPA) of the FACF - FAP segment to be 0^o and the FAP to be located at 2300 ft MSL, 889 ft above and 2.2478 NM away from the threshold. The maximum temperature deviation is assumed to be 25^o C above ISA (ISA+25), approximately 37.2^o C at aerodrome elevation. The value lies in the upper range of local heat records measured in recent decades and should only be exceeded in very few cases in the future [12]. That way, L can be reduced to 500.04 m (0.27 NM), which places the FACF 2.5178 NM away from the threshold. This assumes a root sum square of the vertical navigation errors equal to 30.8793 m as calculated with Eqs. 6 - 9 from [13, pp. II-1-1-App D-6f.]. This error would cause the aircraft to intercept the glideslope right upon reaching the FACF after the last turn without considering any flight technical error. For coding purposes, the FAP is named WS100 and the FACF is named WS101. Their displacement from the threshold is also shown in Fig. 2.

2. *Intermediate Approach: Construction of the double bend and integration with existing approach structure*

Since the RF legs form part of the RNP AR-based intermediate approach, the procedure design rules from Ref. [3] are applied. For the RF leg ending at the FACF, the radius is calculated, aiming for a small value to achieve a tight turn that guarantees sufficient distance to the Untersberg massif. This requires low (true) air and wind speeds, which for a constant indicated air speed (IAS) are achieved at low altitudes [3, p. 3-5]. The turn has been based on an IAS of 180 kt (maximum limitation allowed by Ref. [3]), ISA+25 conditions and a bank angle of 18°. The entry point altitude equals the altitude used for the radius calculation as it is the highest within the turn. Based on the maximum allowed intermediate approach VPA of 3.1°, an altitude of 3000 ft (TAS = 196.2714 kt) has been considered a good compromise since it results in a radius of r = 2.7202 NM and a track change of about 44°. In Fig. 3, the turn can be identified by the green line segment numbered 1. The track change is similar to the existing RNP AR approach and, as shown in Figures 1 and 3, causes the aircraft to sufficiently turn away from the rising terrain of the western flank of the Salzach valley. On the other hand, overshoot is prevented so that the required track change to the WS804 leg does not become too large. The entry point of the RF leg is called WS102 for coding purposes.

The construction of the preceding RF leg is done on a geometric basis as there is only one possible solution for an arc segment that is both tangent to the WS804 leg at a yet unknown entry point and to the succeeding RF leg at WS102 [1]. The resulting RF leg has a radius equal to 4.6768 NM and starts at the newly determined waypoint WS104, which is only 1.8347 NM away from the intermediate fix (IF) WS805, where the intermediate approach begins. In Fig. 3, the turn can be identified by the green line segment numbered 2.

The remaining approach structure up to the start of the initial approach at the initial approach fix (IAF) remains laterally unchanged. To place WS104 vertically, the highest possible VPA that still results in a round (multiple of 100 ft) entry altitude to ensure the greatest obstacle clearance, but does not exceed 3.1°, has been applied to the corresponding RF leg. Likewise, the descent gradients of the preceding segments are adjusted (for initial approach segments we use the maximum allowed initial approach descent gradient of 8% until a fix is again placed at the minimum altitude suggested by the existing RNP AR approach, which is not the case until WS808. However, as those altitudes are minimum altitudes and also coded as such (expressed as e.g. 'A6200+' for 6200 ft), the fixes may also be overflown at higher altitudes. The altitude constraints for the FACF and the FAP must be 'at' constraints (expressed as e.g. 'A2300' for 2300 ft) so that the fixes are overflown at exactly their given height [13, pp. III-5-1-5-ff.].

In addition to the initial approach, also the missed approach has been adopted from the existing RNP AR approach. Fig. 1 illustrates the resulting approach layout with regard to the changes made to the existing RNP AR approach.

3. Obstacle assessment and OCH determination

Due to the proximity of the terrain in the intermediate and the final approach, the narrowest possible protection areas are required there. Consequently RNP 0.3 has been chosen for the less critical initial approach and RNP 0.1 for the intermediate approach, resulting in RNP AR protection areas of 0.6 NM and 0.2 NM semi-width, respectively, which are shown by the symmetrical, light green surfaces in Figures 2 and 3. The minimum obstacle clearance (MOC) equals 300 m for the initial and 150 m for the intermediate approach but must be doubled in "mountainous terrain" according to Ref. [3]. Even though the criterion to establish mountainous areas in Austria deviates from the one promulgated in ICAO guidance material as of today, we decide to double the MOC for all segments, except for the final approach and for the last RF leg of the intermediate approach leading to the FACF. That is because 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.

For the merging of the RF leg protection areas with the OAS system of the CAT I segment, we apply the rules exposed in section II.A also to our approach with the result being illustrated in Fig. 3 by the surface area numbered 3, bounded

Table 1 Comparison of obstacle clearance altitudes for different final approach guidance variants

Final Approach Guidance	Controlling Obstacle	OCA(H) [ft]
RNP AR 0.3	TWR Antenna (47.7933,12.9967) Elev. 1619ft	1780(369)
RNP AR 0.3 to LPV CAT-I curtailed	TWR Antenna (47.7933,12.9967) Elev. 1619ft	1717(306)
RNP AR 0.1	Tree (47.8001,12.9946) Elev. 1530ft	1722(311)
RNP AR 0.1 to LPV CAT-I curtailed	Light Pole (47.7908,13.0022) Elev. 1468ft	1629(218)

by bold, red lines. In our case, the very short FAS and the small RF leg protection areas cause the 15-degree splay (see Fig. 3, number 5) to intersect the D-D”-line before it is actually extended, whereby the splay also cuts through parts of the Y surface. However, since cutting off those parts of the OAS system would not achieve any benefits in terms of obstacle clearance, we refrain from doing so.

At this point, we convert the ILS CAT I OAS system presented in section II.B.1 into a suitable SBAS CAT I OAS system. As described in section II.A, standard SBAS CAT I OAS systems have the Y and the Z surface curtailed to a constant semi-width of 0.95 NM [13, pp. III-3-5-4ff.]. Moreover, if the X surface has a semi-width of less than 0.95 NM at the FAP, an intermediate approach protection area semi-width of 0.95 NM (including the intermediate approach MOC) must be applied between the FAP and the point where the OAS system reaches the same semi-width, i.e. the system is first curtailed and then artificially widened towards the FAP [13, p. III-3-5-3]. Those changes are due to the underlying navigation performance of RNP 0.3 and are illustrated in Fig. 2 by the purple and dark green surfaces associated with number 2. For our approach, implementing the changes would result in the OAS system being stretched to 0.95 NM semi-width at the FAP due to the short FAS, getting very close to the terrain. To overcome this issue and based on the rationale exposed in section II.A, we decide to code an RNP value of 0.1 for the final and the missed approach and to curtail the Y and the Z surface 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. This corresponds to the red surfaces, numbered 3, in Fig. 2. To ensure containment within the RNP 0.1 corridor during the LPV interception, we also require that the transition to SBAS navigation is not made until the remaining distance to the FACF equals 0.5 NM or less as shown on the navigation display (ND) [13, p. III-3-5-2]. Including the along-track tolerance (ATT), that should prevent the aircraft from leaving the RNP 0.1 corridor under LPV guidance with sufficient probability.

The last step is the OCH determination based on the curtailed OAS system depicted by number 3 in Fig. 3. In accordance with 5.4.5.9 of Ref. [13], the calculation method for ILS CAT I approaches following 1.4.8.8.2.1 of Ref. [13] has been used. The most relevant obstacle has been found to be a main apron light pole 976 m behind and just under 52 ft above the 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 and also being the controlling obstacle for the existing RNP AR 0.3 approach) now

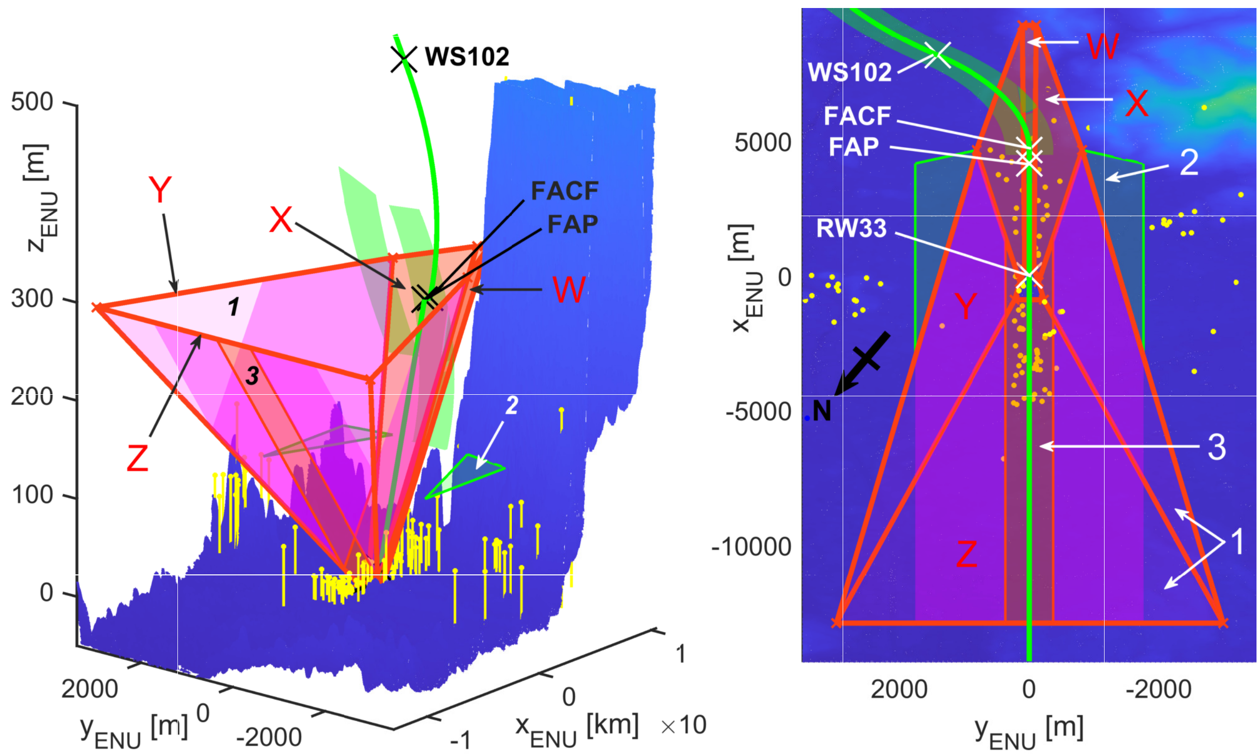

Fig. 2 3-D (left plot) and 2-D (right plot) representation of the different OAS systems (ILS CAT I, SBAS CAT I, our solution adapted to RNP 0.1).

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). Last but not least, it should be mentioned that the CAT I segment normally ends when the Z surface reaches a semi-width of 0.95 NM according to the OAS formula. For RNP 0.1 performance, this value should be changed to 0.2 NM. Any obstacles located within the then following straight missed approach are subject to a different criterion for ensuring obstacle clearance (see 5.5.2 of Ref. [13]). Since this is met for the OCH of 218 ft, we consider the obstacle assessment complete and the approach safe to fly. The final merging of the RNP AR protection areas with the curtailed OAS (including W and X surfaces cut off on the outer side of the final turn) in relation to the surrounding terrain and controlling obstacles is shown in Fig. 4. Table 1 shows the impact of the final approach guidance and RNP value on the OCH for the designed approach procedure.

III. Procedure Coding

The coding of approaches for the database of navigation systems must follow the ARINC 424 standard [14]. In addition, it may be influenced by (confidential) data quality requirements (DQRs) between the individual coding providers and FMS manufacturers, which further regulate the format in which the data to be coded must be sent. As of now, ARINC 424 does not provide for the combination of RNP AR with LPV. Under ARINC 424, each leg is described by at least a primary record and, where necessary, one or more continuation records. The primary record contains,

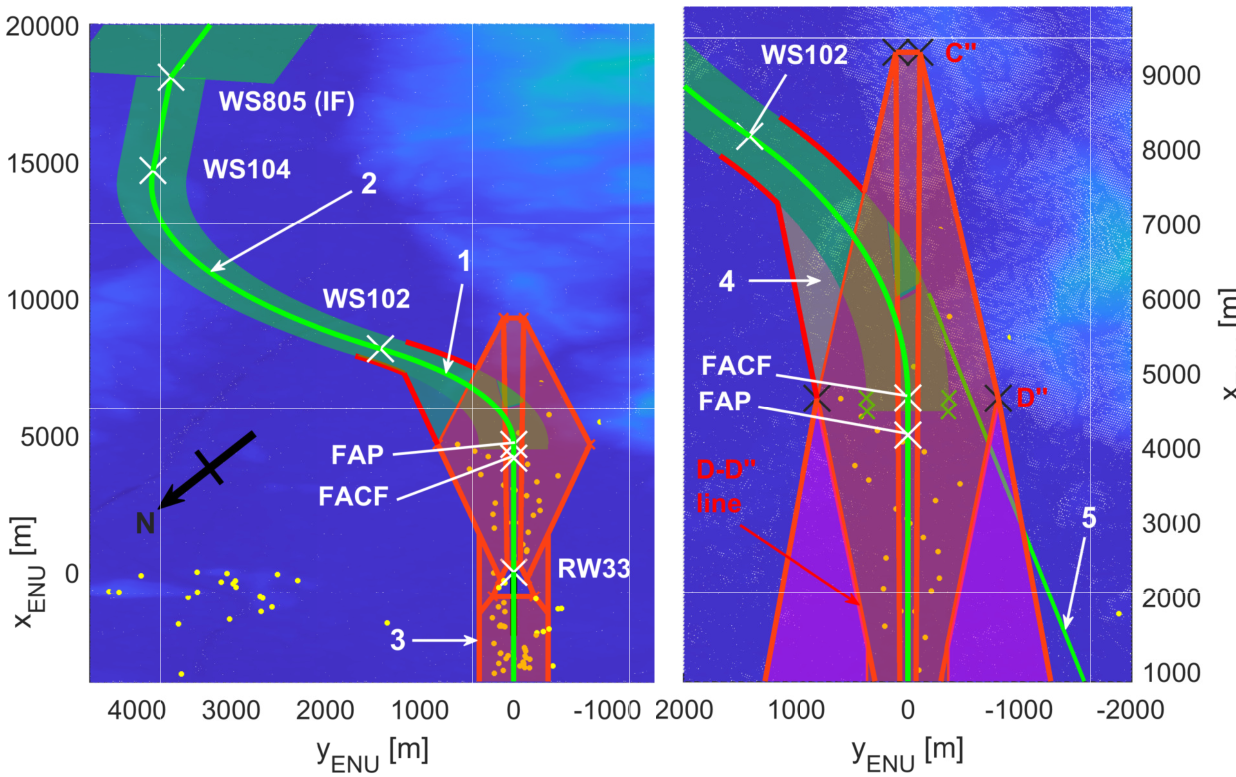

Fig. 3 2-D view of the intermediate approach and the CAT I segment with their protection areas and obstacle assessment surfaces, respectively (left plot) as well as a detailed 2-D view of the area where the intermediate approach protection areas are merged with the OAS system (right plot).

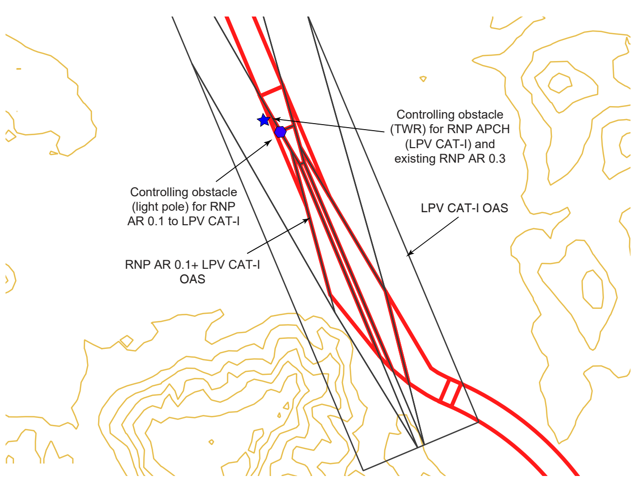

Fig. 4 Depiction of the controlling obstacles and the OAS for LPV CAT-I and RNP-AR 0.1 to LPV CAT-I, respectively

Table 2 Simulator assessment scenarios

Run	Wind [^{o} / kt]	Temperature	End of Scenario	Remarks	Intended Wind (if different)
#1	NIL	ISA	Go-Around	Baseline	
#2	All levels: 055/35	ISA	Go-Around	TURB: 50%	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	TURB: 50%	1000 ft: 063/35
#4	All levels: 109/50	ISA+15	Go-Around	TURB: 50%	1000 ft: 243/35, Surface: 250/35
#5	All levels: 109/50	ISA+25	Approach only	TURB: 50%	1000 ft: 243/35, Surface: 250/35

amongst others, the applicable RNP value but also two to three route qualifiers, with one of them having to assume the value F for RNP AR approaches. The procedure data continuation record for the final approach sequence contains, amongst others, the authorized levels of service. For RNP AR, that is the RNP value whereas for LPV approaches it is LPV [14]. Our applicable DQRs prevented the combination of RNP AR with LPV at this point because the RNP AR qualifier could not be combined with LPV as level of service. However, the qualifier is only used as a filter function by FMSs to filter out RNP AR approaches if the aircraft is not RNP AR certified.

Instead, the approaches have been coded as advanced RNP (A-RNP) with a path point record provided (also required for LPV) and LPV200 as the approved level of service. A-RNP approaches normally have 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 [2, p. II-A-1-2]. In our case, however, the applicable DQRs allowed the RNP values on the primary records to be selected lower than 0.3. Even though VPA values are usually not coded outside of the FAS, we also calculate and code the VPA between the altitude restrictions at the waypoints throughout the intermediate approach to avoid dive-and-drive maneuvers in managed mode to the extent possible.

IV. Simulator Assessment

After coding the procedure, it has been tested and validated on an aircraft platform. Here, the simulator assessment fulfills three tasks. First, to validate that the selected coding results in the correct representation of the approach on-board. The procedure must be treated as an RNP AR approach with the appropriate lateral and vertical deviations being displayed on the pilots' primary flight display (PFD) for all approach segments except the final approach. The coded RNP values must be the ones used by the FMS [2, pp. II-C-6-10ff.]. In the final approach segment, LPV guidance must be available and usable [2, pp. II-C-5-24ff.]. Secondly, to validate that RNP 0.1 performance can be achieved in all approach segments except the initial approach. Thirdly, to validate that the approach is flyable at both very high (ISA+25) and very low (ISA-32, -20^o C aerodrome temperature) temperatures. This mainly concerns the FACF – FAP segment, which must prevent the interception of the LPV glide path from above at high temperatures, but also the non-applied double MOC in the RF leg to the FACF at low temperatures (true altitude is lower than indicated). The assessment took place on FT72, a Lufthansa Aviation Training A350-900 level D full flight simulator in Munich, Germany, in January 2022 [15]. The flight crew consisted of one flight validation pilot, which was A350 rated and flying as PIC plus one commercial pilot that was not rated on the A350 but current on A320 acting as first officer. Both had not trained or flown this particular RNP AR approach previously.

To accomplish the given tasks, the approach was tested in both standard and extreme temperatures and in winds as summarized in Table 2. The wind was supposed to make achieving RNP 0.1 performance as challenging as possible since the TSE is characterized primarily by a low flight technical error (FTE), i.e, the guiding accuracy of the aircraft by the pilot or the autopilot [16]. All approaches were started from a pre-specified position between WS808 and WS809 to bring the aircraft into the correct configuration by the IF. The aircraft gross weight equaled 185000 kg, 20 t below the maximum landing weight [17]. The last two validation tasks are analyzed based on the difference between the simulated aircraft position, which was extracted together with other parameters during the assessment, and the nominal flight path. This difference was calculated by determining the laterally and vertically perpendicular distances between the simulated position and the nominal approach track. Thus, the analyzable TSE consists only of the cross-track error (XTE) and the vertical error (VE).

A. On-board representation of the approach

During all runs, the desired presentation of the approach was obtained: 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 Navigation Display (ND), the coded RNP values 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. The GA TRK mode appeared only for 0.5 s on the flight mode annunciator. On the Primary Flight Display (PFD), the RNP AR lateral and vertical deviation bars were displayed as well as the indication "RNP AR" in green to the right below the artificial horizon (except during the phases mentioned above). 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 and as shown in Fig. 5, the RNP AR indicator on the PFD correctly switched to the satellite landing system (SLS) associated with LPV by Airbus, and the diamonds appeared immediately [18]. However, these did not instantaneously replace the RNP AR deviation bars, which disappeared only upon transitioning to the final approach under LPV guidance. Outside of this phase, both deviation bars overlapped both laterally and vertically when LS was active, meaning that at no point during the approach under RNP AR guidance the RNP AR deviation bars disappeared (see Fig. 5). Consequently, the selected coding does not only compensate the missing RNP AR qualifier, but represents the best possible fulfillment of the requirements of Ref. [2] for both RNP AR and LPV, at least with the FMS we used.

B. Error performance and temperature effect on the approach

Figure 6 shows the XTEs and VEs for all runs. Although strong wind and turbulence caused larger XTEs than calm conditions, the maximum XTE equaled 42 m over all segments and flight phases, 23% of the maximum permitted value of 182.5 m.

The wind was specified for three layers (3000 ft altitude upon entry into the first RF leg, 1000 ft above threshold just before the FACF, ground). We wanted to create the maximum permissible tailwind under RNP AR for 3000 ft (corresponding to wind from 109^o with 50 kt), and crosswind with respect to the final approach course with the maximum tailwind speed permissible under RNP AR for 1000 ft above threshold (corresponding to wind from 063^o or 243^o with 35 kt) [3, p. 3-5]. On the ground, the crosswind was realized close to the A350 operating limits, corresponding to crosswind at 35 kt in dry standard conditions and 25 kt for very cold temperatures [19]. Especially the crosswind was supposed to drive the aircraft towards the outer boundary of the RNP 0.1 corridor, thus provoking the largest possible XTE. However, despite entering the specified wind values at the instructor station, the wind was not always simulated as specified (see Table 2). In the fourth and fifth runs, for instance, the wind on the ground as well as in 1000 ft above threshold represented the wind from the highest layer, which would not have been permitted due its direction and speed [19]. Nonetheless, RNP 0.1 was maintained during all runs (see Fig. 6).

Up to the FACF, the VE is relevant only in terms of the coded minimum altitudes, which were met in all cases. From the FACF on, deviations above (positive VE) as well as below (negative VE) the nominal path are relevant. Run 1 (dark green) was characterized by very low VEs down to -9 m, which increased slightly to -14 m with wind but standard temperatures in run 2 (light green). With very low temperatures and wind (run 3, blue), the VE did not become greater which can be attributed to the use of temperature-corrected altitude restrictions to compensate for the temperature-related altimeter error. The corrections were calculated with an A350 electronic flight bag application based on the simulated temperature and manually entered into the FMS before commencing the approach, which overwrote the coded restrictions. Since the corrections prevented flying too low, it was assumed that their consistent operational use at cold temperatures compensates for the partial use of the single instead of the double MOC.

High temperatures were represented by ISA+15 (run 4,brown and the ISA+25 (run 5, orange) used for the approach design, each with wind. They led to higher true altitudes and hence the VE remained positive, i.e., the aircraft flew higher than it was supposed to. In run 4, the VE was +24 m at the FACF and +8 m at the FAP, with the LPV glide path still being intercepted from below. That is illustrated in Fig. 7, where the VE for runs 1 (dark green), 4 (brown) and 5 (orange) is shown with respect to both the horizontal FACF – FAP segment (VPA = 0°) and the LPV glide path (GPA = 3.5°) in that area.

The VE with respect to LPV was negative at the FACF and became positive towards the FAP, expressing the interception of the LPV glide path from below. Compared to run 1, the intersection point was located much closer to the FACF, which was due to the temperature-related higher VE: If the VE with respect to the horizontal segment shifts upwards along the y-axis, the VE with respect to LPV is shifted likewise, moving the intersection point with the x-axis (VE = 0) towards the FACF. The horizontal segment was designed such that the intersection point for ISA+25 coincides exactly with the FACF. That assumes that the actual VE is equal to the one calculated based on the Appendix D of Ref. [13] formulae, although it may of course be smaller. For ISA+15, the actual VE was very slightly below the calculated one. For ISA+25, significantly larger VEs of +81 m at the FACF and +43 m at the FAP were obtained. 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. However, the high error can be attributed to insufficient configuration management by the pilots, specifically the failure to extend the speed brakes to increase drag during descent, as well as the fact that the approach was started too high and, therefore, continuously flown above the target profile. By means of video recordings made in the simulator, the run can nevertheless be evaluated based on the vertical deviations displayed on the PFD. Above the FACF, they equaled 170 ft (51.8 m) for RNP AR, which corresponds exactly to the VE with respect to LPV at that point (see Fig. 5). Assuming that no configuration errors are made, the RNP AR deviation should be zero with the deviation brick centered, i.e. the deviation of 170 ft can be subtracted from the actual VE, rendering the VE with respect to LPV approximately zero at the FACF.

This is consistent with the design of the FACF - FAP segment based on Appendix D of Ref. [13], where the assumed VE at the FACF corresponds exactly to the height difference between the FACF and the LPV glide path above the FACF. However, it must be added that this type of design does not include any margin, so that the slightest deviations from the behavior described by the appendix formulae can theoretically lead to missing the glide path (as it did in our case of configuration mismanagement). For example, the vertical system error is modeled smaller than under RNP AR because the FTE is not included [13, p. II-1-1 App D-6][2, p. II-C-6-7]. Due to time constraints, we were not able to repeat the run during the assessment so that the flyability of the approach at ISA+25 has not yet been proven.

V. Conclusion

An RNP AR approach with intermediate approach RF legs onto a final approach segment based on LPV has been successfully developed for RWY 33 of Salzburg airport. To achieve the lowest OCH, it is required that all segments outside the initial approach are coded with an RNP value of 0.1, allowing us to limit the Y and the Z surface of the OAS system protecting the final approach segment against obstacles to a semi-width of 2x 0.1 NM, and to not have to artificially widen the X surface to the semi-width of 0.95 NM otherwise required for LPV. By doing so, the proposed procedure was successful in avoiding critical terrain within the approach on the one hand, and in reducing the OCH from 369 ft to 218 ft on the other. The approach has been coded as an advanced RNP (A-RNP) procedure with the newly chosen RNP values coded on their respective sequences, with LPV200 as the authorized level of service for the final approach and with a path point record provided. Simulator tests on an Airbus A350 level D full flight platform

Fig. 5 Simulator assessment: PFD view during run 5 upon passing the FACF with LS activated (top) and during run 1 within the initial approach (bottom).

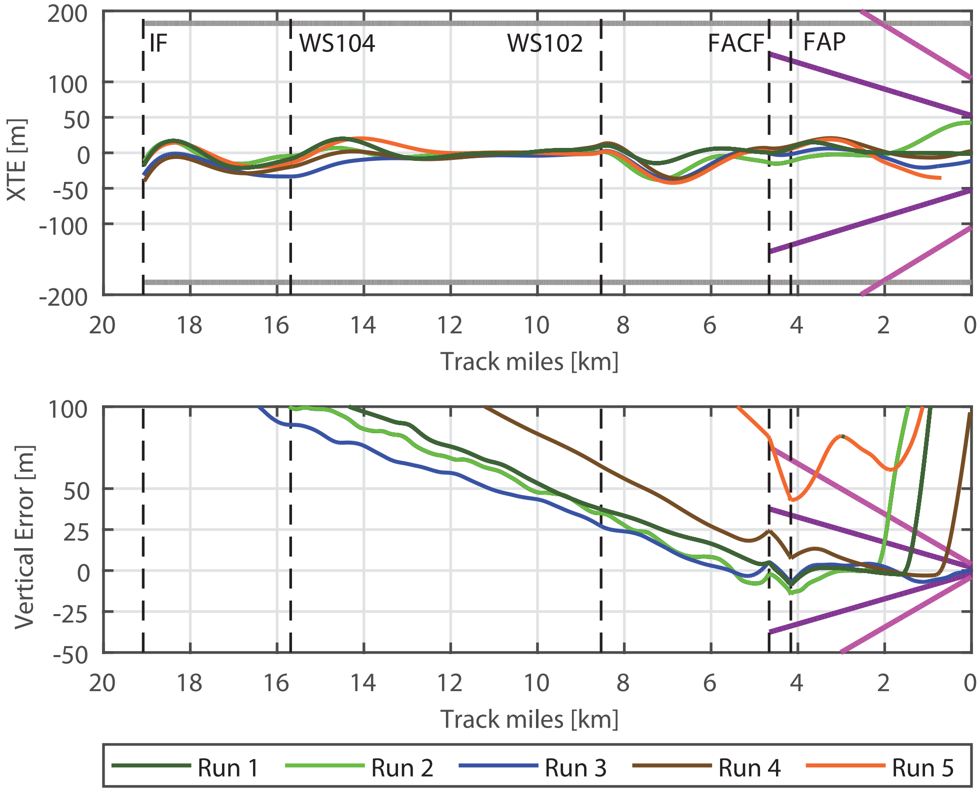

Fig. 6 Simulator assessment: Cross-track error (upper plot) and vertical error (lower plot) during the runs. For orientation, the respective half and full scale LPV deflections are plotted in purple and magenta, respectively. The RNP 0.1 TSE two-sigma value of ±182.5 m is plotted in gray.

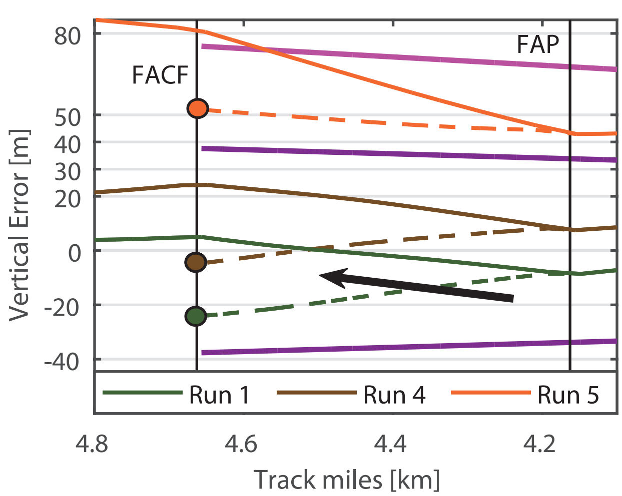

Fig. 7 Simulator assessment: Vertical error during runs 1 (baseline), 4 (ISA+15) and 5 (ISA+25) across the FACF - FAP segment. For orientation, the vertical half and full scale LPV deflections are plotted in purple and magenta, respectively.

revealed this coding to be sufficient for the approach to be recognized and presented to the pilots as RNP AR, where the RNP AR deviation bricks can be overlaid with those of LPV on the PFD except within the final approach under LPV guidance. During the test runs, RNP 0.1 performance was achieved even with the most adverse, yet permissible wind and in considerable turbulence, validating the truncation of the OAS system and the resulting lower OCH. While the vertical error performance and the glide path interception were generally smooth, the glide path was missed due to pilot configuration errors for the maximum temperature assumed in the approach design (ISA+25). Even though we can still show that the interception would likely have happened properly in the correct configuration, further assessments are needed to investigate whether the horizontal transition segment between the RF legs and the LPV segment, which we minimized in length, might be too short to compensate for the temperature-induced altitude difference when changing from barometric to LPV altitude. For safety reasons, it is in any case advisable to limit the approach to a temperature slightly below ISA+25 to provide some buffer for off-nominal behavior.

A recent attempt to use the same coding for the Rockwell Collins FMS of an Airbus A220 failed because the coding requirements imposed by Rockwell Collins did not allow our implementation. Moreover, it is possible that our coding will only work for a limited amount of time since the next edition of the PBN manual foresees changes to the A-RNP specification where A-RNP can, among other things, no longer be used for the FAS [20]. Assuming that existing DQRs are updated accordingly, our coding would then be generally prohibited since it uses A-RNP for the final approach.

As long as universal coding solutions are not guaranteed, the publication of generalized procedure design rules does not make sense either as those are ultimately based on a certain navigation performance. However, based on our work, we expect that OAS systems can be curtailed for RNP AR to LPV approaches according to the RNP value coded for the final (and missed) approach segments (2x RNP value semi-width), which constitutes an advantage over conventional LPV approaches even for RNP 0.3. Regarding the merging of RF leg protection areas with OAS systems, we consider it safe to adapt the existing rules for RNP to LPV to RNP AR, provided that the transition to LPV guidance is shifted towards the LPV segment for low RNP values in the intermediate approach. Regardless of possible limitations in the LPV segment, that can already help achieve significant benefits for approaches where the feeder segments are subject to tight spatial constraints.

Lastly, choosing a length of less than 3 NM for the final approach did not cause difficulties of any kind during our tests. It might therefore be an option to review the minimum length requirement of Ref. [13] to provide for more flexible approach design options in the future.

Our experiment showed the potential of straight final approaches guided by a FAS-DB (SBAS as in our case or possibly also based on a ground-based augmentation system, GBAS [21]) combined with RNP AR to optimize the obstacle protection, thus achieving lower minima in complex environments while increasing safety and efficiency. However, the following actions will need to be taken to guarantee a harmonized implementation in the future:

In the area of standards and regulations, the RNP AR navigation specification needs to be modified to include LPV final approaches. RNP AR procedure design criteria need to be further developed likewise to incorporate straight final approach segments guided by a FAS-DB. Current RNP AR airworthiness and operational approval requirements may also require a revision. With regard to coding, the current route qualifier policy in the ARINC standard 424 [14] will require a revision to ensure that procedure data continuation and path-point records, as required for FAS-DB-guided approaches, can also be used for RNP AR approach procedures. Further assessments are needed in the field of training and human factors to investigate the workload and the margin for pilot error when flying tight turns to intercept very short precision approaches in obstacle critical environments and extreme conditions. Last but not least, the avionics industry and research institutions need to assess whether changes or improvements in the display of information to the pilot are required when flying these approaches. As a minimum and based on our experiment, we suggest the presentation of RNP AR lateral and vertical deviation bars in all phases but driven by the FAS-DB within the final approach and augmented by a second deviation indication which represents the alternative navigation sensor, during transition phases. Moreover, the combination of lower RNP values for the final approach and higher RNP values for the missed approach still needs to be investigated with regard to the actual navigation performance in the case of a go-around as long as FMS behavior similar to conventional LPV approaches cannot be assured.

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