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Analysis of safety performances for parallel approach operations with performance based navigation

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Abstract—**This paper presents a sensitivity analysis of safety performances for independent parallel approach (IPA) operations, using performance based navigation (PBN) transitions connecting to final approaches still relying on ground based landing system (ILS, MLS or GLS). The analysis relies on a stochastic modelling (Monte Carlo simulations), addressing both normal and non-normal (blunder) operations, with a total of 1.700.000 runs for normal operations and 180.000.000 runs for non-normal. The focus is on the intercept phase with two parameters considered: runway spacing and location of the intermediate fix. The results indicate that, assuming a lower blunder rate, performance based navigation transitions to final provides a better safety performance in terms of loss of separation and risk of collision than vectoring to final. They also reveal that the risk of collision with performance based navigation to final is more sensitive to the location of the intermediate fix, thus requiring a careful design.**

Keywords: parallel approach operations, performance based navigation, safety performance, collision risk modelling.

I. Introduction

This paper presents a sensitivity analysis of safety performances for independent parallel approach operations using performance based navigation (PBN).

The focus is on the intercept phase, with PBN transitions connecting to the final approaches still relying on ground based or ground-augmented landing system (ILS, MLS or GLS – collectively referred to as 'xLS'). The motivation is to assess the safety benefits of using such transitions in replacement of conventional radar vectoring, and to determine their appropriate geometry and design properties.

The analysis relies on a mathematical / stochastic modelling (Monte Carlo simulations), addressing both normal and non-normal (blunder) operations, with a total of 1.700.000 runs conducted for normal operations and 180.000.000 runs for blunder.

After a state of the art review, the paper briefly introduces the context of the study, the regulatory aspects and safety objectives. It then describes the mathematical / stochastic modelling, and presents the experimental setup, followed by the results of the analysis for both normal and non-normal (blunder) operations.

This study has been conducted as part of SESAR2020 programme (PJ01-03A).

II. State of the Art

A. Regulations and specifications

Simultaneous operation of parallel runways is specified in ICAO *Doc 9643 Manual on Simultaneous Operations on Parallel or near parallel Instrument Runways (SOIR)* [1]. The basic layout and constraints of a dual parallel approach configuration is depicted in Figure 1.

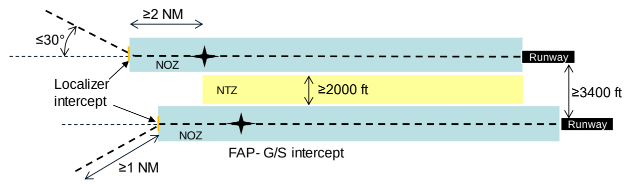

Figure 1. Schematic runway configuration and approach layout as specified by ICAO

Until recently, only vectoring was permitted to intercept the final approach segment at a maximum angle of 30° and at least 2 NM ahead of the Final Approach Point (FAP). However a new ICAO SOIR amendment specifies that the final approach course or track can now be intercepted either by radar vectoring or by a published arrival and approach procedure that intercepts with the Initial Approach Fix (IAF) or Intermediate Fix (IF). Before intercept and until established on extended runway centerlines, aircraft on adjacent tracks have to be separated by 1000ft vertically or 3NM laterally. As soon as vertical separation is reduced, a No Transgression Zone (NTZ) at least 2000ft wide must be installed between both approach tracks acting as safety net. In case an aircraft penetrates the NTZ, the controller gets visual notification and has to advice the crew to return to the intended flight path and potentially threatened aircraft to break out of the approach sequence. Additionally, requirements for technical equipment are fixed (e.g. radar accuracy, update frequency, etc.).

While ICAO specifies dual parallel runway operation only, FAA permits independent operation even for triple parallel runways. In all cases, the minimum runway spacing is 3400ft – or 3000ft, providing that additional requirements are met [2].

B. Safety studies

Safety analyses around parallel approaches procedures started as early as in the 1960s, mainly driven by the FAA and MITRE Corporation. Studies aimed at developing the safety requirements to allow for simultaneous parallel runway operation [3, 4]. FAA started three related programs: the Precision Runway Monitoring (PRM) Demonstration Program, the Multiple Parallel Approach Program (MPAP), and the Converging Approach Standards Technical Working Group (CASTWG). All studies so far assumed that separation during intercept is granted via procedure design at all times. Consequently, research focused on the final approach part only, where lateral and vertical separation is reduced [5, 6, 7].

In 2011, the *Established on RNP* (EoR) concept was proposed by the FAA Performance-based operations Aviation Rulemaking Committee (PARC) [8]. Here, aircraft are considered established well before intercepting final approach course when following an RNP flight leg. This concept allows more flexible procedure designs. The concept studies found the collision risk to be acceptable for dual parallel runways if spaced at least 3,600ft (3,900ft for triples) and if intercepting final approach at 10° for a track-to-fix design [9]. A following study with radius-to-fix procedures led to similar results [10]. For dual and triple parallel runway configurations, EoR procedures are meanwhile permitted by FAA Order JO 7110.65X [2]. The ICAO SOIR amendment also makes provision for a similar concept, which is distinguished from the FAA concept in that it specifically requires the use of RNP AR APCH navigation specification.

With the foundation of a collision risk model framework focusing on aircraft approaching large airports with parallel runways, in 2010, TU Dresden started the development of a high performance computing tool. This tool is able to both represent normal operating aircraft behavior affected by navigation tolerances using a Monte-Carlo simulation engine and abnormal behaviour induced by various hazards (e.g. potentially poor man-machine-interaction) using an agent based model simulation approach (ABMS) [11, 12, 13, 14, 15, 16, 17, 18].

Recent research started investigations on replacing straight-in ILS guided final approach by RNP procedure also for independent parallel approaches [19, 20, 21, 22]. The focus is still on the final approach part, only.

C. *Hazard identification*

Originally, research focused on non-normal operation (i.e. blunder events) along the final approach leg, after aircraft are established on ILS. A blunder is an aircraft that unexpectedly deviates from its intended flight path for reasons other than navigation accuracy. In 2010, an investigation of 1 000 000 flight tracks led to a probability of one blunder per 24 000 approaches [23]. Reasons could be equipment failures or human error [24].

Reducing separation during intercept requires however investigating abnormal events upstream of the final approach, as well. With the EoR concept, FAA started to study blunder events during turn-on final approach course [9, 10].

D. *Modelling techniques*

For their studies, FAA developed a two-phase simulation model: *Airspace Simulation and Analysis for TERPS* (ASAT). During the first phase, data is acquired in real-time human-in-the-loop (HITL) simulations (e.g. human performance, aircraft behaviour, etc.). After fitting those data with probability distribution functions (PDF), a Monte-Carlo fast-time simulation is started in which this data is complemented by data from technical documentation [25]. This approach allows increasing statistical significance of the results. During MPAP, this simulation was used to investigate dual, triple, and quadruple parallel runway configurations in the US [6]. Since then, a new version of the tool (ASAT Next Generation, ASAT^{ng}) was developed.

III. CONTEXT AND APPROACH

This study is part of a project aiming at improving parallel approach operations using PBN, under high traffic peaks, in high density and complexity environments.

One of the motivation is to reinforce safety, in particular reduce the risk of loss of separation at interception. Other motivations involve reduction of environmental impact, increase of arrival capacity and improvement of flight efficiency.

The concept [26] is based on the combination of two elements as depicted in Figure 2 below:

- Initial PBN route structures supporting capacity requirements, with specific geometrical properties to facilitate path stretching/shortening and sequencing;
- PBN transitions connecting to the final approaches and supporting Safety improvements by ensuring segregation of arrival flows and enabling standardized intercepts through closed trajectories.

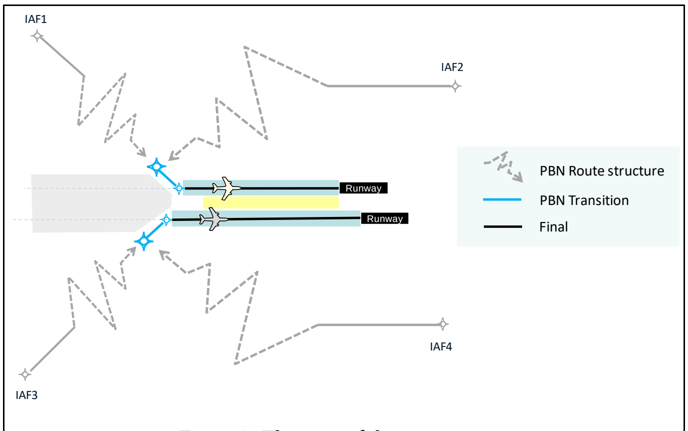

Figure 2. Elements of the new concept

Traffic flows for each runway are sequenced to a single merge point where they join the PBN transition. Since it is a PBN to xLS procedure, it still requires vertical separation prior to being established on final approach.

The present study addresses specifically the second element, i.e. PBN transitions. Investigations on the first element, i.e. initial PBN route structures, may be found in [27] and [28].

The safety risks associated to independent parallel approaches (as described in ICAO SOIR Manual [1]) may be split in two parts: when at least one aircraft is intercepting and when both aircraft are established on final (see figure 3). The latter have been well studied already relying on the notion of NTZ. As this part is considered identical when intercepting with

PBN or with vectoring, the study focuses on the safety risks at/around the interception, prior invoking the NTZ.

Two cases relevant for the safety risk analysis are addressed:

- normal case where the aircraft/pilot respects the prescribed route and/or ATC instruction which could however lead to a safety risk;
- non-normal (blunder) case where the aircraft/pilot deviates from the prescribed route and/or ATC instruction without detection at flight crew level[1].

In this paper, the safety risk associated to the normal case is characterized by the risk of loss of prescribed ATS surveillance separation minima (3NM/1000ft separation minima infringement) whereas the safety risk associated to the blunder case is characterized by the risk of collision (500ft miss distance criteria violation / slant range distance between aircraft equal or less than 500ft). It is assumed for the latter case that the ATC tactical conflict management barrier is no more (or not sufficiently) efficient, hence the use of the collision criterion instead of the loss of separation criterion.

The target levels of safety per approach called safety criteria are assumed in this paper to be 10^{-5} per approach for loss of separation and 5×10^{-8} per approach for collision.

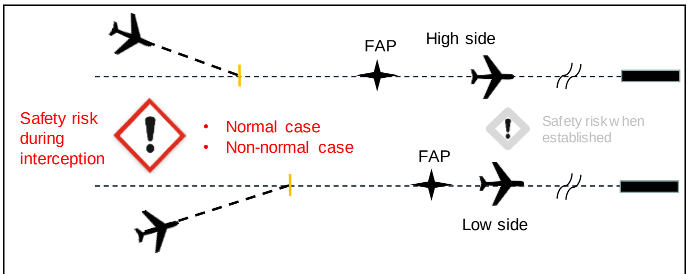

Figure 3. Safety risks associated to independent parallel approaches

IV. MODELLING

A. Overview

The collision risk model is designed and implemented as a twofold fast-time Monte-Carlo simulation [29, 30]. The implementation is based on an air traffic simulation framework developed at TU Dresden, which has been successfully employed in several safety studies [11, 12, 13, 14, 15, 16, 17]. On the one hand, critical blunder events are modelled explicitly to estimate collision risks imposed by aircraft behaving abnormally. This extension of the current model and simulation is highly inspired by the approach as employed in FAA's ASAT tool [25]. Additionally, the scope is extended from final approach to the upstream intercept area, where blundering aircraft may also occur, as introduced in Section III (e.g. due to missed intercept). On the other hand, the probability for separation infringement during normal operation is modelled at macroscopic level [11]. Separation infringements are of particular interest in the intercept area, where no further safety net – like the NTZ during the final approach – is installed.

The model allows configuring the approach environment as either a vector to xLS or a PBN to xLS setup. The main parameters of the geometry are runway spacing, threshold displacement, final approach length, nominal intercept point and intercept angle. The actual intercept point of an approaching aircraft depends on the traffic configuration. It could be a Normal- or a Weibull distribution, depending on traffic load and the procedure in use. Further stochastic traffic parameters are aircraft separation and aircraft speed distributions.

B. Separation infringement / normal operation

For determining the probability of a separation infringement, no dedicated events (like a blundering aircraft) could be isolated for simulation. Rather, an infringement can occur during normal operations. Therefore, a macroscopic approach has been chosen to determine the safety metric [11], i.e. other than for blunder events, where aircraft-, human- and surveillance performance was modelled explicitly (cf. section IV.C below). With this approach, nominal aircraft trajectories are simulated and deviations from that path are represented by distribution functions. Those functions include all possible sources of error and reflect the so-called Total System Error (TSE) as given by e.g., required navigation performance (RNP) or based on data analyses and the resulting actual navigation performance (ANP) [31, 32].

Encounters are simulated for a single aircraft versus a sequence of aircraft on the adjacent approach track. The scope of simulation comprises those parts of the approach environment, for which separation requirements apply, i.e. the pre-intercept flight leg, the intercept itself and begin of the straight-in approach leg, until the NTZ starts, at which separation is reduced by design. At each step of the simulation, the probability for a separation infringement (laterally and vertically) between two adjacent aircraft m and n is computed, cf. Equation (1). Equation (2) exemplifies the calculation for the vertical part (Z-Axis), which is a convolution of the vertical track tolerances of the two aircraft at time t given as probability density function g.

$$P_{SI}(m,n,t) = \prod_{d\in\{x,y,z\}} P_d(m,n,t) \qquad (1)$$

$$P_z(m,n,t) = \int_{-S_z}^{S_z} \int_{-\infty}^{+\infty} g_{m,z}(u,t)\cdot g_{n,z}(u+s,t)\,du\,ds \qquad (2)$$

The calculation is performed for each simulation step. After simulation of an approach event has finished, all those single (momentary) values are cumulated, giving the probability value $P_{SI}(m,n)$. Since an approaching aircraft may encounter multiple adjacent aircraft, the probability for a separation infringement is calculated by computing the counter probability of no separation infringement between the aircraft m and any of the adjacent aircraft $(n_1 \dots n_k)$, as depicted in equation (3).

$$P_{SI}(m) = 1 - \left[\left(1-P_{SI}(m;n_1)\right)\cdot\left(1-P_{SI}(X;n_2)\right)\cdot \dots \cdot \left(1-P_{SI}(X;n_k)\right)\right] \qquad (3)$$

Finally, the overall probability of separation infringement of the whole approach scenario is calculated over all N simulated

[1] For the purpose of this paper the aircraft deviation (blunder) is characterized by an aircraft not intercepting the xLS axis and continuing its flight at the same altitude and same heading/track with no ATC recovery unless NTZ is invoked.

approaches using equation (4). This finally results in the probability of separation infringement per approach operation safety metric.

$$P_{SI} = \frac{1}{N} \sum_{l=1}^{N} P_{SI}(m_l) \qquad (4)$$

C. Blundering aircraft

For the simulation of blunder events, real aircraft trajectories are simulated based on aircraft dynamics, human performance (e.g., reaction time), navigation accuracy, and surveillance capabilities (radar accuracy and update rate). Aircraft are considered to be constantly monitored during approach. For the intercept part, it is assumed that neither crew nor ATC intervention prevents aircraft from eventually crossing the adjacent approach path. This limitation results in conservative (more pessimistic) results. Reasons for blunder during intercept are not modelled explicitly. Rather, the overall probability for such an event can be configured accordingly. The simulation begins at the point at which the blunder starts to leave its intended flight path. Depending on the individual point and angle of intercept, aircraft may penetrate NTZ even if not initially established on final approach. In case of such NTZ violation, evasive maneuvers are commanded. The blundering aircraft is consequently supposed – for most of the cases – to revert to its original flight track. Any threatened aircraft on the adjacent approach track (the *evader*) has also to react on that threat and perform a breakout, so leaving the approach stream and being re-sequenced. In few cases, it is assumed that blundering aircraft may not follow to the ATC instructions. This event is called a *worst-case blunder*. At each simulation step, the slant range between blunder and the nearest aircraft operating on the adjacent approach track is calculated and the overall minimum distance for the entire approach is recorded. If this value falls below a pre-set minimum (called test criterion), a test criterion violation (TCV) is recorded. The test criterion represents the threshold below which a mid-air aircraft collision is assumed. The collision risk itself is the *expected* number of TCVs per approach: $P(TCV)$. It is calculated as given in equation (5) with N_{TCV} being the number of recorded TCVs and N_{event} the total number of simulated blunder events. The factor two compensates for always considering two aircraft and thus two approaches per event. Since only abnormal events are simulated, the factor $P(Blunder)$ is applied, which gives the probability of a blunder event to occur at all.

$$P(TCV) = P(Blunder) \cdot \frac{N_{TCV}}{2 \cdot N_{event}} \qquad (5)$$

V. Experimental Setup

The objective of this paper is to assess whether, in the context of independent parallel approaches, a PBN transition replacing the vectoring phase could improve the safety level. The focus is on a reduction of the risk of loss of separation and/or collision for the approach interception part.

The probability of loss of separation (due to e.g. navigational errors/inaccuracies) and collision risk (due to blunder during interception) are only accounted for prior to the time when the NTZ can be invoked i.e. close to, or at intercept, before aircraft are established on adjacent final approach courses or tracks.

The study finally provides a sensitivity analysis of the safety level with respect to key parameters.

The experimental setup is therefore supporting a comparison between a 'reference' scenario based on xLS interception through radar vectoring for both runways, and a 'future' scenario based on a PBN transition to xLS for both runways, while varying specific parameters.

Figure 4 and 5 describe these two scenarios. In both cases, the procedure and/or operating method is assumed to incorporate at least a 1000ft vertical separation between aircraft until established on the appropriate adjacent approach path.

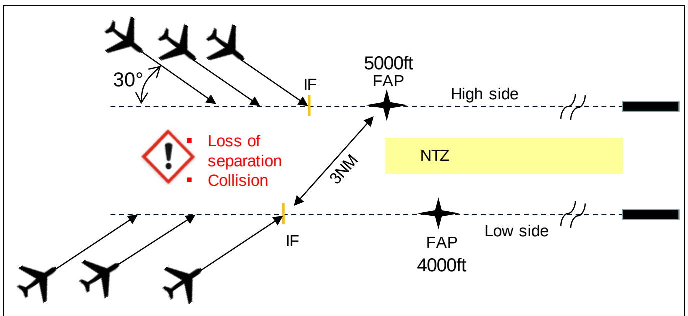

Figure 4. Approach structure and traffic distribution for the reference scenario (vectoring)

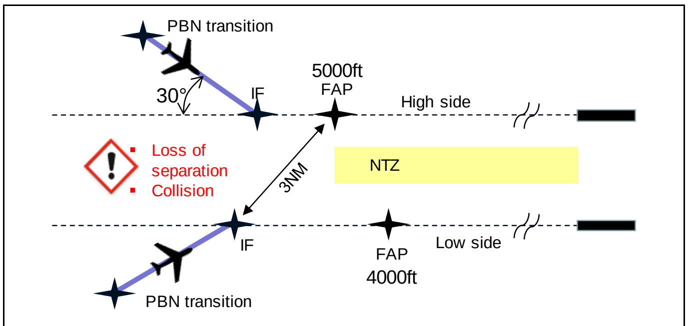

Figure 5. Approach structure and traffic distribution for the future scenario (PBN transition)

Notes:

- In the considered approach structure, the IF is considered to be the nominal interception limit of the final course or track.
- In order to avoid systematic losses of separation between low side aircraft closing the IF but not having intercepted yet their final approach course or track, and high side aircraft starting their descent on the glide slope, provision shall be made for a minimum 3NM diagonal distance between the low side IF and the high side FAP. Indeed, the NTZ cannot be invoked in this situation.

Several parameters could influence the safety risks identified in section III above, and are varied in the experimental setup:

- *Runway spacing and FAP-IF offset*: these two parameters as illustrated in Figure 6 below are equally applicable to the reference and future scenario, for both risks (loss of separation or collision). The runway spacing will be varied between 0.56NM (3400ft)[2] and 3NM (18228ft). The 'FAP-IF offset' designates a displacement of the low side IF (hence of the low side PBN transition to final), with respect to its nominal location at a 3NM diagonal distance from the high side FAP. Such an offset may need to be considered to account for local constraints such as populated areas. It will be varied between 0NM and +4NM. The Intermediate Fix (IF) corresponding to an offset of 0NM is called IF0, as another example an Offset of +3NM is called IF3.

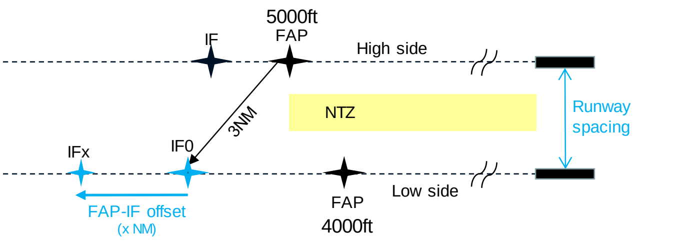

Figure 6. Runway spacing and FAP-IF Offset parameters

Note: the locations of the high side IF, FAP and low side FAP are considered fixed once the intercept altitudes are defined (here resp. 5000ft and 4000ft). The position of the low side IF is determined by the values of 'runway spacing' and 'FAP-IF offset'.

- *Radar vectoring distribution*: the radar vectoring dispersion of intercept point will be varied using a Weibull distribution (λ and k parameters) in order to represent peak traffic and medium traffic situations as illustrated in Figure 7. The peak traffic situation uses a wide vectoring distribution (λ=3.9167583; k=1.1126423) and the medium traffic situation uses a narrow vectoring distribution (λ=1.9; k=1.3) as shown in Figure 9. These parameters are only applicable to the reference scenario, for both risks (loss of separation or collision).

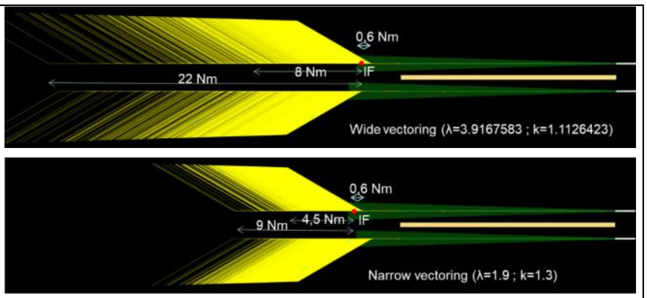

Figure 7. Modelling of vectoring: 'wide' vs. 'narrow' distributions

- *Blunder rate*: this parameter as described in figure 8 below is only applicable to the collision risk in both reference and future scenario. This parameter will be varied between 10-1 and 10-5 in this experiment. The literature [33] shows that a blunder rate between 10-4 and 10-5 is more realistic. It is expected that this rate would be lower for PBN than for vectoring.

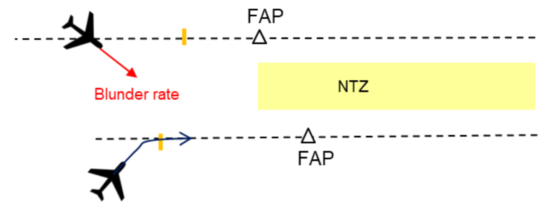

Figure 8. Blunder rate parameter

The RNP value was not varied for this first analysis. Instead we used a fixed value which was determined based on observed performance (e.g. actual radar measurement) corresponding to an RNP value of 0.22 (see [34] and [35]) however different RNP values can be set in the configuration module and could be considered in further studies.

VI. Analysis

The analysis of modelling results are presented for the normal case and non-normal case in relation with the key parameters identified above.

A. Normal case (loss of separation)

The safety risk for the normal case is characterized by the probability of loss of separation (1000ft or 3NM) and we are assuming in this paper that a probability of less than 10^{-5} per approach is an acceptable safety criterion (other criteria may be considered e.g. at ANSP level). The threshold for the loss of separation was set at 2.9NM and 850ft in the CRM configuration module.

The probability of loss of separation as a function of FAP-IF Offset for the PBN, wide and narrow vectoring scenarios has been analyzed for different runway spacing as shown in Figure 9 below (each chart for a given runway spacing). In absolute terms, the probability is always lower than the 10^{-5} per approach limit in all scenarios.

Comparing the scenarios, the probability is always lower with the PBN transitions than with narrow vectoring, itself being lower than with wide vectoring. This ranking between the different interception types in terms of safety benefit is an effect of the induced levels of trajectory dispersion at intercept around the IFs.

The variation of the FAP-IF Offset affects the probability for all interception types (PBN, wide and narrow vectoring). For positive FAP-IF Offset (IF>IF0) as studied, the risk of loss of separation increases with the FAP-IF offset value. This increase is due to a longer exposure to the risk of losing the 1000ft separation minima when a 3NM lateral separation is not provided between a pair of aircraft on adjacent runway extended centerlines, at least one of which is not yet established on its final course. For higher values of the FAP-IF offset, the probability remains stable since that exposure does not increase anymore (this is more visible for runway spacing of more than 2NM).

[2] Shortest runway spacing for independent parallel operations.

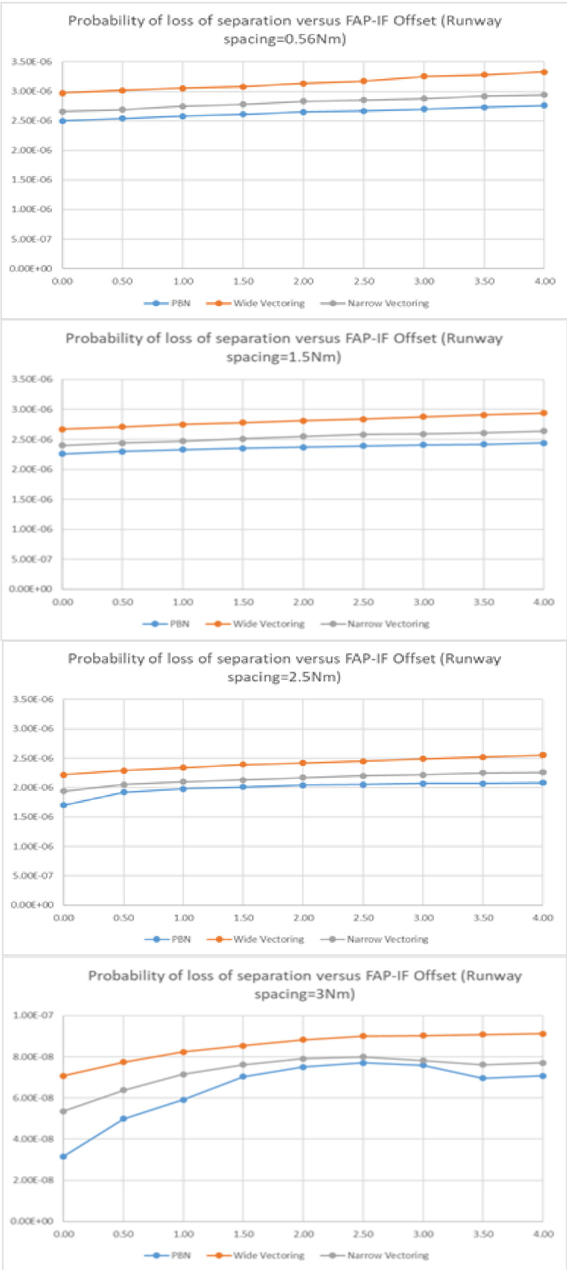

Figure 9. Loss of separation with different FAP-IF Offset (normal case)

Logically, increasing the value of runway spacing results in smaller probabilities of losing separation. When the runway spacing is close, or equal to 3NM the probability of loss of separation decreases significantly and is well below the 10^{-5} threshold for all types of interception. In that case, the occurrences of loss of separation are due to a combined exposure to the risks of losing the 3NM lateral separation and the 1000ft vertical separation, on much more localized portions of trajectories. The peak observed at a 2.5NM offset corresponds to the low side IF located abeam the high side IF - maximizing this combined exposure.

Figure 10 below provides a 'transverse' view of the probability of the loss of separation as a function of runway spacing, for the three interception cases (PBN, wide and narrow vectoring) and in the case of a FAP-IF Offset set at 0NM (IF0).

The probability of losing the separation reduces with the increase of the runway spacing for all types of interception. There is a gradual reduction rate of the probability between 0.56NM and 2.5NM runway spacing followed by a sharp decrease after 2.5NM (for PBN a reduction from 2.10^{-6} per approach for a 2.5NM runway spacing, to 3.10^{-8} per approach for a 3NM runway spacing). This is due to the lower risk of infringing the 3NM separation minima with such runway spacing for all types of interception (PBN and vectoring).

Looking at a quantification of the potential safety improvement between the various scenarios, Figure 11 below shows that, for runway spacing between 0.56NM and 2.5NM, a FAP-IF Offset set at 0NM, the loss of separation probability is reduced by an average of 20.3% with PBN transitions compared to wide vectoring and 7.7% compared to narrow vectoring. The same trend is observed for other values of the FAP-IF, with respective reductions in the range of 18 to 21% and 6 to 9%.

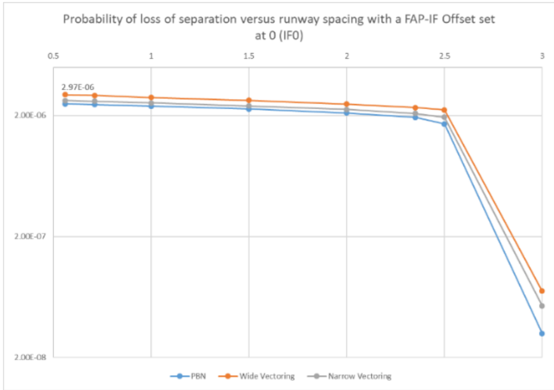

Figure 10. Loss of separation with different runway spacing

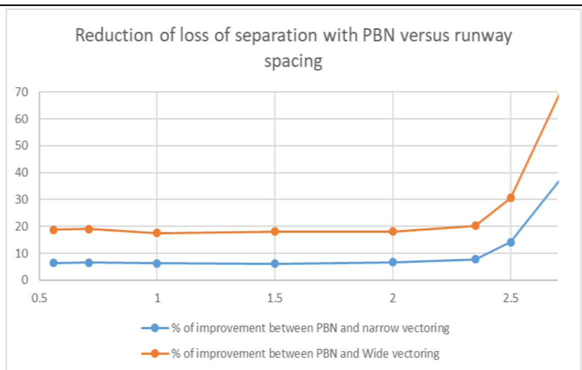

Figure 11. Safety improvement for different runway spacing

B. *Non-normal case (risk of collision)*

The safety risk for the blunder case is characterized by the probability of collision (500ft slant range distance) and we assume in this paper that a probability of collision of $5x10^{-8}$ per approach is an acceptable safety criteria but it does not prevent to use a different criterion locally.

The risk of collision is determined considering different runway spacing with different blunder rates and for the three interception types (wide or narrow vectoring and PBN). The following figures present results with a same blunder rate for vectoring and PBN but it is expected that the blunder for PBN would be lower (see remark below Figure 16).

It can be seen in Figure 12 below for FAP-IF Offset set at 0NM (IF0) that a simple arithmetic relationship exists between the blunder rate and the risk of collision. For instance if we consider a runway spacing of 2NM, the safety criteria (5x10-8/approach) is exceeded for a blunder rate greater than 10^{-2} whereas it is never exceeded for lower blunder rates (e.g. 10^{-3}).

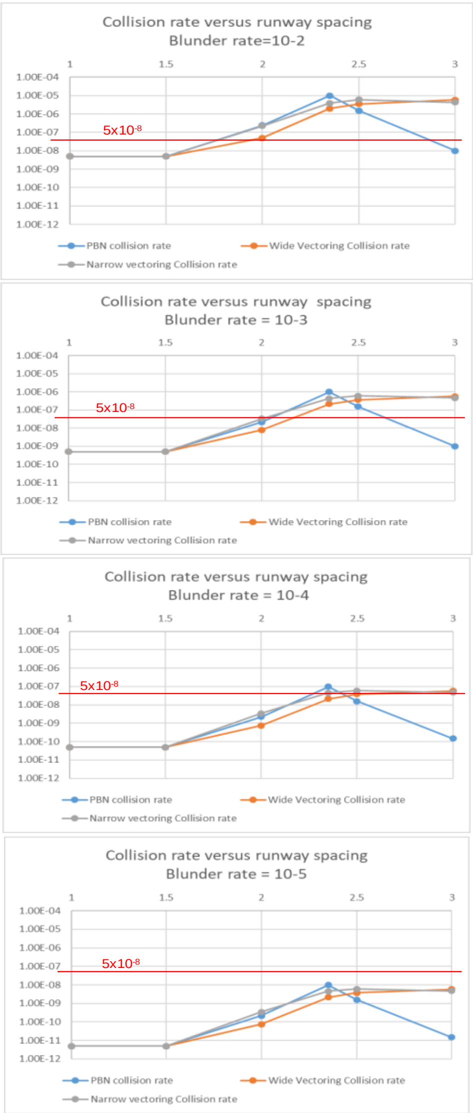

Figure 12. Collision rate with different runway spacing

Figure 12 above shows also that for a runway spacing of 2.35NM there is a collision rate peak for PBN and vectoring (narrow/wide). This peak is due to a specific geometry leading to a systematic closing between aircraft missing their xLS interception at 4000ft (on the xLS low side) and other aircraft descending on the glide through 4000ft (on the xLS high side) as illustrated in Figure 13 below. The red dotted line shows the trajectory leading to this maximum collision rate on the xLS high side in case of blunder[3]. This trajectory is characterized by the IF location (IF0 in this case) and the interception angle therefore for each runway spacing there is an IF location which will lead to this collision rate peak as shown in Figure 14.

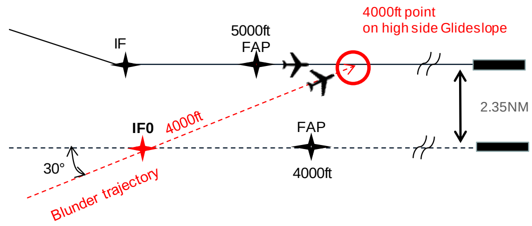

Figure 13. Maximum collision rate trajectory at 2.35NM runway spacing

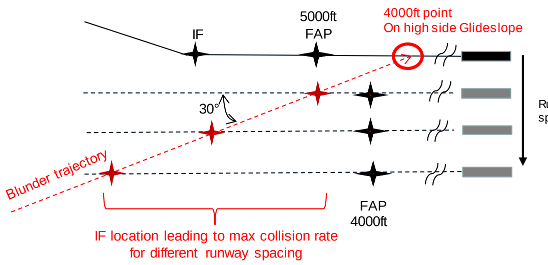

Figure 14. Maximum collision rate trajectory for different runway spacing and IF location

For such IF locations and runway spacing lower than 2NM, the risk of collision in case of blunder is greater with PBN compared to wide vectoring and almost equivalent compared to narrow vectoring. However with such runway spacing and with a blunder rate of 10-3, the risk of collision never exceeds the safety target set at 5x10-8 per approach.

The analysis of the probability of collision as a function of the FAP-IF Offset allowed us to identify for each runway spacing the most appropriate IF location. Figure 15 illustrates the safest IF location satisfying the safety target set at 5x10-8 per approach for a runway spacing of 2.35NM with a focus of the offset between 0NM and +2NM. In such case for PBN, IF should not be located between [IF0] and [IF1] because the collision risk then exceeds the safety target.

[3] With a blunder as defined in this paper: level off at 4000ft with no lateral deviation and no ATC recovery unless NTZ is invoked.

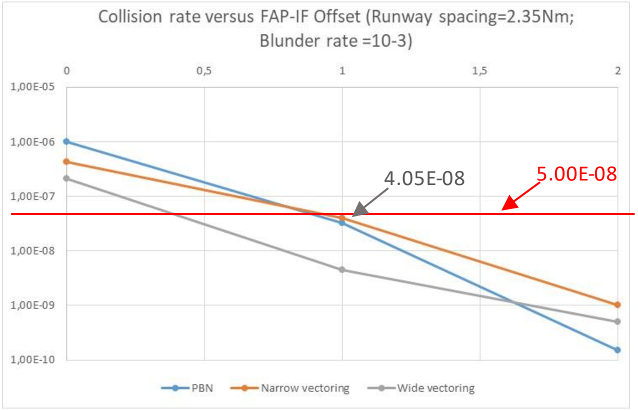

Figure 15. Collision rate with FAP-IF Offset variation

For a runway spacing of 3NM, the risk of collision with PBN is significantly lower compared to vectoring (wide and narrow). This is due to the smaller trajectory dispersion with PBN and the presence of the NTZ for the particular geometry under analysis. Indeed with such geometry (runway spacing and IF location), the collision risk with PBN is prevented by ATC monitoring and recovery for blunders penetrating the NTZ. Figure 16 shows that for PBN (on the upper part), not only as expected the intercept part is quite localized and easier to monitor, but also more blunders are penetrating the NTZ and can therefore be recovered by ATC. On the other hand for wide vectoring (on the lower part) the intercept area is significantly larger, and less blunders are penetrating the NTZ; therefore this mechanism is not triggered to support ATC detection/recovery. The yellow rectangle shape represents the NTZ in figure 16.

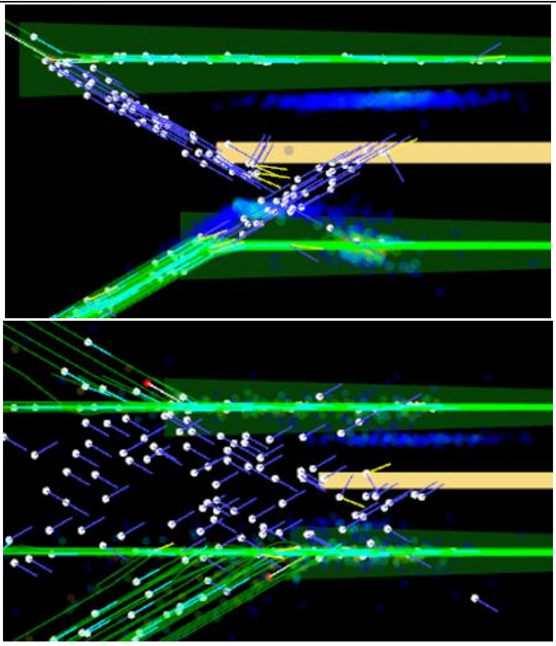

Figure 16. NTZ impact on PBN (top) and on wide vectoring (bottom) for a runway spacing of 3NM

Finally, an important remark is that, as stated above, in this paper we have compared PBN and vectoring (wide and narrow) considering the same blunder rate. In reality, the blunder rate should be different between PBN and vectoring because the risk of not capturing the xLS approach or capturing a wrong xLS approach is highly dependent on the publication (AIP, charts), flight crew procedure and aircraft equipment. PBN to xLS, offering built-in mitigations by nature, should therefore result in lower blunder rates.

VII. CONCLUSION

This paper presented a sensitivity analysis of safety performances for independent parallel approach operations, using PBN transitions connecting to xLS (ILS, MLS or GLS) final approaches. The focus was on the intercept phase, and the analysis used a mathematical/stochastic Monte Carlo modelling relying on a high number of runs in order to achieve statistical significance.

In the two main cases covered by the assessment (normal and non-normal operations), PBN transitions to final provided a better safety performance compared to vectoring to final.

For normal operations, the probability of losing the separation was found to be always lower than the 10^{-5} per approach threshold for both scenarios. Nevertheless the PBN to xLS scenario showed a significant safety improvement: for runway spacing between 0.56NM and 2.5NM and with FAP-IF Offset set at 0NM, the loss of separation probability was reduced by an average of 20.3% compared to a wide vectoring scenario and 7.7% compared to a narrow vectoring scenario. The probability of losing the separation was found to be minimum when FAP-IF offset is the smallest (corresponding to the shortest exposure to the risk of losing the 1000ft separation minima when the lateral separation is reduced).

For non-normal operations (blunder), the measurements showed that for runway spacing smaller than 2NM and blunder rate lower than 10^{-3}, the risk of collision is always lower than the 5×10^{-8} approach safety criteria. The risk of collision with PBN is more sensitive to IF location, which necessitates a careful selection of this location in order to achieve equivalent or even better performance compared to vectoring. However, it should be highlighted that the study used the same blunder rate for PBN and vectoring, although in reality this parameter should be lower with PBN, leading to an even lower risk of collision when compared to vectoring.

Finally, the collision risk model presented in this paper facilitates the demonstration *a priori* of the safety performance during interception (risk of loss of separation and risk of collision) based on a given geometry of the approach (runway spacing, FAP location, FAP-IF Offset). Conversely, it can also help to identify the most appropriate design parameters when they are not fixed yet. Importantly, a given geometry (e.g. IF location) could be optimal for the blunder case whereas it is not optimal for the normal case, therefore a trade-off may be necessary. In addition local constraints (e.g. populated areas) may also influence the design geometry.

Further work should involve the refinement of the blunder model in particular to incorporate a vertical blunder and the ATC recovery. Furthermore different RNP performance should be tested in order to identify their impact in normal and non-normal cases.

References

[1] ICAO, *Doc 9643 Manual on Simultaneous Operations on Parallel or near parallel Instrument Runways (SOIR).*

[2] FAA, *Order JO 7110.65X - Air Traffic Control*, 2017.

[3] A. L. Haines and W. J. Swedisch, "Requirements for Independent and Dependent Parallel Instrument Approaches at Reduced Runway Separation," 1981.

[4] S. V. Massimini, "Simultaneous Independent and Dependent Parallel Instrument Approaches," MITRE, Virginia, USA, 2006.

[5] PRM Program Office, „Precision Runway Monitoring Demonstration Report," 1991.

[6] FAA, „Terminal Air Traffic Control Radar and Display System Recommendations for Monitoring Simultaneous Instrument Approaches," National Technical Information Service, Springfield, Virginia, 1999.

[7] FAA, „Evaluation of Triple Independent Instrument Landing System Approaches to Runways Spaced 4,000 Ft and 5,300 Ft Apart Using A Precision Runway Monitor System," 2002.

[8] D. Nakamura, PARC RNP Benefits Sub-Team "RNP Established-Parallel Approach", 2011.

[9] FAA, „Safety Study on Simultaneous Independent Approaches Using Established on Required Navigation Performance Approach Procedures with Track-to-Fix Design (DOT/FAA/AFS400/2016/R/01)," Flight Technologies and Procedures Division, AFS-400, Washington, 2016.

[10] FAA, „Safety Study on Simultaneous Independent Approaches Using Established on Required Navigation Performance Authorized Approach Procedures with Radius-to-Fix Design (DOT/FAA/AFS400/2017/R/16)," Flight Technologies and Procedures Division, AFS-400, Washington, 2017.

[11] M. Vogel, C. Thiel und H. Fricke, „Simulative Assessment of Reduced Lateral Separation Minima for the Terminal Airspace," in *International Conference on Research and Air Transportation (ICRAT)*, San Francisco, 2012.

[12] M. Vogel, C. Thiel und H. Fricke, „A Quantitative Safety Assessment Tool Based on Aircraft Actual Navigation Performance," in *4th International Conference on Research and Air Transportation (ICRAT)*, Budapest, 2010.

[13] M. Vogel, C. Thiel, M. Kaiser und H. Fricke, „Model-Based Quantitative Safety Assessment of Innovative Operational Concepts," in *9th USA/Europe Air Traffic Management Research and Development Seminar (ATM2011)*, Berlin, 2011.

[14] M. Vogel, C. Thiel und H. Fricke, „Assessing the Safety Impact of Pilot-to-Airliner HMI Latencies in the context of ATM," in *2nd International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS)*, London, 2012.

[15] K. Schelbert, M. Vogel, C. Thiel und H. Fricke, „Adapting Enroute ATM Complexity Metrics for Terminal Airspace Safety Assessments," in *5th International Conference on Research and Air Transportation (ICRAT)*, Berkeley, 2012.

[16] M. Vogel und H. Fricke, „Investigating the Safety Impact of Time Buffers in Current TMA Arrival Operations," in *28th International Congress of the Aeronautical Sciences (ICAS)*, Brisbane, 2012.

[17] M. Vogel, K. Schelbert, H. Fricke und T. Kistan, „Analysis of Airspace Complexity Factors' Capability to Predict Workload and Safety Levels in the TMA," in *10th USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)*, Chicago, 2013.

[18] M. Vogel, C. Thiel und H. Fricke, „Experimental Quantification of Times Needed to Comply With Air Traffic Control Advisories (FCU & MCDU Interaction)," in *5th International Conference for Research in Air Transportation (ICRAT)*, Bologna, 2015.

[19] G. McCartor und S. Ladecky, „Safety Study Report on Triple Simultaneous Parallel Instrument Landing System (ILS) and Area Navigation/Required Navigatio Performance (RNAV/RNP) Approaches at George Bush Intercontinental Airport (KIAH)," 2005.

[20] FAA, „Safety Study Report on Simultaneous Parallel ILS and RNAV/RNP Approaches - Phases 1A and 2A (DOT-FAA-AFS-440-29)," 2007.

[21] C. Hanses und B. Korn, „Designing segmented independent parallel approach procedures for a mixed-equipage environment," in *Integrated Communication, Navigation and Surveillance Conference (ICNS)*, Herndon, 2015.

[22] C. Hanses, M. L. Ulrey, J. D. Musiak und M. Lapis, „Considerations on aviation standards for simultaneous independent and dependent parallel approaches," in *Integrated Communications Navigation and Surveillance (ICNS)*, Herndon, 2016.

[23] S. V. Massimini, G. C. McNeil und N. Tene, „Frequency and severity of deviations during simultaneous independent approaches to parallel runways," in *Integrated Communications, Navigation and Surveillance Conference (ICNS)*, Herndon, Virginia, USA, 2010.

[24] Y. S. Ebrahimi, „NASA Contractor Report 191549, Volume 1, Parallel Runway Requirement Analysis," 1993.

[25] EUROCONTROL / FAA, „A Concept Paper for Separation Safety Modeling," 1989.

[26] SESAR, „Solution 01-03A: OSED for V1, Edition 00.01.02," November 2017.

[27] B. Favennec, P. Marx, A. Trzmiel, K. Zeghal, P. Berthault und G. Vincent, „How the geometry of arrival routes can influence sequencing," in *AIAA Aviation Technology, Integration, and Operations Conference*, Atlanta, Georgia, USA, 2018.

[28] SESAR, „Solution 01-03A: Validation Report (VALR) for V1, Edition 00.01.00," July 2017.

[29] S. Förster, H. Fricke and M. Vogel, *Collision Risk Assessment Methodology for Parallel Approach Operations*, London: Modelling and Simulation in Flight Simulation Conference, 2017.

[30] H. Fricke, S. Förster und M. Vogel, „Using agent-based modeling to determine collision risk in complex TMA environments: the turn-onto-ILS-final safety case," *Aeronautics and Aerospace Open Access Journal (AAOAJ)*, Bd. 2, Nr. 3, 2018.

[31] C. Thiel und H. Fricke, „Collision Risk on Final Approach – A Radar Data Based Evaluation Method to Assess Safety," in *International Conference on Research in Air Transportation (ICRAT)*, Budapest, 2010.

[32] C. Thiel, C. Seiss, M. Vogel und H. Fricke, Safety Monitoring of New Implemented Approach Procedures by Means of Radar Data Analysis, 2012.

[33] ICAO, „INFORMATION PAPER SASP/2-IP/03," 07/05/18.

[34] C. Seiss, Bestimmung der Navigationsungenauigkeiten von Luftfahrzeugen bei segmentierten RNAV-Anflügen (Segmented RNAV Approach), Dresden: Diploma Thesis, 2012.

[35] F. Nagel, „Lufthansa SESAR AAL Trials," Online Proceedings of Final Approach Operations Symposium, URL: http://www.eurocontrol.int/events/final-approach-operations-symposium, Brussels, 2017.