

AIRBORNE COLLISION AVOIDANCE CONSIDERATIONS FOR SIMULTANEOUS PARALLEL APPROACH OPERATIONS

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Abstract

Required Navigation Performance (RNP) procedures to closely-spaced parallel runways that include curved approach transitions afford many benefits such as reduced track miles, less fuel burn and emissions, and the potential for routings around noise sensitive areas. The Federal Aviation Administration (FAA) NextGen program plans to roll out “Established on RNP” (EoR) simultaneous approach procedures to suitable airports across the U.S. National Airspace System. In addition, International Civil Aviation Organization (ICAO) is planning revisions to guidelines related to these procedures which initially rely on lateral vs. vertical separation.

A major challenge that needs to be addressed for simultaneous approaches to closely-spaced parallel runways relates to nuisance Airborne Collision Avoidance System (ACAS) alerts during normal approach operations. This paper documents joint research by Boeing and DLR to answer this challenge. The objectives were to make recommendations for the proposed ICAO rule changes, compare and contrast analysis methodologies, and suggest mitigation strategies for nuisance ACAS alerts.

1 Introduction

With the advent of satellite navigation and Performance Based Navigation (PBN), more flexible approach procedures with shorter approach lengths (inclusive of curved approach paths or “transitions”) are possible, compared to standard straight-in Instrument Landing Procedure/Area Navigation (ILS/RNAV) approaches [1]. The Federal Aviation

Administration (FAA) has already authorized the use of Required Navigation Performance (RNP) and RNAV approaches for simultaneous approaches to parallel runways [2], and International Civil Aviation Organization (ICAO) is planning similar changes to the simultaneous approach guidelines [3].

However, using only straight-in (final course aligned) approach transitions during these operations, often at large, busy airports, will not enable full realization of the potential benefits of PBN operations. To ensure this is not a constraint in the future, projects have been initiated in the U.S. and Europe to evaluate possibilities of applying curved approach transitions to simultaneous approaches.

Within the FAA’s NextGen framework, Established on RNP (EoR) operations have been implemented at Seattle-Tacoma airport in Washington State, Denver International Airport in Colorado, and planned for further candidate airports [4]. In Europe, ongoing research is evaluating possibilities to implement simultaneous operations involving curved RNP AR transitions at Frankfurt Airport, amongst other cities. Because of the opportunity for curved approach transitions with RNP AR operations to closely-spaced parallel runways, as compared to classical straight-in approaches, a thorough evaluation of safety related aspects such as collision risk and wake encounters needs to be done, as well as the potential for unwanted interaction with commonly used systems such as ACAS [6]. This “nuisance ACAS alert” problem, which refers to ACAS alerts that would arise during normal operations if not carefully prevented by proper approach geometry and procedure design, is the topic of this paper.

The current ACAS implementation, TCAS II [7], basically extrapolates past aircraft lateral and vertical positions into the future, and compares the calculated time to collision or near miss to fixed time-based thresholds. Approach transitions that turn towards the final segment in parallel runway environments increase the risk of nuisance ACAS alerts, particularly during simultaneous operations, and especially without altitude separation. ACAS compatibility therefore requires special attention for procedures intended to be used for these operations.

In this paper, two methods developed in two different projects will be applied to generic approach scenarios with parallel runways. The primary goal is to compare the methods and their results while using them to assess the compatibility of proposed ICAO guidelines for RNP operations, specifically with regard to nuisance ACAS alerting. Finally, we will make recommendations for ACAS-compatible curved simultaneous approach procedures. The paper's sections:

1. Introduction to the issue of ACAS in the design of simultaneous approach operations and the goals of the study
2. Relevant aspects of current ICAO and FAA guidelines for simultaneous approaches to parallel runways
3. Proposed revisions to ICAO and FAA guidelines for simultaneous approach operations
4. ACAS functionality and alerting logic
5. DLR's and Boeing's ACAS evaluation methods
6. Generic approach scenarios and modeling assumptions
7. Results of DLR methodology
8. Results of Boeing methodology
9. Conclusions and recommendations for future design guidance for simultaneous approaches, based on ACAS considerations.

2 Simultaneous Approaches: Today

In this section, current requirements to conduct dependent and independent approaches towards

parallel runways are discussed. We will focus on guidelines drafted by ICAO and by the FAA and identify major similarities and differences. The draft ICAO guidelines will then be discussed.

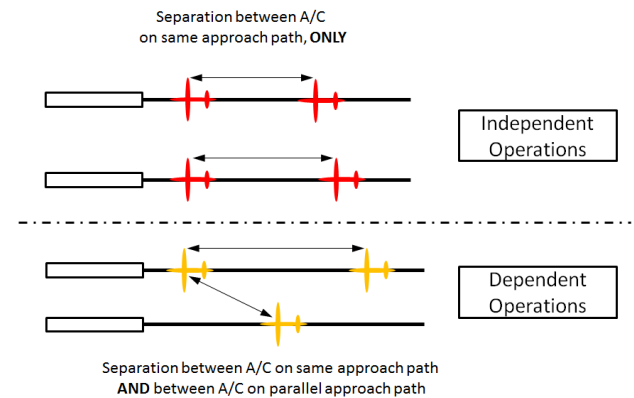


Figure 1. Simultaneous Approach Modes (ICAO [3]).

The ICAO PANS-ATM [8] and Manual on simultaneous Operations on Parallel or Near-Parallel instrument Runways (SOIR) [3] documents as well as the FAA's Controller Handbook [2] identify two modes of simultaneous approach operations to parallel runways: independent and dependent. They stipulate traffic separation during simultaneous modes of operations: independent simultaneous approach operations require wake-based minimum separation with respect to aircraft operating on the same approach path, but as the name implies, there is no requirement for separation between aircraft on the two different approaches as shown in Figure 1. For dependent operations, a diagonal separation between aircraft on the different approaches as well as a wake-based separation to aircraft operating on the same approach path are required as shown in the figure.

2.1 Independent Operations

The general collision risk mitigation strategy with respect to independent operations of parallel runways relies on being "established" or stabilized on a precision instrument approach. By design and the limitations of controller guidance, aircraft operating on their respective approaches intended for use during simultaneous operations shall not interfere with one another,

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nor cause a threat to the other operationally. To maintain system integrity, the procedure is safeguarded with mandated ground-based monitoring of a region between the approach paths, a Non-Transgression Zone (NTZ), using radar surveillance: If an aircraft deviates towards the NTZ, a monitoring controller instructs the threatened aircraft in an escape maneuver, or instructs the deviating aircraft back towards its intended course [3].

As the monitoring task is highly time critical, the update rate of the surveillance system and its accuracy, as well as the display type controllers use, are a major factor in determining the minimum spacing between centerlines of parallel runways eligible to conduct independent approach operations. For a comprehensive discussion of the monitoring concept and the way the minimum runway spacing is determined, refer to SOIR [3].

However, ICAO and the FAA requirements for independent runway operations differ in some of the details.

The current version of SOIR [3], issued in 2004, defines a minimum separation of parallel runway centerlines of 3400 ft for independent approach operations. For runway centerline spacings between 3400 ft and 4300 ft, ICAO guidance requires a radar surveillance system with an accuracy of 0.06° and a 2.5 sec. update rate. Furthermore, a high resolution radar display with position predicting and alert capabilities are mandated. While SOIR explicitly requires this Precision Runway Monitor (PRM) based on radar technology, amendment 4 to ICAO's document 4444 released in 2012 does not strictly require radar any more [8]. Other surveillance technologies like multilateration (MLAT) may be used if they ensure a similar level of performance. These changes are also in a draft SOIR revision, expected for publication in 2018.

A second major category of performance requirements is defined in SOIR for runway spacings larger than 5000 ft., requiring a radar surveillance system with an update rate of at least 5 seconds and an angular accuracy of 0.3° . SOIR does not address the need for a specific high

resolution type of radar display or even position prediction and alerting capabilities.

As a third category, runway spacings between 4300 ft and 5000 ft are mentioned in the standards. For these runway spacings, a PRM system may be used. Alternatively, if a safety case is made that shows a sufficient conflict resolution performance, a surveillance system as required for runway spacings greater than 5000 ft may also be implemented.

In summary, current ICAO guidelines for independent simultaneous approach operations consist of three categories, two which depend on specified performance, and one intermediate category which depends on a separate safety case. See Figure 2.

Besides general ICAO requirements, the FAA defines specific requirements to conduct independent simultaneous approaches in the United States. In contrast to ICAO's rules, FAA guidelines allow independent runway operations for minimum runway spacings down to 3000 ft. For runway spacings between 3000 ft and 3400 ft, one of the localizers or final approach tracks needs to be offset with regard to the parallel approaches by $2.5\text{-}3^\circ$ [2].

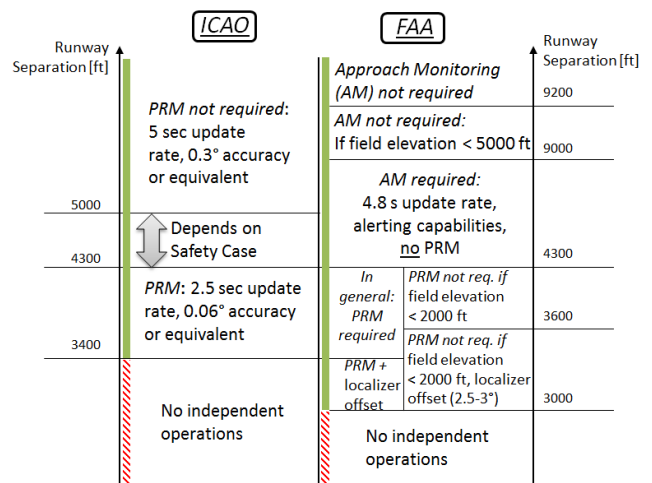


Figure 2. Summary of ICAO and FAA Requirements for Independent Simultaneous Approach Operations

With regard to approach monitoring requirements for independent operations, two cases can be distinguished according to a FAA notice from August 2015 [10] later reflected in

[2]. In a first general case, a PRM is required for runway centerline spacings below 4300 ft. Under certain conditions, however, a PRM is not mandatory.

For runway spacings above 3600 ft (and below 4300 ft) and an airport elevation below 2000 ft, a general approach monitoring aid with an update rate of 4.8 seconds and alerting capabilities may be used instead of a PRM in the United States. A non-PRM approach monitoring aid may additionally be used for runway spacings between 3000 ft and 4300 ft in case the airport elevation is below 2000 ft and a localizer offset is utilized. When runway spacings exceed 4300 ft, a PRM is not required in any case. A separate safety case, as defined under ICAO's guidelines is also not required.

While ICAO's guidelines make no statement with regard to a runway spacing at which approach monitoring is not required, this case is explicitly mentioned in FAA's guidelines: For runway spacings beyond 9200 ft, no approach monitoring is required. This value is reduced to 9000 ft for airports with a field elevation lower than 5000 ft [10].

In summary, the requirements on runway spacings for simultaneous independent approach operations as defined by ICAO are generally more conservative than the FAA's guidelines. The FAA allows independent approaches for smaller runway spacings, and is less demanding in specifying the use of PRM. Furthermore, for large runway spacings, FAA regulations require no approach monitoring at all while this case is not acknowledged by ICAO. A comparison of selected requirements is provided in Figure 2.

2.2 Dependent Operations

ICAO SOIR requires a minimum 3000 ft runway spacing to conduct dependent parallel runway operations. It stipulates the use of radar vectors to guide aircraft towards the final approach. Furthermore, SOIR requires two separate radar controllers (one per approach) for the task of sequencing and spacing of the arriving aircraft. To monitor approaches, SOIR requires a radar surveillance system that achieves update rates of at least 5 s and an angular accuracy of 0.3° or the

equivalent (e.g. based on technology like MLAT or Automatic Dependent Surveillance - Broadcast (ADS-B)). Furthermore, it is required that aircraft on different approach tracks are diagonally separated from each other by at least 2 NM.

The FAA permits dependent runway operations for runway spacings of at least 2500 ft. Within a runway spacing range of 2500 ft to 3600 ft, a minimal diagonal separation of 1 NM is required with respect to a FAA notice from August 2015 [10]. This value increases to 1.5 NM for runway spacings greater than 3600 ft and to 2 NM for runway spacings between 4300 ft and 9000 ft [2]. See Appendix B for an explanation of the non-intuitive *increase* in required aircraft diagonal spacing as the distance between runways increases. A summary of both ICAO's and FAA's requirements is provided in Table 1.

Table 1. Diagonal Runway Spacing for Dependent Simultaneous Operations

Source	Runway Spacing [ft]	Minimum Diagonal Separation [NM]
ICAO	> 3000	2
FAA	2500 – 3600	1
	3600 – 4300	1.5
	4300 – 9000	2

Again it can be seen that ICAO's requirements are more conservative. FAA regulations permit considerably smaller diagonal separations for runway spacings below 4300 ft.

3 Revising ICAO's Guidelines on Simultaneous Parallel Approach Operations

This section will address some proposed revisions for the ICAO SOIR and PANS ATM documents. We divide the proposed changes in two main categories: Changes to general operating requirements and changes to the applicable approach guidance technologies.

3.1 General Operating Requirements, SOIR

Classically, radar was the only available and permissible surveillance technology to monitor simultaneous parallel approaches. As already mentioned, different surveillance technologies such as ADS-B and MLAT are covered by

amendments to ICAO’s document 4444 [8] and are also in work to support a revised SOIR.

The current edition of the SOIR requires radar vectors to intercept the final approach track with a maximum intercept angle of 30°. This limitation is prudent to ensure proper capture of the final approach guidance. But in the future, in addition to radar vectors, published arrival and approach procedures to intercept the final approach track should be available. This change allows the design of procedures leading directly to a final approach in a simultaneous approach operation. In general, this may require less effort by air traffic controllers guiding aircraft towards the final approach compared to issuing radar vectors, and provides for a more stabilized (and therefore safer) approach.

Table 2. SOIR - Status Quo and Proposed Revisions

	<i>Current SOIR</i>	<i>Proposed Revisions to SOIR</i>
Surveillance technology	Radar only	Radar or ADS-B and MLAT, covered in guidance material
Interception of final approach	Radar vectors only, max 30° intercept angle	Final approach course or track may be intercepted by use of vectoring AND a published arrival and approach procedure that intercepts the IAF or IF. Max angle still 30°
Runway controller allocation	One controller per runway	Default: One controller per runway. One controller for more than one runway possible if safety assessment is presented and approved

A third proposed change deals with controller staffing allocations to approaches. While the current guidelines require one controller per runway in all cases, if a safety case can support a change, it may be allowable for one controller to be responsible for more than one runway. While there are obvious implications for their workload,

there might actually be reductions in some aspects as well, as less coordination would be necessary. Before any such reduction is allowed, it is suggested that an appropriate safety assessment be presented and approved. This safety case must consider the typical arrival flow and traffic mix for any specific facility together with the required approach performance.

Please refer to Table 2 for a summary of the proposed operational changes to SOIR.

3.2 Approach Selection and Design Considerations for SOIR

Generally speaking, any changes to the SOIR should designate approach performance, sufficiently mitigate collision risk, meet approach stabilization criteria, and minimize opportunities for wake encounters and ACAS nuisance alerting. Of course, procedures must also provide traditional terrain avoidance.

Current standards for dependent and independent parallel approaches require precision approaches based on either the ILS or the Microwave Landing System (MLS) [3].

In addition to the general changes mentioned above, the proposed updates to SOIR expand the available approach types to include all precision approach technologies as well as performance-based navigation approaches (RNP AR APCH meet the recommended performance).

As RNP AR APCH procedures permit the specification of multiple performance levels, particularly in the intermediate segment (prior to the final approach fix), two general design rules are suggested for an RNP AR APCH:

In dependent operations and in independent operations above 4,000 ft runway separations, the ¼ runway spacing requirement defines the minimum recommended RNP designation. However, protecting NTZ penetration defines the maximum recommended RNP values during independent operations with more closely-spaced runways.

In summary, the lower of the following two calculations represents the maximum recommended RNP value:

- the designated RNP should not exceed $\frac{1}{4}$ of the distance between runway centerlines (to minimize collision risk and ACAS interference) and
- the designated RNP should be equal to or less than $(d-2000)/2$ ft, where d (in ft) represents the distance between the runway centerlines (to mitigate nuisance NTZ alerting during independent ops.)

But to unlock the full potential that curved RNP procedure segments could provide, such as reduced population noise exposure and/or shorter tracks, more needs to be done to enable full flexibility in RNAV procedure design. The efforts to secure waivers for the first curved transitions for use at Seattle-Tacoma and Denver International Airport in the U.S. point to some of the issues to address and methods to manage implementation globally. This initial work has caught the attention of other candidate airports worldwide, such as Frankfurt Airport.

The rest of this paper will address one of these issues, namely how to analyze and predict adverse ACAS interactions associated with proposed parallel approach related standards.

4 ACAS Functionality and Alerting Logic

ACAS generates two kinds of alerts: traffic advisories (TA) and resolution advisories (RA). A TA provides the crew with information on potentially hazardous traffic that might result in a conflict in a predefined amount of time. In general, a TA is primarily for traffic situation awareness, as aircrews are not expected to initiate any avoidance maneuvers based on a TA. In contrast, an RA provides information on a critical, threatening conflict, and necessitates immediate evasive maneuvers [11] [12].

The generation of both kinds of alerts requires aircraft to be equipped with a transponder system. To generate a TA, the transponder of the intruding aircraft needs to be at least “Mode A” capable – basic functionality to respond to an interrogation. To generate an RA, the intruder’s transponder must be able to transmit altitude

information (Mode C or Mode S). Most busy airspace requires ACAS equipage that in turn requires Mode C or Mode S fitment.

Based on transponder interrogations, ACAS determines the main parameters of a potential conflict situation: the range between the conflict aircraft and their altitudes, as well as the range and altitude rates. The bearing is also calculated, and although it is sometimes shown to a flight crew, it cannot be used for conflict resolution due to its limited accuracy. As a result, ACAS only generates vertical avoidance instructions.

Due to the obvious danger of vertical maneuvers near the ground, ACAS applicability is limited at low altitudes. RAs are partly inhibited below an altitude of 1650 ft above ground level (AGL) and completely inhibited below 1000 ft AGL. Moreover ACAS alerts are inhibited whenever other, more time critical warning systems are activated, such as the ground proximity warning system or the windshear warning system [11].

Simultaneous approaches present another challenge for ACAS. As separation between aircraft during approach is small compared to en-route operations, if an aircraft deviates from or wanders around its intended path, such motion and the proximity itself might trigger a TA or an RA, even during normal approach operations. This might lead to a missed approach, and thus adversely affect airport capacity and safety. In turn, this could reduce confidence in the operation and usability of the systems during the approach phase of flight [13]. This situation is further exacerbated when at least one of the approaches has curved segments, since closing speeds between aircraft on the different approach paths are increased compared to parallel straight-in approaches. This behavior will be evident in some of the scenarios in this study.

Since suppressing or ignoring ACAS alerts is not preferred nor prudent, it is very important for the proposed simultaneous approach operations and the individual procedure designs approved for use to be compatible with ACAS. During these operations, ACAS alerts should only be triggered when an aircraft leaves its intended approach path and “blunders” towards the adjacent approach path. They should not be caused by

normal variation while executing an authorized procedure that didn't consider ACAS.

4.1 ACAS logic for conflict detection

In general, the ACAS logic for conflict determination conducts two kinds of tests to identify an encounter as a threat and generate alerts: a range test and an altitude test [11]. Simultaneous satisfaction of both test criteria is necessary for an alert to be generated.

4.1.1 Range Test

The basis of an ACAS range conflict determination is a so called range tau criterion. If the predicted time τ until the closest point of approach between two aircraft falls below a threshold τ_0 , a TA or RA is generated, depending on the threshold.

Over the years, the range tau criterion has evolved from a simple to a modified, and finally to the so-called Bramson criterion. See Appendix A or [11] [14] [18] for details about these criteria. The Bramson range tau criterion is used in this paper, and it has the following form:

$$\tau_0 \geq \tau = -\frac{\left(r - \frac{D_m^2}{r}\right)}{\dot{r}} \quad (1)$$

where τ_0 denotes the warning time threshold, τ denotes the calculated time to closest point of approach, r denotes the relative (slant) range between the two aircraft, \dot{r} denotes the relative range rate (the negative of the closing rate), and D_m denotes the "distance modifier". The purpose of the distance modifier is to insure that the range criterion for an alert is met even at low closing speeds, if the two aircraft are also sufficiently close together.

Figure 3 shows a comparison of the simple and the Bramson thresholds for a TA alert based on a 25-second time to closest approach and a distance modifier of 0.33 NM. The range tau condition for an alert is satisfied whenever the range/closing-rate combination falls *below* the corresponding line. Therefore the Bramson range tau threshold (blue) provides more protection against close encounters at slow closing speeds (0.33 NM at zero closing rate) than the simple

range tau threshold does (red). Also the Bramson threshold approaches the simple threshold (25-sec warning time) as closing rate increases.

Selected values for the parameters τ_0 and D_m are shown in Table 3 below (based on Table 2 from [11]). These parameters are a function of altitude as well as the type of alert (TA or RA). In general, ACAS warning times decrease with decreasing altitude, and no RAs are generated below a height of 1000 ft AGL, based on the aircraft that is *closer* to the ground.

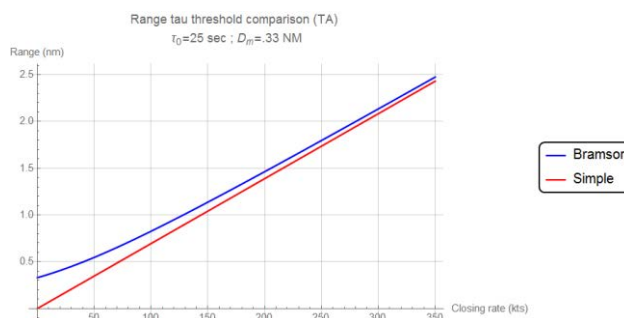


Figure 3. Comparison of simple (red) and Bramson tau thresholds (blue) for a 25 second TA (DMOD = .33 NM).

Table 3. ACAS range tau sensitivity levels for altitudes below 10000 ft [11].

Alt [ft]	Sens. Level	TA [sec]	RA [sec]	TA [NM]	RA [NM]
< 1000 (AGL)	2	20	N/A	0.30	N/A
1000 - 2350 (AGL)	3	25	15	0.33	0.2
2350 - 5000	4	30	20	0.48	0.35
5000 - 10000	5	40	25	0.75	0.55

Each of the altitude ranges is associated with a corresponding *sensitivity level*. These levels range from 2-7 but only levels 2-5 are shown. Note that for altitudes below 2350 ft, radio altimetry is utilized, while for altitudes above this threshold, barometric altitude is used to determine the sensitivity level. For a more

comprehensive discussion of ACAS functionalities and alerts, refer to [11] [12].

4.1.2 Altitude Test

The basis for the altitude test is similar to the range test. The warning times to co-altitude are the same as for the time to closet-point-of-approach (CPA) for the range tau. In place of the distance modifier “DMOD”, however, there is a fixed vertical (z) distance threshold called “ZTHR”. This serves a similar purpose, namely to protect against sudden vertical accelerations when the vertical closing rate is small and the aircraft are close.

Table 4. ACAS altitude tau sensitivity levels for altitudes below 10000 ft [11].

Alt [ft]	Sens. Level	TA [sec]	RA [sec]	TA [ft]	RA [ft]
< 1000 (AGL)	2	20	N/A	850	N/A
1000 - 2350 (AGL)	3	25	15	850	600
2350 - 5000	4	30	20	850	600
5000 - 10000	5	40	25	850	600

For sensitivity levels 2-5 (below 10,000 ft) there are only two ZTHR values – 850 ft for a TA and 600 ft for an RA. Again there is no RA when the aircraft closer to the ground is at less than 1000 ft AGL. Figure 4 is an example of the threshold curves for a TA and an RA at sensitivity level 5. The two horizontal lines for low vertical rates correspond to the two ZTHR values. The slanted lines which continue on from there correspond to the constant times to co-altitude thresholds.

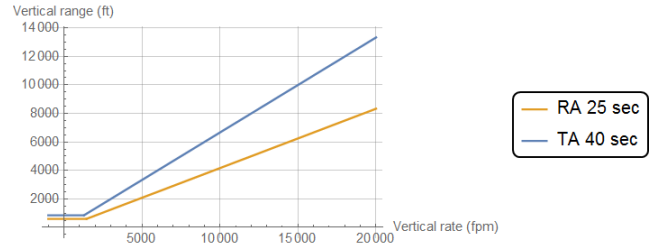


Figure 4. Altitude tau thresholds for a 25 second RA (ZTHR = 600 ft) and a 40 second TA (ZTHR = 850 ft).

5 DLR and Boeing Analyses

In this section, we briefly describe and compare the DLR and Boeing methodologies used to determine ACAS compatibility of the approach procedures considered in this paper.

5.1 DLR’s Analysis Method

DLR’s approach was an analytical (as opposed to simulation), worst-case analysis. This analysis focused on a scenario with simultaneous independent runway operations in which one straight-in approach is combined with one curved approach, as illustrated in Figure 5.

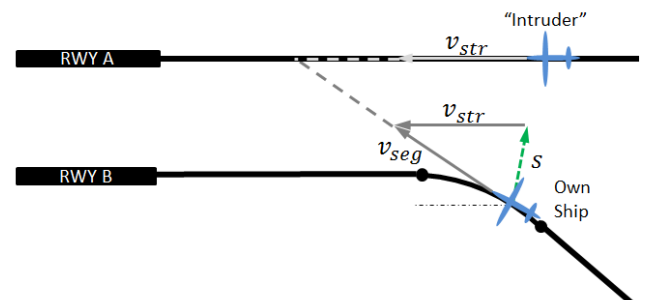


Figure 5. Approach scenario as addressed in DLR’s analysis.

We divide the curved approach path into a large number of distance-wise equally distributed calculation points and determine the maximum distance between aircraft on the two approach paths that could generate either a TA or RA for at least one calculation point. By varying runway spacing, a global critical runway spacing can be identified for either a TA or an RA. In a basic scenario we assumed that aircraft operate precisely on their intended approach paths while we add a buffer for uncertainties in a second scenario.

To determine the critical spacing between two aircraft that would not issue either TA or RA, a

simple kinematic model based on the ACAS logic for conflict detection was developed. For reasons of simplicity, it is assumed that aircraft on both tracks proceed with an unaccelerated motion. We assume that one aircraft performs a straight in approach (RWY A) while another aircraft follows an approach that contains a turn towards the final approach (RWY B). Based on these assumptions, we calculated the relative speed between the aircraft for every discrete calculation point on the curved approach path.

Utilizing the relative speed for a specific calculation point and the altitude of the aircraft on the segmented approach path, the dimensions of the ACAS alerting volume can be calculated. As a next step, we determine the tangent of the alerting volume with the straight approach towards RWY A. This means that we “move” the approach towards RWY A for every calculation point to a position at which the alerting volume touches the straight approach towards RWY A at one point. If for a given relative speed, the aircraft on the approach towards RWY A is located on exactly this position, an alert would be generated. This represents the worst case for a given and fixed position of the ACAS aircraft on the segmented approach path.

We conduct the described routine for every calculation point equally distributed on the curved approach path. Taking into account the influence of the approach geometry, an overall critical runway spacing to generate either TA or RA can be obtained and uncertainty buffers can be added. Please refer to [6] for a more comprehensive introduction to the method used.

5.2 Boeing’s Analysis Method

The Boeing Company analyzed the same scenarios as DLR plus some additional dependent approach cases, based on the approach geometries illustrated in Figure 5. But in contrast to DLR’s geometric analytic method, Boeing employed a parameterized fast-time (“Monte Carlo”) simulation model. A large number of paired approaches were run for each scenario and different parameter settings, and the rate of nuisance ACAS alerts recorded.

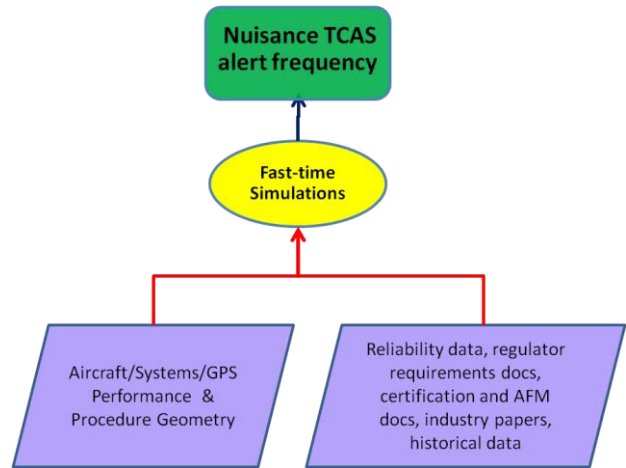


Figure 6. Fast-time simulations generate TCAS alert data based on requirements and system performance.

Several parameters and conditions can be set before each simulation, such as runway separation, approach geometry, aircraft performance (e.g., lateral and vertical FTE), GPS errors, and speeds. Figure 7 shows a typical example.

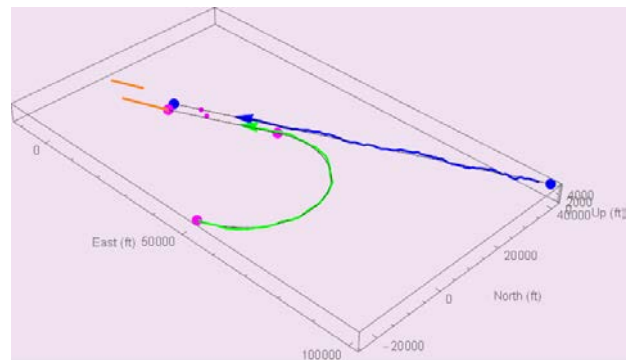


Figure 7. Example of fast-time simulation 3D approach geometry. 2500 ft runway spacing with moderate “noise” on each approach, with 10 second “offset” (blue a/c ahead of green a/c). Smaller pink dots indicate where closest point of approach (CPA) occurs for each a/c.

Figure 8 shows a typical simulation range/closing-rate profile (corresponding to the example in Figure 7) superimposed on a set of RA range test thresholds (slanted lines). If the range/closing-rate profile (blue curve) dips below any of the lines, the range test is satisfied for at least one of the thresholds. Of course other factors must be checked in order to generate an alert, such as the corresponding altitude test and whether or not the aircraft altitudes correspond to the appropriate sensitivity level. The same

principle applies to altitude tests and TA's, though the details will differ.

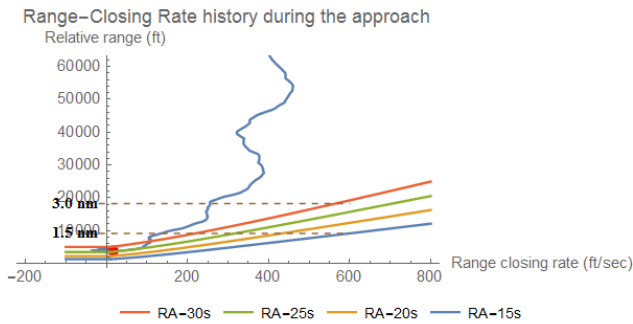


Figure 8. Range test: Approach range/closing-rate profile (squiggly blue curve) compared to various RA range thresholds.

The simulation model is exercised multiple times for each scenario and set of cases, thus producing data for statistical analysis and visualization. Examples of visual output are displayed in Figure 9 and Figure 10. The occurrences of ACAS alerts are shown as blue dots for TA's and red dots for RA's. In each case, both the range test and the altitude test had to be satisfied for 3 seconds before declaring an alert.

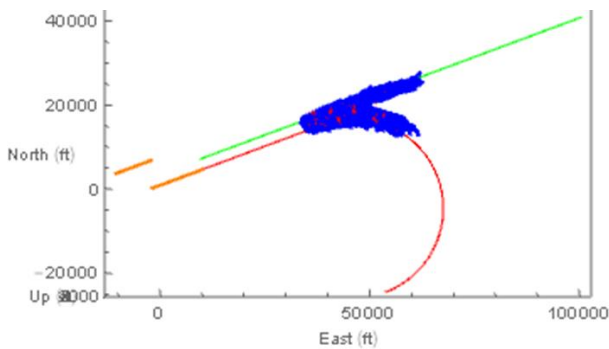


Figure 9. Multiple fast-time simulations output – blue dots indicate TA's and red dots indicate RA's. Data from 1000 simulated simultaneous approaches.

The utility of the representation in Figure 10 is that it shows generally how far apart the aircraft should be in time at the start of the scenario in order to avoid alerts. The horizontal scale at the top of the figure indicates the closest point of approach (CPA) of the two aircraft in nautical miles during the entire operation from start to landing. The vertical line at 0 indicates that the two aircraft actually end up wingtip-to-wingtip at some point during the scenario. A -2 NM, for example, indicates that the ILS aircraft is behind

the RNP aircraft and 2 NM distant (slant range), while a +2 NM indicates that the ILS aircraft is ahead of the RNP aircraft and 2 NM distant (slant range). At the bottom of the figure is shown the initial separation in seconds for the two aircraft. For example, -20 seconds indicates that the ILS aircraft starts 20 seconds behind the RNP aircraft and +20 indicates that the ILS aircraft starts 20 seconds ahead of the RNP aircraft. If it is desirable to avoid ANY alerts, including TA's, then the figure shows that the initial separation should be on the order of -34 seconds (or less) or +20 seconds (or more), corresponding to CPA's of slightly less than 1.5 NM in the first case and slightly less than 1 NM in the second case.

If it is desired to avoid RA's only, then these limits can be reduced somewhat to just enclose the red regions shown, with some buffer if desired.

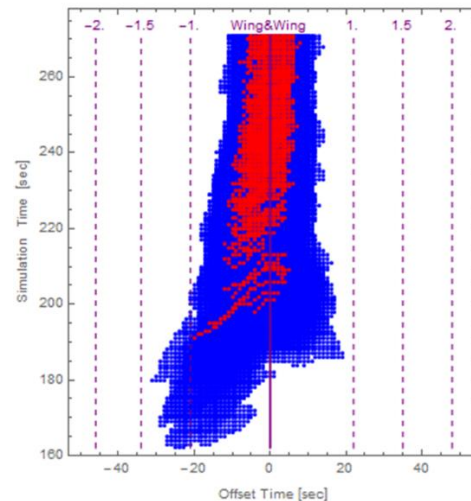


Figure 10. Same data as in Figure 9. Bottom horizontal axis indicates how many seconds ILS a/c is behind or ahead of RNP a/c at start of simulation. Top horizontal axis indicates closest point of approach (CPA) in NM during the entire approach. Vertical axis indicates time into simulation.

5.3 Comparison of methodologies

The methodologies employed by DLR and Boeing are both intended to determine whether unwanted ACAS alerts are generated based on variables such as runway spacing, approach geometry, procedure design, and aircraft capabilities. Both are capable of providing guidance concerning this issue. However, there

are some methodological differences as outlined in Table 5 below.

Feature	DLR	Boeing
Method	Analytical	Fast-time simulation
Approach types	Independent	Independent & Dependent
Approach geometry	2D	3D
Deviations from path	Worst case	Variable based on FTE, GPS errors
Assumed operational conditions	Normal (non-faulted)	Normal (non-faulted)

Table 5 Some key differences/similarities in the two methodologies.

6 Approach Scenarios

6.1 Approach geometry

For this work, we consider a generic approach layout at which straight-in ILS approaches are conducted towards one runway (RWY A) while RNP approaches that include a turn onto the final approach are performed towards another runway (RWY B). The approach layout is characterized by the distance between the runway centerlines (d), the length of the final approach towards RWY B (l), as well as the turn radius (r), and turn angle (α) as illustrated in Figure 11.

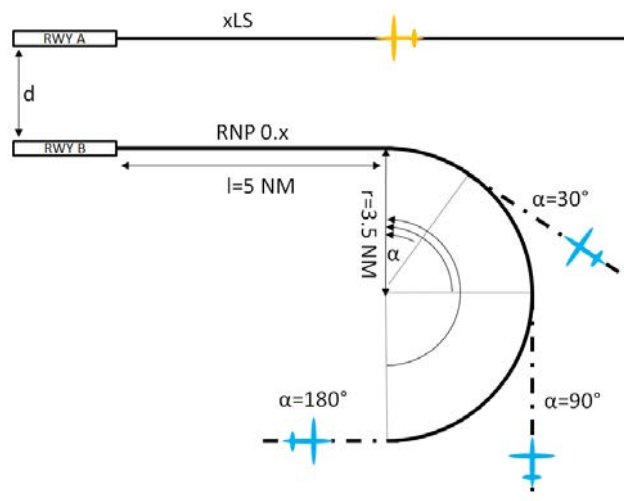


Figure 11. Generic approach layout in this paper.

To reduce the number of variables, we define a constant final approach length of 5 NM for every scenario. The length of the final approach directly influences the altitude of the aircraft and therefore the ACAS sensitivity level, based on a constant glide path of -3° assumed for both approach paths. In general, ACAS look ahead times decrease the closer aircraft approach the ground/airport. See Tables 3 and 4 or [11]. ACAS mode changes (sensitivity level changes) take place at altitudes of 1000 ft and 2350 ft AGL based on radar altitude as described previously. Assuming a GPA of -3° and a more or less flat terrain, mode changes take place approximately at 3.1 NM and 7.4 NM in front of the threshold on either approach path. Although it must be noted that the final approach length might have an influence on the results, we did not consider this factor.

The selected turn angles towards final approach are based on current implementations of curved approaches or proposed implementations. For example, turn angles towards the straight final approach of roughly 30° are being suggested at Frankfurt Airport in Germany, and turn angles of 180° are being used at Seattle-Tacoma airport in the U.S.. A turn angle towards the final approach of 90° represents an intermediate scenario that will also be considered in this work.

A variation of the turn angle towards the final approach (RWY B) has two effects on ACAS alerts. On the one hand, larger turn angles lead to higher extrapolated relative speeds between aircraft on the two approaches, while on the other

hand higher turn angles increase the range between aircraft on the two approaches. Therefore, the turn angle onto the final approach (RNW B) can be considered as one major parameter influencing ACAS alerts and will therefore be varied.

With regard to the turn radius, we proposed a value of 3.5 NM for this work and checked whether this value is in line with current procedure design requirements. Our turn radius considerations are based on ICAO standards detailed in document 8168 (PANS OPS) [15]. The minimum turn radius depends on the assumed bank angle of 18° - a recommended standard design bank angle according to [15] - which is well below the defined maximum of 25° as defined in [19]. It also depends on the True Airspeed (TAS) and a maximum tailwind component which is defined by ICAO and is subject to altitude.

For the True Airspeed and tailwind component ICAO requires the highest value to be expected in a turn to be selected. Using the specified GPA of -3° for both approach paths, the highest altitude at the start of turn will be reached for a turn angle of 180°. The remaining approach length from the start of the 180°-turn to the threshold of RWY B can be easily calculated as 16 NM (assuming a 3.5 NM turn radius) leading to a height above the threshold of about 5100 ft for the start of the turn.

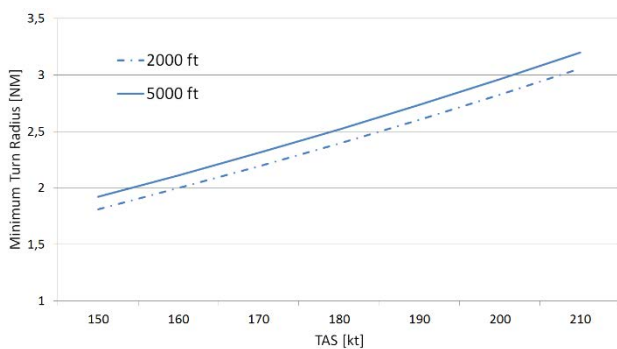


Figure 12. Minimum turn radii for different speed and altitude combinations and a bank angle of 18°. [17].

Figure 12 indicates that a turn radius of 3.5 NM fulfills the ICAO requirements on the minimum turn radius even for True Airspeeds of 210 kt and turn angles of 180°. The geometric parameters common to all scenarios are summarized in Table 6.

Table 6. General geometric parameters.

Parameter	Value
Length of Final Approach [NM]	5
GPA (ILS and RNP) [°]	-3
Turn Angle Towards Final Approach [°]	30, 90, 180
Turn radii [NM]	3.5

6.2 Scenario I: Runway spacings and RNP-values according to proposed SOIR revisions

Independent approach operations

The first scenario addresses ACAS alerts during independent runway operations. We will analyze whether current ICAO efforts to modify SOIR allow turns onto one of the final approaches, solely from an ACAS compatibility perspective.

In the current SOIR, runway spacings of 3400 ft and 4300 ft are defined as critical values. 3400 ft signifies the minimum runway spacing to permit independent parallel approach operations requiring a Precision Runway Monitor (PRM). A spacing of 4300 ft still requires monitoring the parallel approach paths. However, a PRM is not required.

Based on these and the proposed requirements for maximum RNP level as discussed in 3.2, the maximum recommended RNP values for each scenario can be calculated. For a runway spacing of 3,400 ft, a RNP value of 0.11 NM or below would be required according to the (d-2000)/2 rule, while a runway spacing of 4300 ft. requires an RNP of 0.17 or less according to the ¼ runway spacing rule.

Table 7. Independent approach scenario definitions.

<i>Scenario ID</i>	<i>IND1_ICAO</i>	<i>IND2_ICAO</i>
Runway spacing [ft]	3400	4300
Performance on RNP approach	RNP 0.11	RNP 0.17
Groundspeed [kt]	150, 170	150, 170

With regard to the groundspeed on the approach paths, we considered a baseline scenario with an average groundspeed on both approach paths of 150 kt and subsequently increased the speed to 170 kt to assess the impact of speed variations on the overall result. Please refer to Table 7 for a summary.

Dependent approach operations

Current efforts to modify ICAO’s guidelines in Doc 9643 also include dependent approaches to parallel runways. Per the Section 3.2 discussion, the following criteria are suggested to enable dependent approaches:

- A runway spacing of at least 3000 ft
- RNP value for RNP AR APCH: Distance between runway centerlines divided by 4

Table 8. Dependent Approach Scenario Definitions.

<i>Scenario ID</i>	<i>DEP_ICAO</i>
Runway spacing	3000 ft
Guidance on curved approach	RNP 0.12
Groundspeed during Approach [kt]	150
Min. diagonal separation [NM]	2

Considering the minimum required runway spacing of 3000 ft that is intended to allow dependent approach operations according to [3], a maximum RNP 0.12 could be recommended for some airports. Furthermore, it is stated in the guidelines that a diagonal separation of at least 2 NM needs to be maintained to conduct dependent approach operations. This constraint was integrated into the simulation. With regard to the approach speed, we considered a constant groundspeed of 150 kt for this scenario. The scenario definitions are summarized in Table 8.

6.3 Scenario II: Determine critical runway spacings for standard RNP values

The main goal of the second scenario was to identify minimum runway spacings that would allow either dependent or independent runway operations for standard RNP values from an ACAS perspective.

The approach geometry remains unchanged for this scenario, which means that we still consider the combination of one straight approach with one curved approach as illustrated in Figure 5. We furthermore assume a constant groundspeed of 150 kt again and a 2 NM diagonal separation for the dependent approach sub scenario.

Table 9. Variable definitions for Scenario II.

Scenario ID	Scenario II
Guidance on curved approach [RNP]	0.1, 0.3
Groundspeed [kt]	150
For Dependent Approaches, only: Min. diagonal separation [NM]	2

With regard to RNP values, we analyze RNP 0.1, and 0.3. RNP 0.3 can be characterized as a standard value for RNP final approaches as recommended for example by ICAO procedure design standards [15]. RNP 0.1 is typically the most demanding RNP value that may be defined for RNP AR APCH procedures. Refer to Table 9 for a summary of the scenario variable settings.

7 Results: DLR method

As DLR’s analysis approach was originally intended to evaluate independent approach procedures, results will be presented only for those scenarios defined in section 6 that address independent approach procedures.

The following results were determined utilizing DLR’s analysis method as described in section 5.15.1. Recall that two scenarios were analyzed for every run: One scenario at which aircraft are assumed to operate exactly on their intended approach path, and a second worst-case scenario including an uncertainty buffer. The following assumptions with regard to those uncertainty buffers were made, consistent with the required performance defined in the standards [15] [16]:

- ILS: Standard deviation of the total error: $\pm 0.281^\circ$, 1σ
- RNP: Standard deviation of the total error: \pm RNP-value, 2σ

We then defined the worst case uncertainty buffer as 3 times the standard deviation of either the ILS, or the RNP total error, assuming a normal distribution of these errors.

The DLR results are presented in plots involving distance-to-go to the threshold. Since corresponding altitudes are discussed in the text, the following plot (Figure 13) is inserted to assist the reader in relating distance-to-go to altitude (for the curved approach).

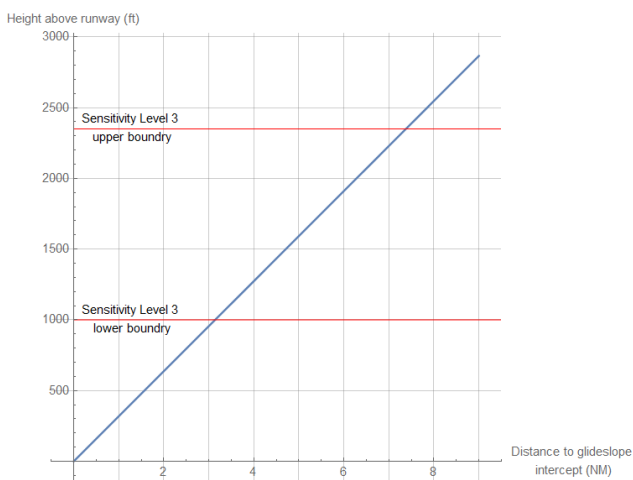


Figure 13. Height above runway vs. distance from the threshold for a 3° GPA (blue curve). Upper and lower boundaries of sensitivity level 3 are shown (red lines)

7.1 Scenario I: IND1_ICAO

In the first scenario, independent approaches were analyzed using the scenario definitions of section 6.2.

The results for the first sub-scenario (Figure 14), correspond to a runway spacing of 3400 ft, an RNP of 0.11, and a turn-on angle of 30°.

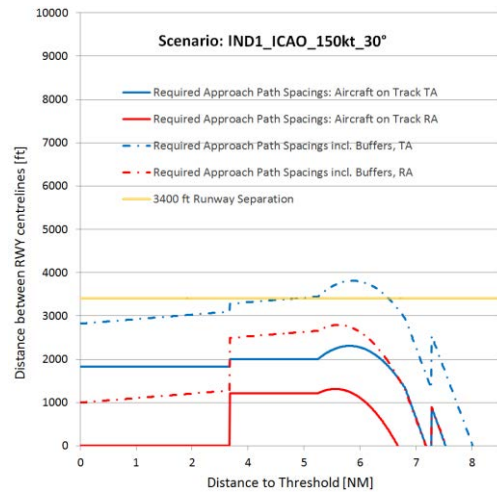


Figure 14. Results Scenario Ind 1, 150kt, 30° turn-on angle.

The horizontal axis represents the distance-to-go to the threshold. The vertical axis represents the distance between the runway centerlines, with the solid yellow horizontal line showing the 3400 ft spacing. The blue lines correspond to TAs and the red lines to RAs. The solid curves in each case represent nominal tracking performance and the dotted-dashed lines represent the worst-case performance (nominal plus buffers). In all cases, there is a potential issue only if one or more of the curves rises *above* the relevant runway spacing line somewhere during the approach.

It can be seen from Figure 14 that for a runway spacing of 3400 ft, no RA will be generated – even under the pessimistic assumptions including the worst-case buffers, since the red curves (both dashed-dotted and solid) never reach values greater than 3400 ft, (orange line). However, at certain parts of the approach, especially during the turn towards the straight final approach, TAs are possible in a worst-case scenario, since the dashed blue curve *does* rise above the 3400 ft runway spacing line.

The “kinks” in the curves at approximately 3.1 NM and 7.4 NM before the threshold are due to the changes in sensitivity level from 2 to 3 (1000 ft) and from 3 to 4 (2350 ft), respectively. See Figure 13 for the correspondence. Note that during the last 3.1 NM before the threshold, no RAs can be generated at all since the aircraft is below 1000 ft (again see Figure 13). The level section between 3.1 and 5 NM before the threshold is due to the fact that the relative speed is zero (ignoring “noise” on the trajectories), meaning that the distance modifier D_m of 0.2 NM (1215 ft) defines the relevant alert distance (for the nominal trajectory).

The turn towards the final approach occurs between approximately 7 NM and 5 NM before the threshold for 30° turn-on-angle-scenario. In this region, due to the curved approach geometry, the relative speed between the two aircraft is increasing (tending to *increase* the alerting volume), while at the same time, the distance between the approach paths is also increasing (tending to *decrease* the alerting volume). This results in the concave down region between 7 and 5 NM before the threshold.

At a height of 2350 ft another change in sensitivity level (from 2 to 3) takes place resulting in the spiky behavior at about 7.3 NM before the threshold.

Similar behaviors for 90° and 180° turn-on angles towards the final approach as can be seen in Figure 15.

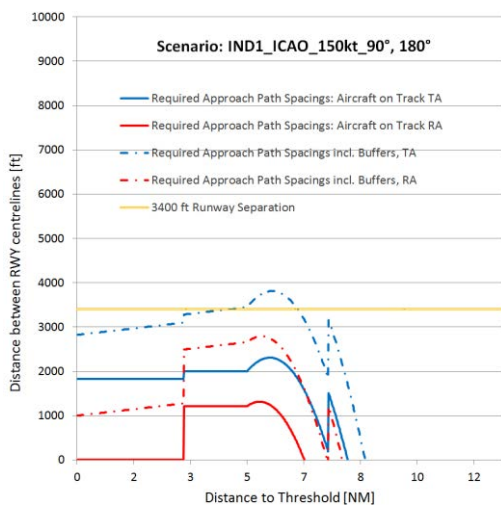


Figure 15. Results Scenario Ind 1, 150kt, 90°, 180° turn-on angles.

Increasing the groundspeed of the aircraft on both approaches leads to results shown in Figure 16 and Figure 17. Although increasing the risk for nuisance TA due to the increased groundspeeds, RA are still predicted to be very unlikely for both scenarios.

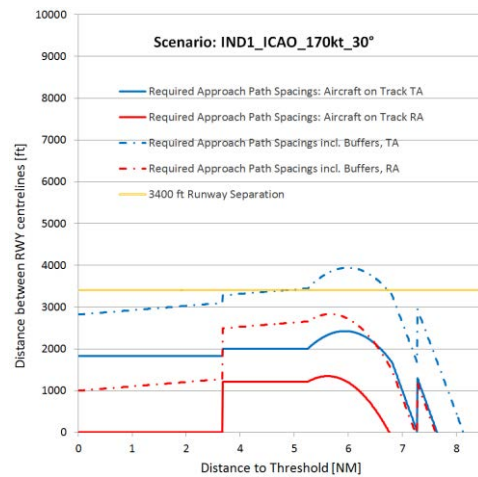


Figure 16. Results Scenario Ind 1, 170kt, 30° turn-on angle.

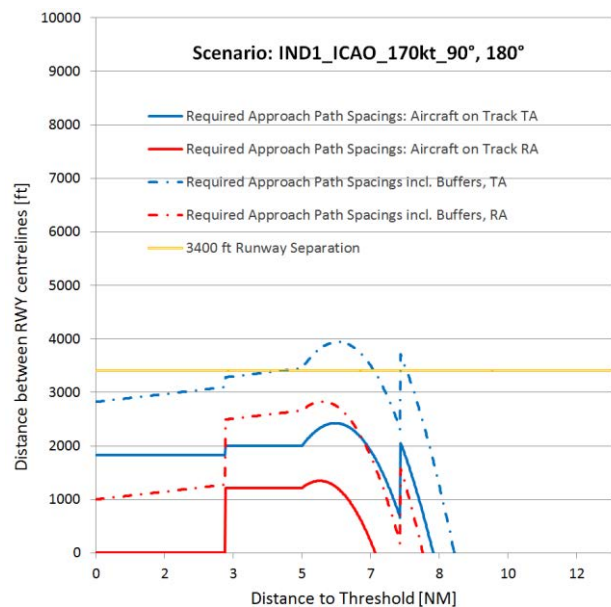


Figure 17. Results Scenario Ind 1, 170kt, 90°, 180° turn-on angles.

7.2 Scenario I: IND2_ICAO

For the second part of Scenario I, the RNP values as well as the runways spacing were varied. A

runway spacing of 4300 ft and a RNP value of 0.17 were defined as constant variables while approach speeds and turn angles towards the final approach were varied in the same fashion as before.

It can be seen from Figure 18 and Figure 19 that for this scenario nuisance RA are very unlikely. With regard to TA it can be said they might occur under worst case conditions during the turn towards the final approach but are very unlikely, as the dotted-dashed worst-case curve for TAs barely touches the 4300 ft runway spacing line. Again, increasing the approach speeds increases the risk for nuisance TA as illustrated for example in Figure 20. However, their occurrence is again very unlikely during normal operations, given the worst case assumptions that were used.

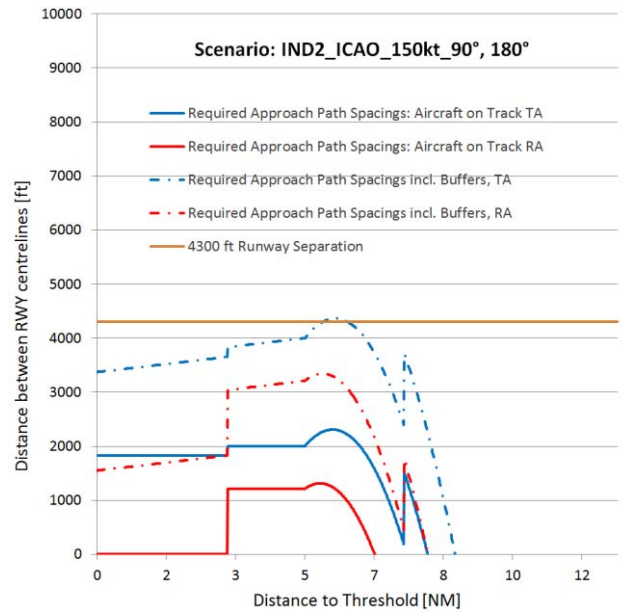


Figure 19. Results Scenario Ind 2, 150kt, 90°, 180° turn-on angles.

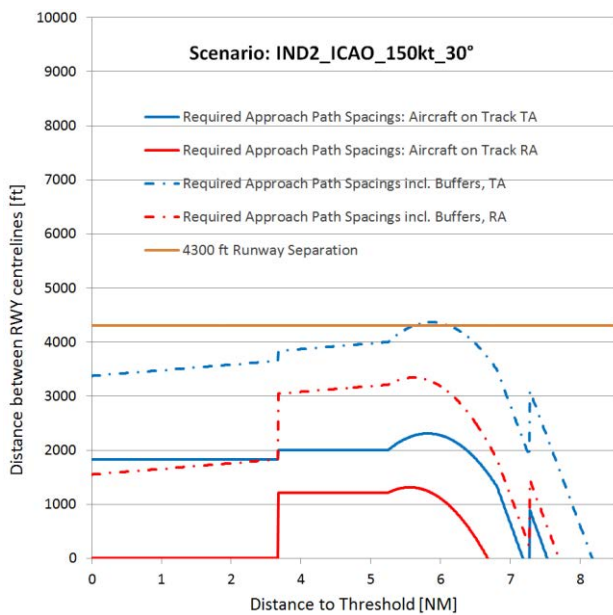


Figure 18. Results Scenario Ind 2, 150kt, 30° turn-on angle.

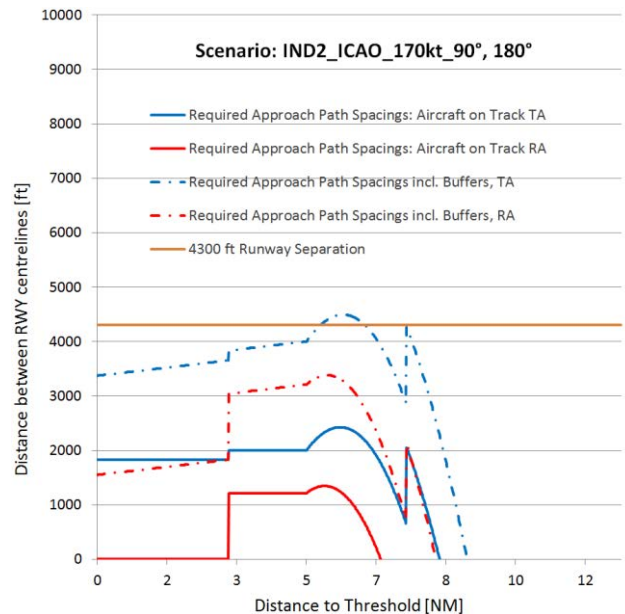


Figure 20. Results Scenario Ind 2, 170kt, 90°, 180° turn-on angles.

7.3 Scenario II: Minimum runway spacings for standard RNP values

The main focus of Scenario II was to identify critical runway spacings that could generate either nuisance TA or RA for given standard RNP-values (RNP 0.1 and 0.3).

AIRBORNE COLLISION AVOIDANCE CONSIDERATIONS FOR SIMULTANEOUS PARALLEL APPROACH OPERATIONS

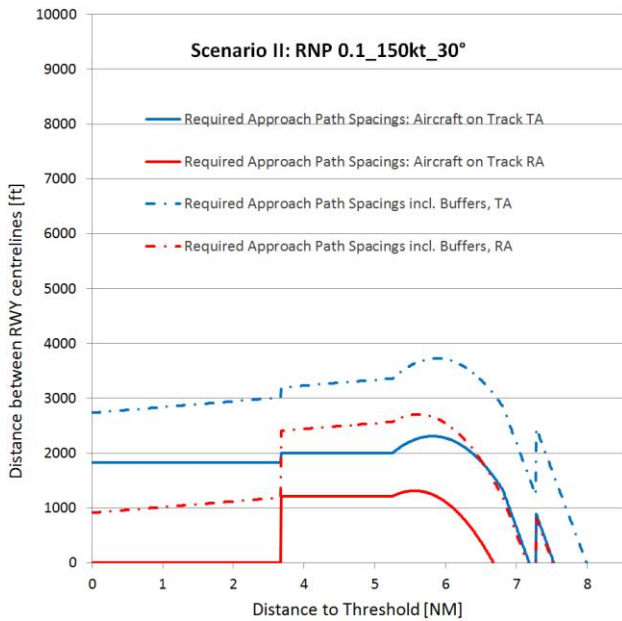


Figure 21. Results Scenario II, 150kt, 30° turn-on angle, RNP 0.1.

Using DLR’s calculation method, the critical runway spacings for generating a nuisance TA or RA are indicated by the maximum values attained by the relevant curves. It can be seen from Figure 21 that for a RNP value of 0.1, a groundspeed of 150 kt and a turn-on angle of 30° towards the final approach, the runway spacings that could generate a nuisance RA are about 2750 ft or below, while for a nuisance TA they are about 3800 ft or below.

Increasing the turn-on angle to 90° or 180° slightly increases those values to approximately 2900 ft and 4000 ft, respectively (Figure 22).

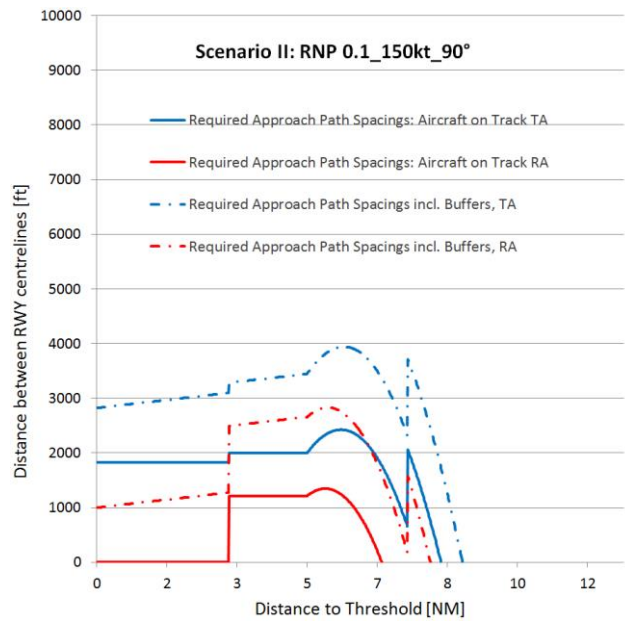


Figure 22. Results Scenario II, 150kt, 90°, 180° turn-on angle, RNP 0.1.

As a next step, we changed the RNP value to 0.3. The corresponding results are shown in Figure 23 and Figure 24. It can be seen that a critical value to issue a TA is about 5500 ft while an RA will most likely not be issued for runway spacings greater than 4500 ft, as applied to independent approach operations.

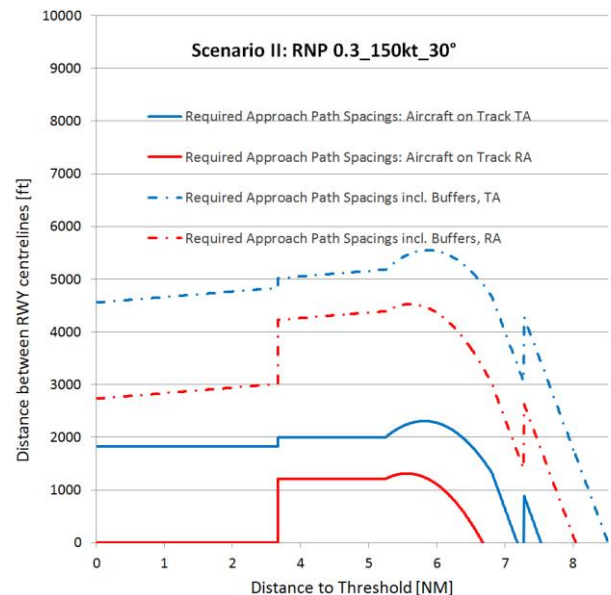


Figure 23. Results Scenario II, 150kt, 30° turn-on angle, RNP 0.3.

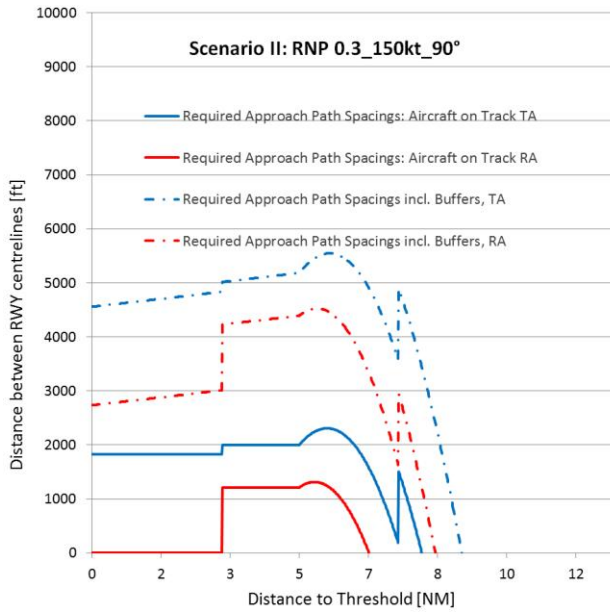


Figure 24. Results Scenario II, 150kt, 90°, 180° turn-on angles, RNP 0.3.

8 Results: Boeing method

This section displays results from 1000 fast-time simulations corresponding to selected combinations of turn-on angle, runway spacing, RNP value, and aircraft speeds. Subsections 8.1, 8.2, and 8.3 are arranged so as to provide a direct comparison to the corresponding DLR results in sections 7.1, 7.2, and 7.3. Only some of the cases are shown in this section, but the interested reader can find all of the plots in Appendix C.

The following graph shows the relationships among simulation time, distance-to-go, and altitude, and will help the reader in the interpretation of the subsequent plots that involve simulation time.

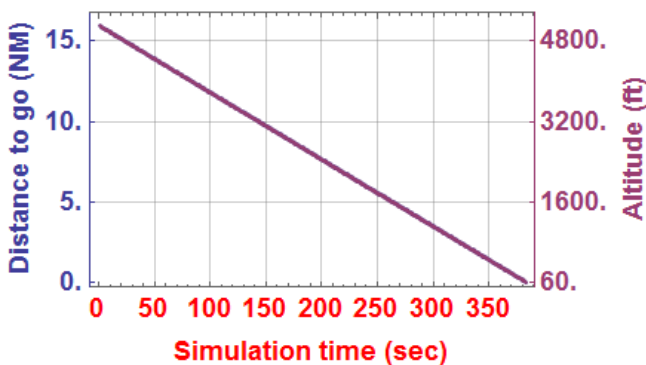


Figure 25. Relationship among simulation time, distance-to-go, and altitude above runway.

Each individual figure to follow combines two different perspectives on the same data. The first perspective shows the TA and RA alerts as a function of position along both trajectories, as experienced by each aircraft. The second perspective shows the TA and RA alerts as a function of both the initial time separation (sec) between the two aircraft and the time into the simulation (sec) – this is where a glance at Figure 25 comes in handy. Note that blue dots indicate a TA and red dots an RA. See section 5.2 on Boeing’s analysis methodology for more details on the interpretation of this kind of display.

8.1 Scenario I: IND1_ICAO

The following five plots can be compared to the DLR results in sections 7.1. The results are similar, in that no RAs are predicted for all of the DLR plots and all of the Boeing plots except one, namely the 180° turn-on with a 3400 ft runway spacing, RNP 0.11, and 150 kts (see Figure 28).

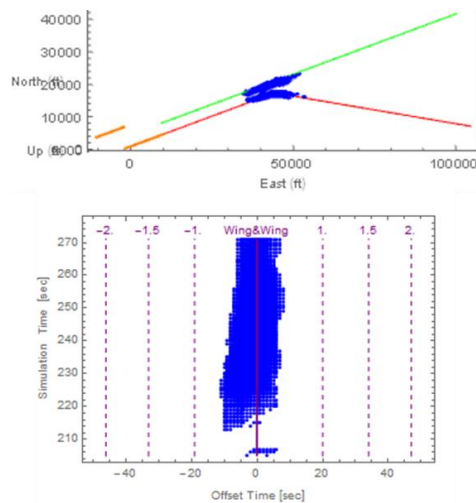


Figure 26. 30° turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.11.

AIRBORNE COLLISION AVOIDANCE CONSIDERATIONS FOR SIMULTANEOUS PARALLEL APPROACH OPERATIONS

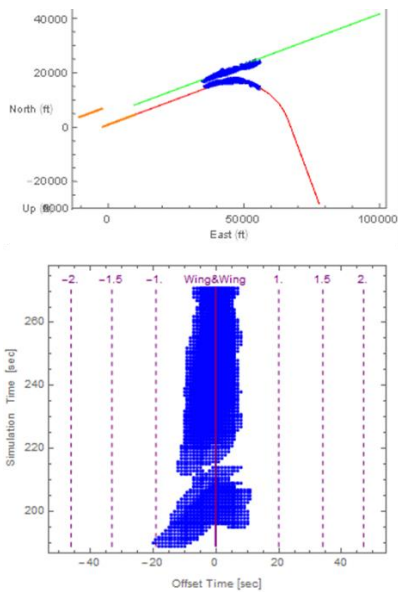


Figure 27. 90° turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.11.

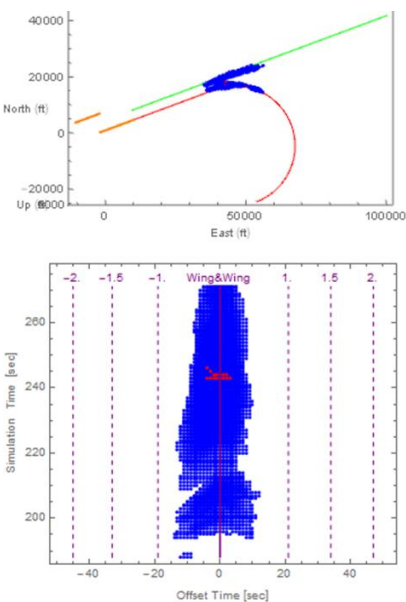


Figure 28. 180° turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.11.

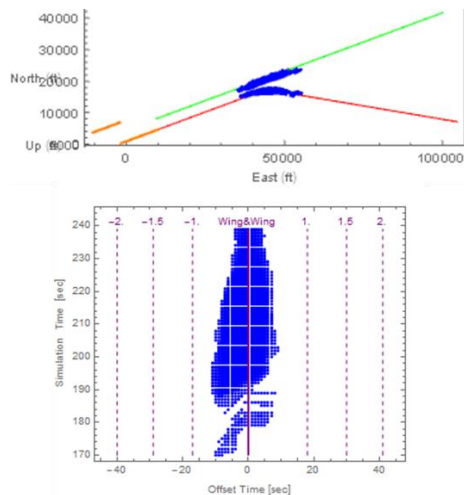


Figure 29. 30° turn-on; 3400 ft runway spacing; speeds 170 kts; RNP 0.11.

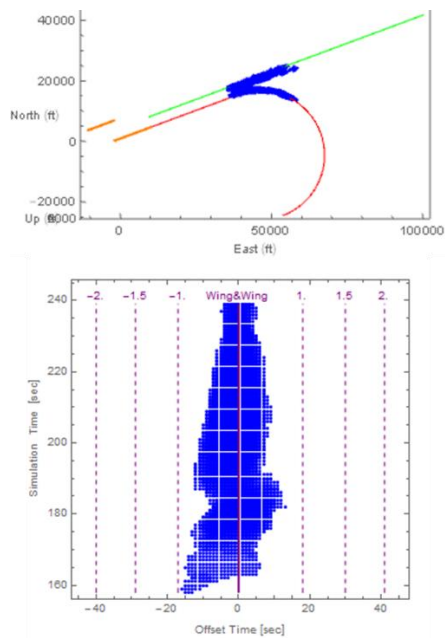


Figure 30. 180° turn-on; 3400 ft runway spacing; speeds 170 kts; RNP 0.11.

8.2 Scenario I: IND2_ICAO

These are similar to the DLR results of Section 7.2, in that some TAs are predicted but not RAs.

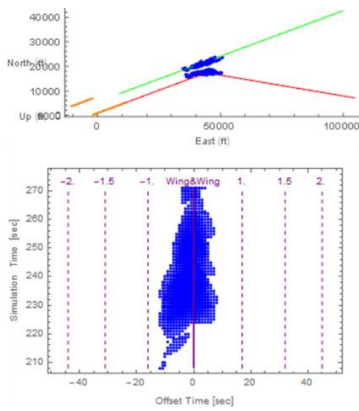


Figure 31. 30° turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.17.

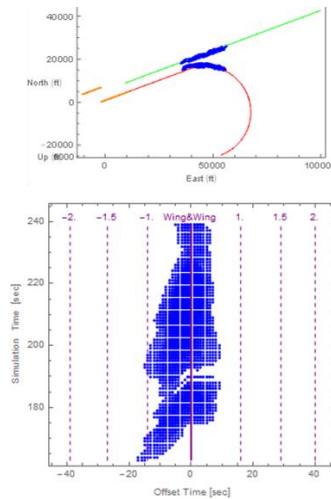


Figure 34. 180° turn-on; 4300 ft runway spacing; speeds 170 kts; RNP 0.17.

8.3 Scenario II: Minimum runway spacings for standard RNP values

The following two plots indicate that RAs are likely for the 2500 ft runway spacing at RNP 0.1 and a 30° turn-on angle, but none show up in the 3400 ft case. This is consistent with the DLR results of Figure 21 in Section 7.3.

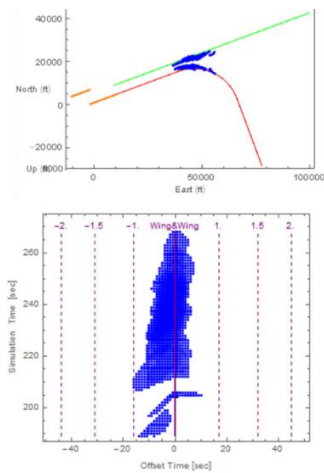


Figure 32. 90° turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.17.

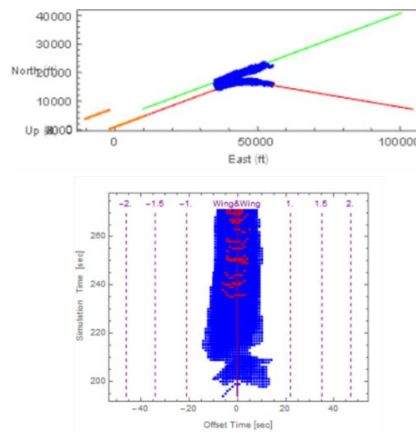


Figure 35. 30° turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.1.

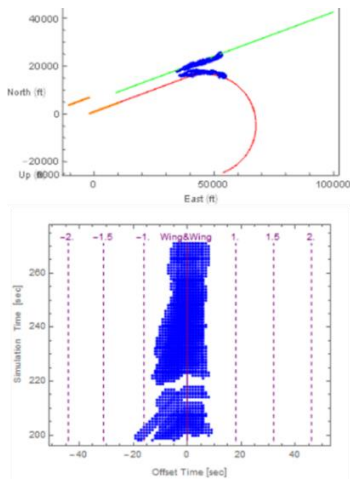


Figure 33. 180° turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.17.

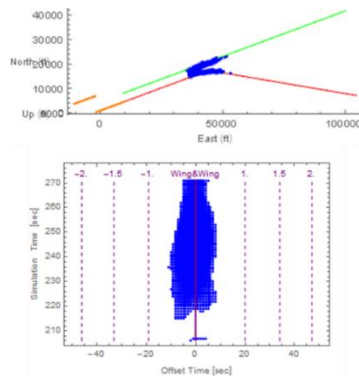


Figure 36. 30° turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.1.

However, in the RNP 0.3 case, RA's are very prominent when the runway spacing is only 2500 ft, and are even possible when the runway spacing is 4300 ft.

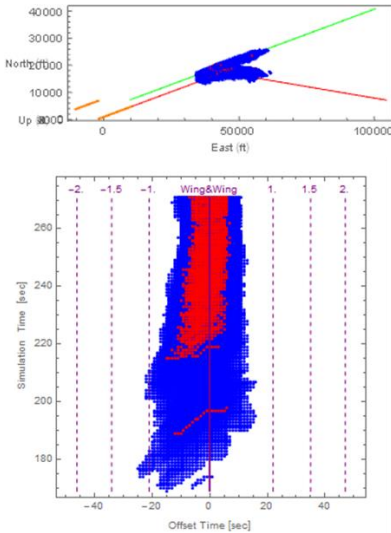


Figure 37. 30° turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.3.

These results are consistent the DLR output shown in Figures 23 and 24.

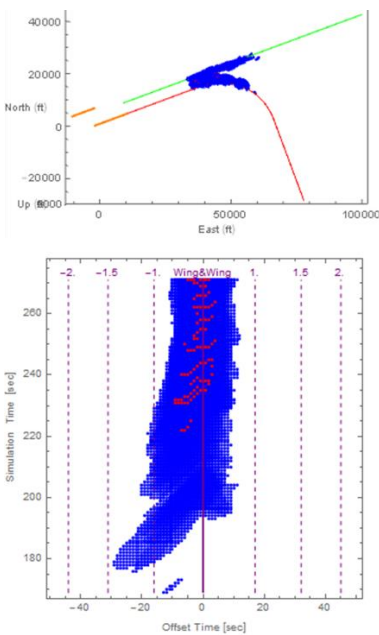


Figure 38. 90° turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.3.

8.4 Key parameters affecting alert totals

Although an attempt was made to include a reasonable number of parameter combinations in the analysis, it was time prohibitive to perform an analysis for every single case in a rigorous design of experiments. We did estimate the number of

alerts as a function of runway spacing, RNP value, and speeds. However, due to limited space, we show only those plots which show numbers of alerts as a function of runway spacing, although the influence of other parameters can be seen by noting the RNP value and speeds associated with each plot.

8.5 Total alerts as a function of runway spacing

The following four plots are samples of TA and RA counts as a function of runway spacing, based on RNP levels RNP 0.1 and RNP 0.3. These are all dependent cases, since there were no independent cases run in which runway spacing varies and RNP value is fixed. There were no TA's or RA's as long as the aircraft maintained the required minimum diagonal spacing. Therefore these plots indicate only what would happen if the dependent operation were run as an independent operation. This is not operationally sensible, of course, but as a simulation, it does indicate the relationship between runway spacing and numbers of alerts. If the total number of alerts seems large, recall that they represent the total for the two aircraft combined over 1000 simulated approach pairs (for each case of RNP value, speeds, turn-on angle, etc.)

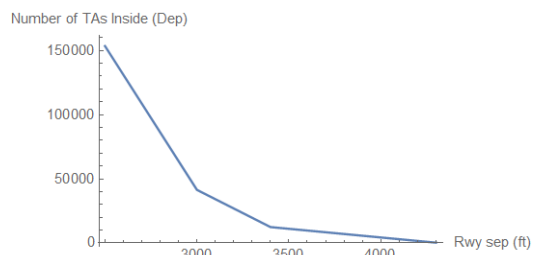


Figure 39. TA's as a function of runway spacing, inside the dependent spacing, 30° turn-on angle, RNP 0.1.

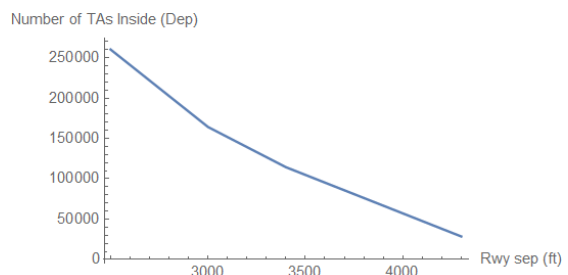


Figure 40. TA's as a function of runway spacing, inside the dependent spacing, 30° turn-on angle, RNP 0.3.

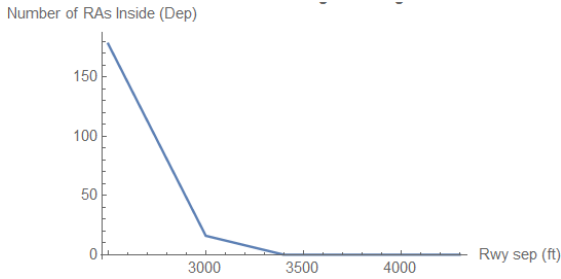


Figure 41. RA's as a function of runway spacing, inside the dependent spacing, 90° turn-on angle, RNP 0.1.

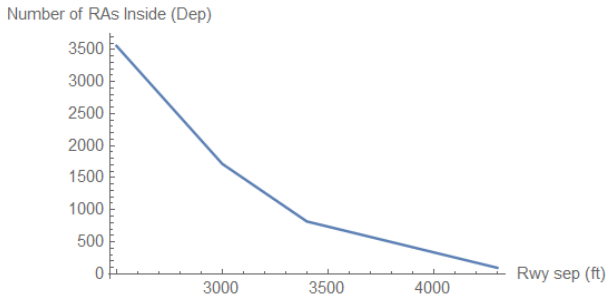


Figure 42. RA's as a function of runway spacing, inside the dependent spacing, 90° turn-on angle, RNP 0.3.

8.6 Summary of Boeing results

Boeing's methodology enables analysis of both independent and dependent scenarios. The key results are:

In each case, for a given fixed setting of the remaining parameters.

1. The number of alerts is *inversely* proportional to the magnitude of the runway separation,
2. The number of alerts is *directly* proportional to the magnitude of the RNP level, and
3. The alert patterns are very similar for the 90°- and 180° turn-on cases.

There are no independent cases that do not have at least some TAs, although the numbers decrease as runway spacing goes up and/or RNP level comes down (that is, becomes more strict). The TAs that were counted in the dependent scenarios only occurred *inside* the minimum diagonal spacing, and therefore should not be a problem if this spacing is maintained during actual (not simulated) operations.

There are several cases with no RAs, as shown in the following table:

Turn-on angle	Runway spacing (ft)	RNP value
30	3400	.10
30	4300	.10
30	3400	.11
30	4300	.17
30	3400	.11
30	4300	.17
90	3400	.10
90	4300	.10
90	3400	.11
90	4300	.17
90	3400	.11
180	4300	.10
180	4300	.17
180	3400	.11
180	4300	.17

Table 10. Cases without RAs

This is a fairly good indicator that the proposed rules for RNP requirements based on runway spacing are about right. Consider the following table which summarizes the two proposed rules:

Runway spacing (ft)	$\frac{1}{4}$ distance between centerlines (NM)	$(d-2000)/2$ (NM)
2500	.10	.04
3000	.12	.08
3400	.14	.12
4300	.18	.19
5000	.21	.25
9000	.37	.58

Table 11. Maximum RNP value (in NM) allowed under the two different rules, based on runway spacing in feet.

9 Conclusions and Recommendations

9.1 Conclusions

The DLR and the Boeing methodologies and output formats are quite different, but the general results are very similar. See Section 7 for the DLR results and see Section 8 and Appendix C for the Boeing results.

Since the DLR methodology is closed-form and analytical, it allows quick trade studies of many possible alternatives early in the procedure design process. The fast-time simulations of the Boeing methodology take some time to run (about an hour for 1000 simultaneous approaches), but the output provides some more details about how the aircraft could be separated in time in order to avoid either TA's or RA's.

The general similarity of results is exemplified by Figures 14 (DLR output) and Figure 26 (Boeing output). Both figures belong to the 30° turn-on case at a 3400 ft runway spacing. It can be seen that each shows a potential for TA's but not RA's. Also both figures show that the potential for TA's is roughly between 7 NM and 5 NM before the threshold.

Both sets of output indicate an *inverse* relationship between the potential for alerts and runway spacing, and a *direct* relationship between alerts and RNP magnitude.

Although not a reflection on the merits of either methodology, the Boeing experiments included more cases than the DLR analysis, namely, dependent approach cases were considered, as well as a "differential speed" case, wherein the ILS aircraft was assigned 170 kts while the RNP aircraft remained at 150 kts.

This resulted in a "shift" of the alert pattern into the negative region of the offset values (See Figures C-38 and C-39 in Appendix C, for example.). This means that alerts are more likely to occur if the ILS aircraft arrives somewhat later to its starting point than the RNP aircraft arrives at its starting point. "Starting point" here refers to the simulation start, which is arbitrary, but can be re-defined to represent operationally significant points in space or time, such as the initial approach fix, for example. In any case, this example shows how controllers may want to

adjust relative positions of the two aircraft during dependent operations, based on different speeds.

9.2 Recommendations

Experimentally speaking, future work should start with a more complete design of experiments (DOE) framework in order to avoid the problem of confounding factors. In the work reported here, it was difficult to separate the RNP effect from the runway separation effect, for example. Also, there was not enough variation in speeds across the other parameters to conclude much about its effect.

Operationally speaking, both analyses have shown the importance of considering nuisance ACAS alerts during procedure design, based on parameters such as runway spacing, RNP value, and time spacing in the case of dependent operations. There is a positive indication that the proposed rules for RNP requirements based on runway spacing and other factors are reasonable.

In short, nuisance ACAS alert investigations should be part of RNPe safety case analysis (along with CPA and wake encroachment prediction).

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Appendix A: Range tau thresholds

The details of the range tau criterion have evolved over the years. There are basically three criteria that have emerged:

The *simple* (or *basic*) *tau criterion* utilizes the measured range r and the negative of range rate (i.e., closing rate)- \dot{r} and has the form:

$$\tau_0 \geq \tau = -\frac{r}{\dot{r}} \quad (A-1)$$

The basic τ -criterion has some drawbacks, however. See the analysis in [14] [18], for example. From equation (1), if $r > 0$, τ approaches ∞ as the closing rate $-\dot{r}$ approaches 0. In other words, it is possible for the two aircraft to be very close together and still not trigger an alert, if $-\dot{r}$ is small enough to make $\tau > \tau_0$. Hence, special logic is necessary to handle exceptional situations like this.

This problem was initially addressed by the so-called *modified tau criterion*, which introduces an additional parameter D_m , called the *distance modifier*. In cases where closing rate is very low (effectively 0), the simple criterion is superseded by a distance criterion, that is, an alert is generated if $r < D_m$. The modified tau criterion relative to a threshold τ_0 has the form

$$\tau_0 \geq \tau = -\frac{(r - D_m)}{\dot{r}} \quad (A-2)$$

The modified tau criterion was in effect for a long time, but it was eventually determined that it was too conservative. Therefore, a further modification to address both issues was developed, and resulted in the so-called *Bramson criterion*, which is currently part of the ACAS conflict determination logic. The Bramson-tau criterion has the following form [11] [13] [17]:

$$\tau_0 \geq \tau = -\frac{\left(r - \frac{D_m^2}{r}\right)}{\dot{r}} \quad (A-3)$$

A comparison of the three criteria is shown in Fig. A-1 below. This representation is from the ownship point of view, which is assumed to be fixed at the origin. The axes are assumed to be rotated so that the velocity vector (to closest point of approach (CPA) on the y-axis) is parallel to the x-axis. For this particular scenario, the closing speed to the CPA is $s = 300$ kts, the relative range rate is $\dot{r} = -s \cos \theta$, the time to CPA is 25 seconds, and the distance modifier D_m is 0.33 NM.

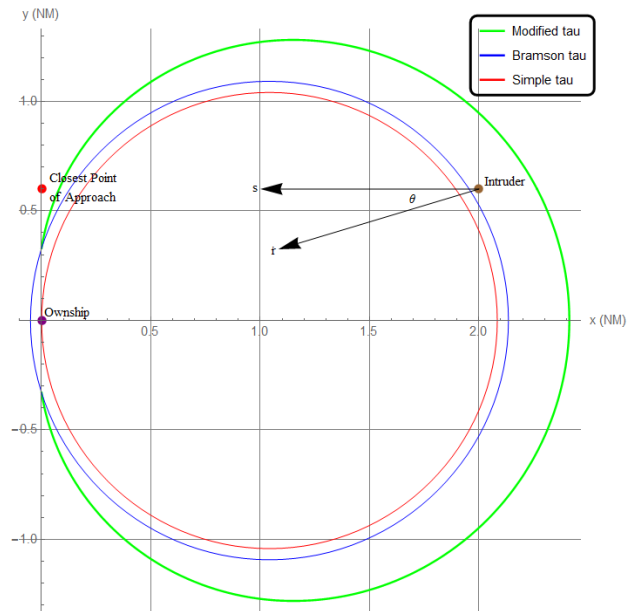


Figure A-1. Range tau criteria comparison for a TA of 25 sec with a distance modifier of 0.33 NM and a closing speed s to CPA of 300 kts (spatial view).

A necessary condition for an alert to occur in each criterion case is that the intruder aircraft crosses the corresponding boundary. (It is not sufficient since a similar altitude criterion must also be satisfied in order to trigger an alert.) Note

that the simple tau and Bramson tau boundaries are circles, whereas the modified tau boundary is a limaçon. In the situation shown, the intruder has violated the modified tau boundary but neither the simple nor Bramson boundaries (yet).

A different representation of the same range tau comparison is shown in Fig. A-2 below. This diagram shows the range tau thresholds as slanted lines in the space of closing rate (x-axis) and slant range (y-axis).

Based on equations (A-1), (A-2), and (A-3) above, the equations for the three different lines are of the form $r = f(\dot{r})$, and are respectively, $r = -\dot{r} \tau_0$ (simple, red), $r = -\dot{r} \tau_0 + D_m$ (modified, green), and $r = 1/2 \left(-\dot{r} \tau_0 + \sqrt{(\dot{r} \tau_0)^2 + 4D_m^2} \right)$ (Bramson, blue).

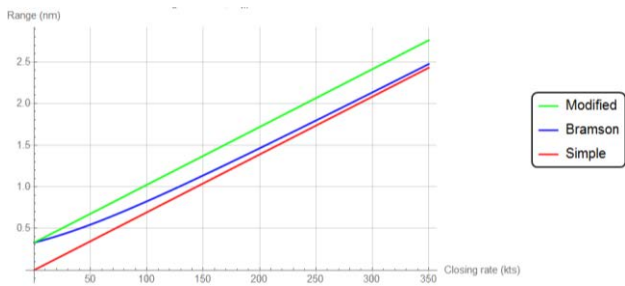


Figure A-2. Range tau criteria comparison for a TA with a time to closest point of approach of 25 sec and a distance modifier of 0.33 NM (range-closing rate view).

A necessary condition for an alert to occur is that one or more points of an approach scenario's (closing rate, slant range) profile falls below the corresponding curve. Again this is not sufficient since a corresponding altitude threshold must also be crossed in order to trigger an alert.

The simple tau criterion line (red) is a constant time line (of 25 sec). Note that the simple tau (red line) does not take into account very slow speed but close encounters. Both the modified and Bramson criteria (green and blue curves, respectively) do take this into account, but the Bramson range tau criterion (blue) is less conservative than the modified tau criterion

(green) and approaches the constant time line as closing rate increases.

In this paper, all results are based on the use of the Bramson range tau criterion.

Appendix B: Runway spacing and diagonal separation rules

Note the requirements for aircraft diagonal spacing of aircraft on dependent parallel runway approaches from the [2], 5-9-6. For runways spaced 2500-4300 ft, the required diagonal spacing is 1.5 nmi, while for runways spaced 4300-9000, 2 nmi are required. This seems the reverse of what it should be. However, there is a reason.

Consider Fig. B-1 below. This shows two aircraft on approach (from "top" to "bottom") to parallel runways.

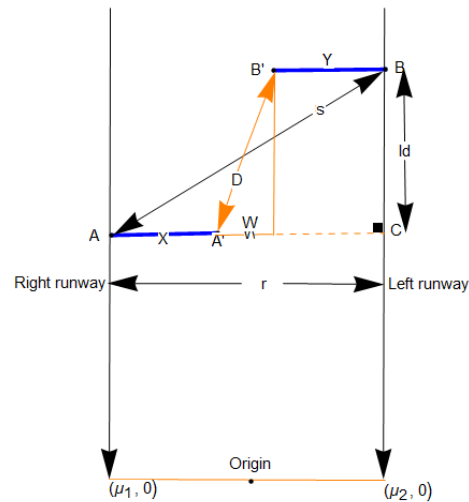


Figure B-1. Geometry of two aircraft A and B on parallel approaches. Runways are spaced r NM apart and aircraft are separated by the minimum diagonal requirement s nmi.

The *nominal* aircraft positions are at point A on the right runway and point B on the left runway. The runways are spaced at r nmi. The required minimum diagonal spacing is denoted by s nmi, the length of the line AB. Assume that the aircraft on the right runway is actually at a distance X to the left of the right runway at the point A' and the aircraft on the left runway is at a distance Y to the right of the left runway at point B' . Then the

actual aircraft spacing is the length D of the line $A'B'$.

Let

- Coordinate system: y-axis positive up parallel to runways, x-axis perpendicular to runways with origin halfway in between somewhere downstream of the two aircraft positions
- X and Y = the (Normal) r.v.'s representing the right and left runway lateral error.
- r = runway spacing
- s = diagonal separation requirement
- ld = longitudinal distance between aircraft (i.e. along a line parallel to runways)
- D = (random) slant distance between aircraft
- W = (random) lateral distance between aircraft
- $\mu_1 = -r/2$ = left runway x-distance wrt origin
- $\mu_2 = r/2$ = right runway x-distance wrt origin.

Then

- $ld = \sqrt{s^2 - r^2}$
- $W = (\mu_2 + Y) - (\mu_1 + X)$

and finally the actual separation between the aircraft is given by

- $D = \sqrt{W^2 + ld^2} = \sqrt{W^2 + s^2 - r^2}$,

Note that, for fixed errors X and Y and for a fixed minimum diagonal separation s , the actual spacing D goes down if the runway spacing r goes up. Fig. B-2 below shows the relationship between runway spacing and actual (miss) distance for a required minimum diagonal spacing of 1.5 nmi. The red dot is at the point

(2500, 1.46), that is a runway spacing of 2500 ft and an actual distance of 1.46 nmi between aircraft.

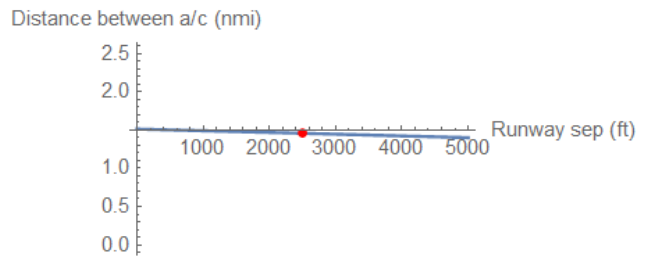


Figure B-2. Relationship between runway spacing (x-axis in feet) and actual miss distance (y-axis in nmi) corresponding to a nominal minimum diagonal spacing of 1.5 nmi and X and Y errors of 0.1 nmi.

Here is a schematic of the runway and aircraft positions corresponding to the red dot in the previous Figure.

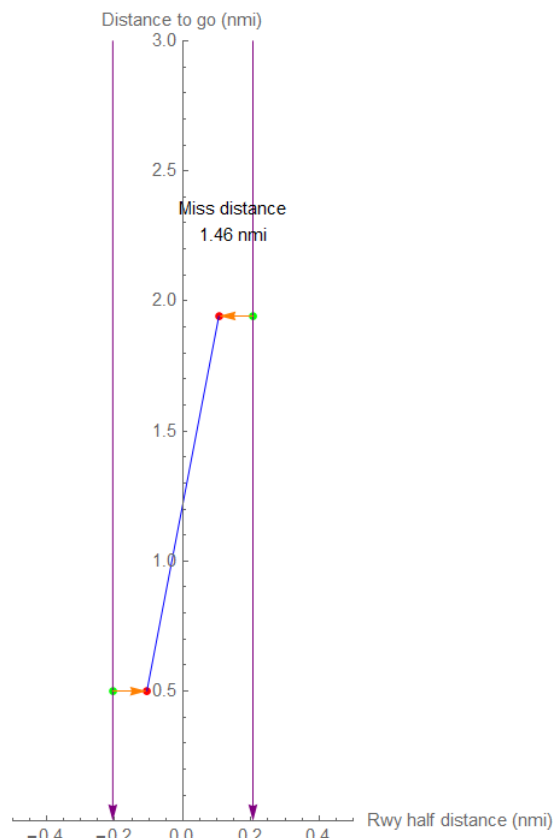


Figure B-3. Example of actual (miss) distance 1.46 nmi of the two aircraft corresponding to a runway spacing of 2500 ft, a nominal minimum diagonal spacing of 1.5 nmi, and X and Y errors of 0.1 nmi.

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The next figure shows the same situation except the runway spacing is 5000 ft. Note that the aircraft are closer together than in the case of 2500 ft runway spacing.

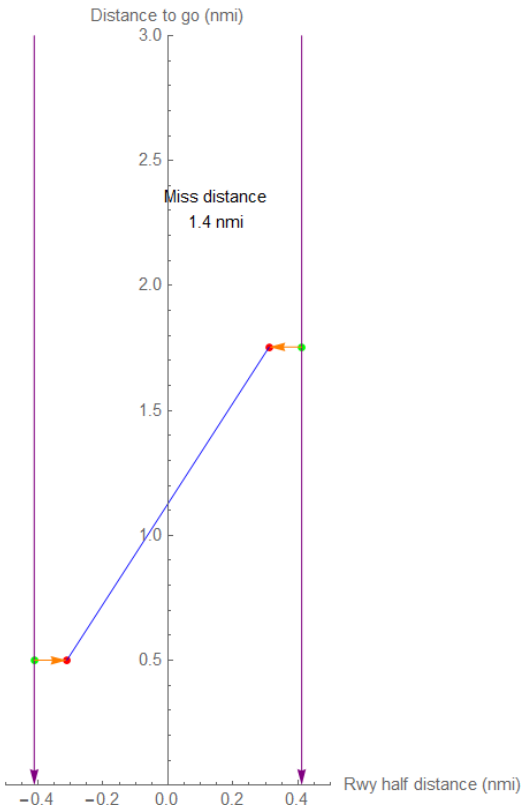


Figure B-4. Example of actual (miss) distance 1.40 nmi of the two aircraft corresponding to a runway spacing of 5000 ft, a nominal minimum diagonal spacing of 1.5 nmi, and X and Y errors of 0.1 nmi.

Appendix C: Boeing results – All TA and RA plots

C.1 30° turn-on cases

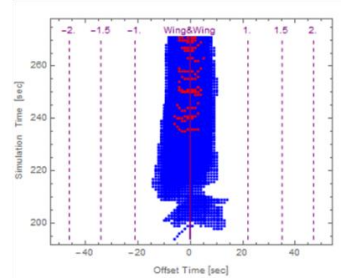
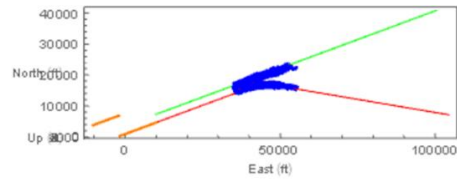


Figure C-1. 30° turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.1.

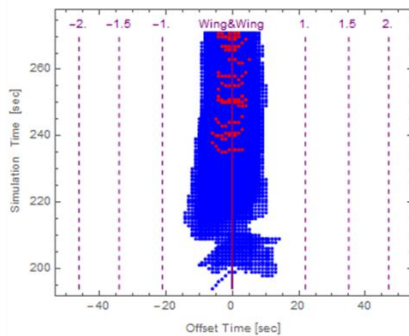
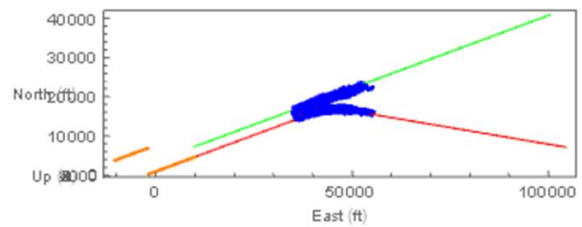


Figure C-2. 30-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.1.

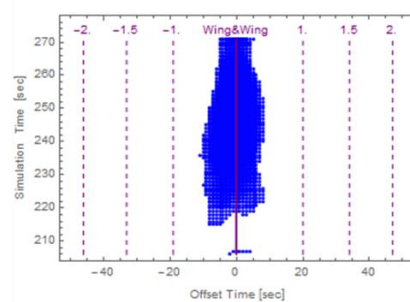
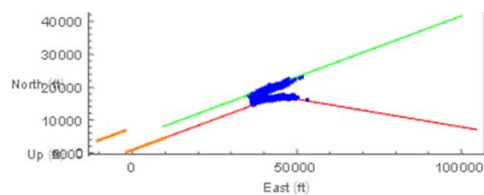


Figure C-3. 30-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.1.

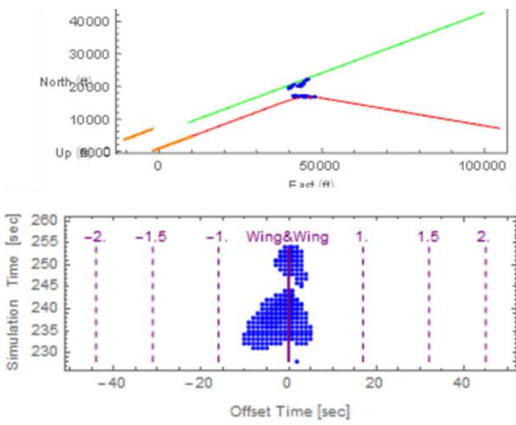


Figure C-4. 30-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP .1.

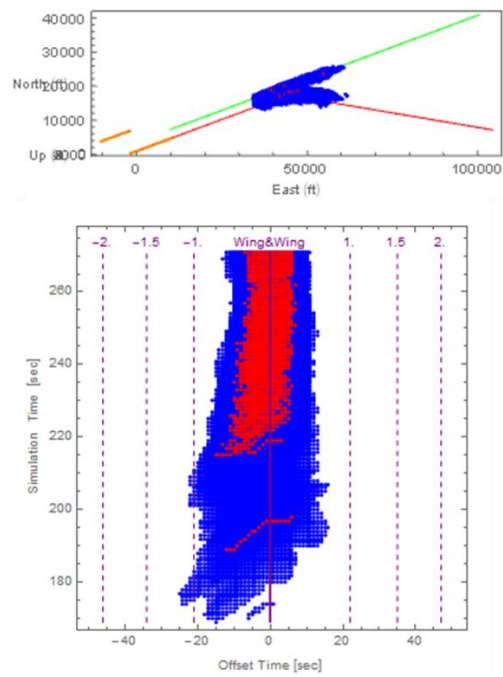


Figure C-7. 30-deg turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.3.

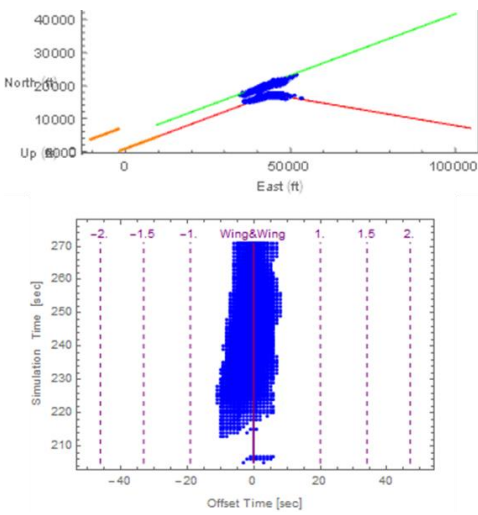


Figure C-5. 30-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.11.

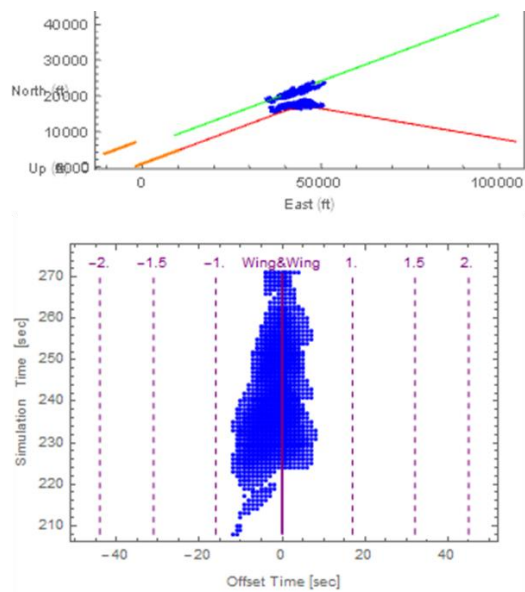


Figure C-8. 30-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.17.

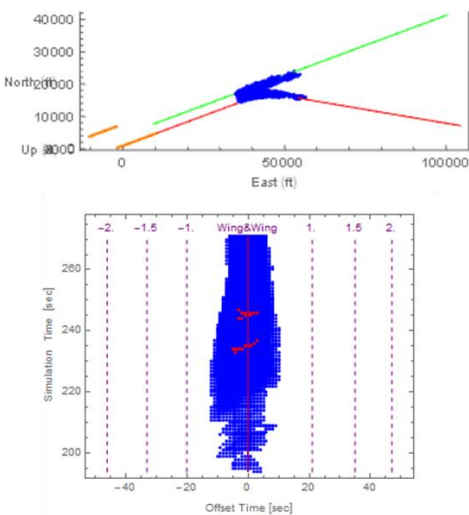


Figure C-6. 30-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.12.

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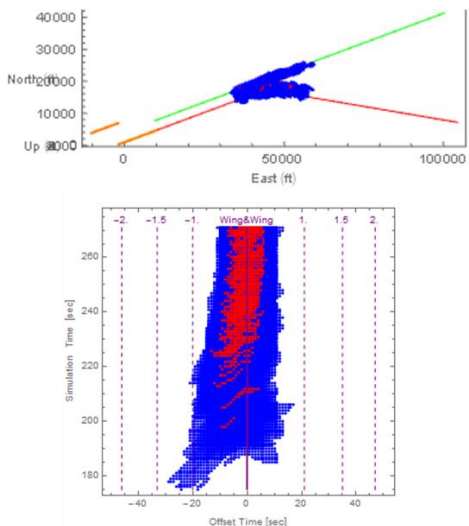


Figure C-9. 30-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.3.

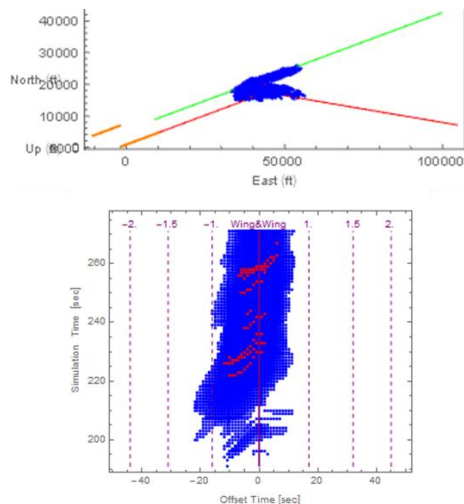


Figure C-11. 30-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.3.

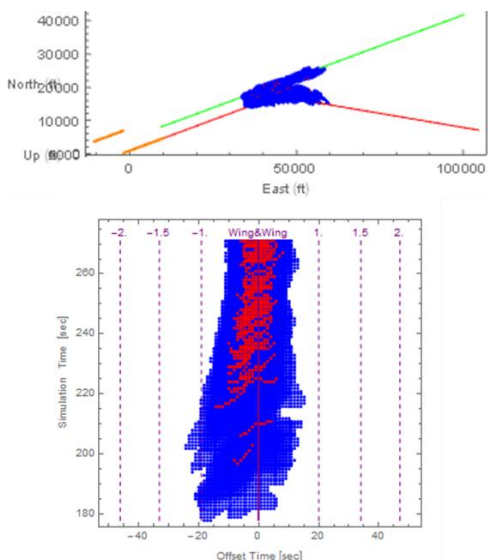


Figure C-10. 30-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.3.

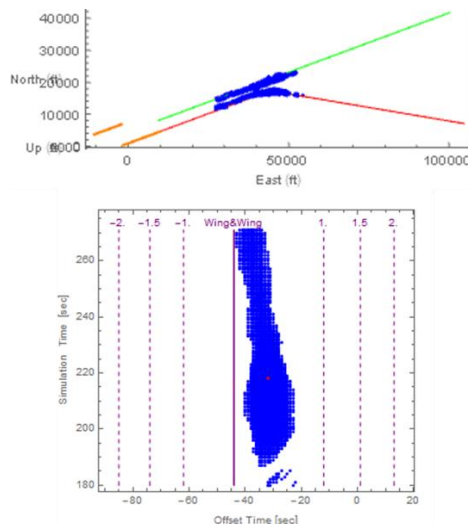


Figure C-12. 30-deg turn-on; 3400 ft runway spacing; speeds 170 kts; RNP 0.11.

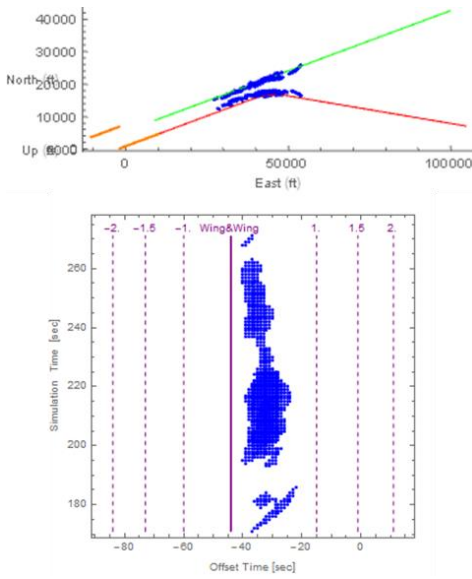


Figure C-13. 30-deg turn-on; 4300 ft runway spacing; speeds 170 kts; RNP 0.17.

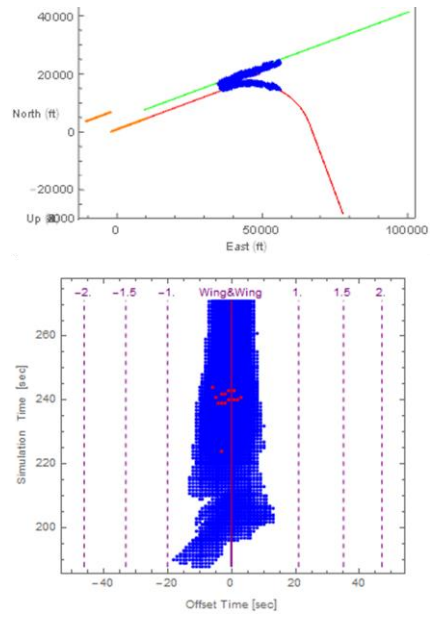


Figure C-15. 90-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.1.

C.2 90° turn-on cases

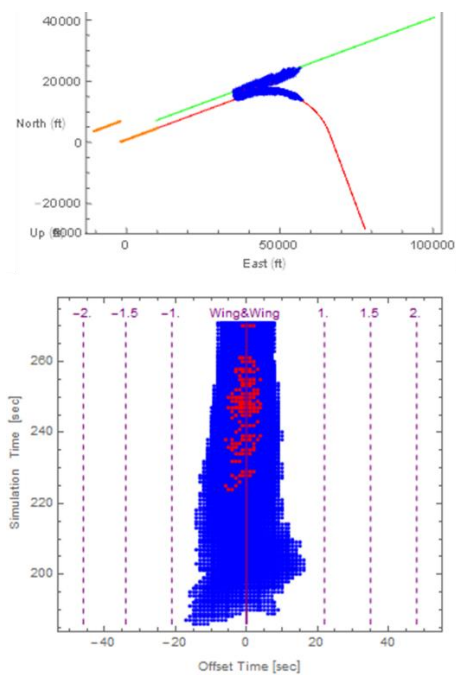


Figure C-14. 90-deg turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.1.

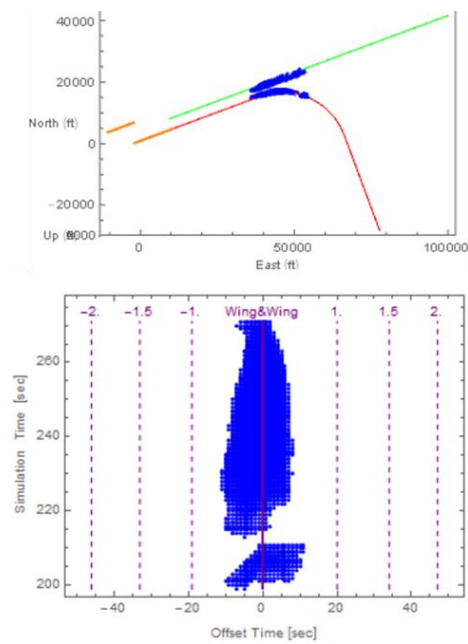


Figure C-16. 90-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.1.

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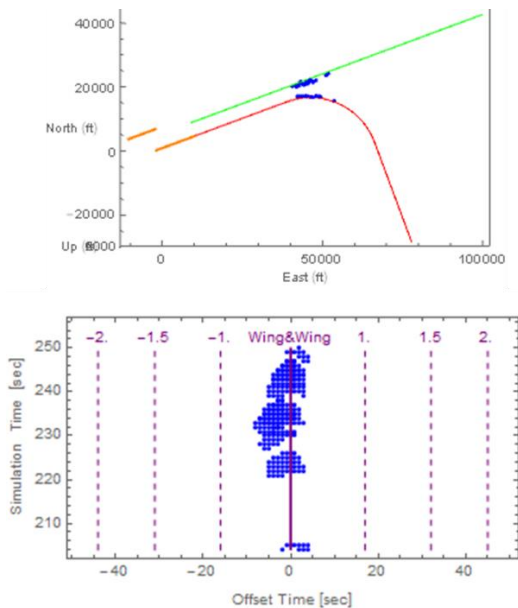


Figure C-17. 90-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.1.

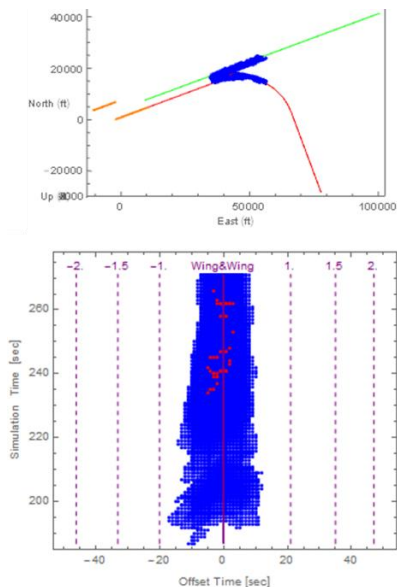


Figure C-19. 90-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.12.

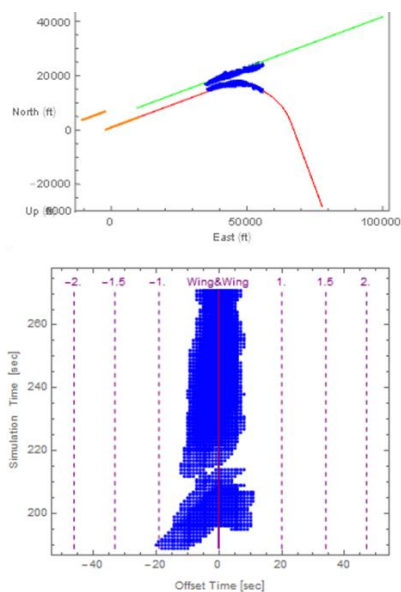


Figure C-18. 90-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.11.

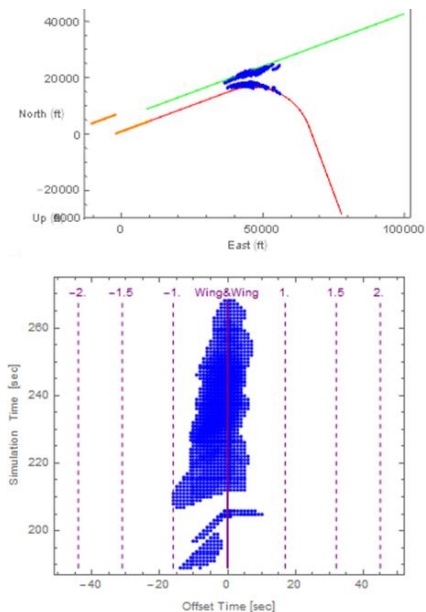


Figure C-20. 90-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.17.

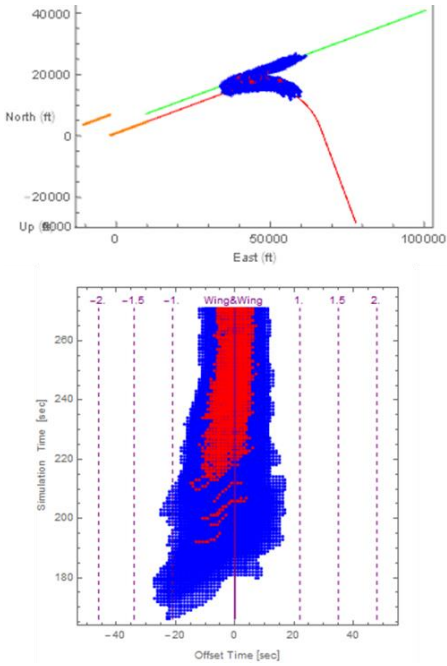


Figure C-21. 90-deg turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.3.

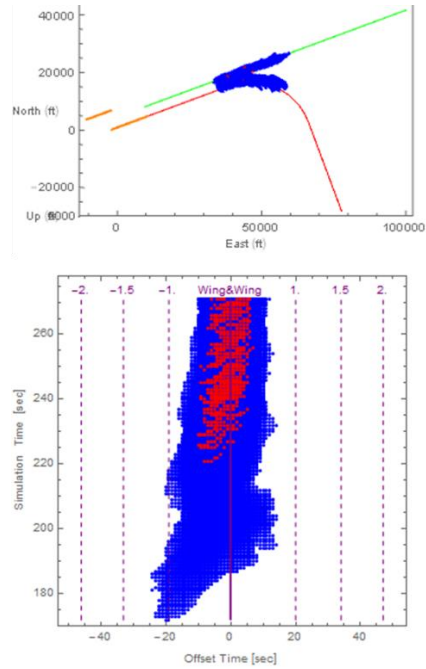


Figure C-23. 90-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.3.

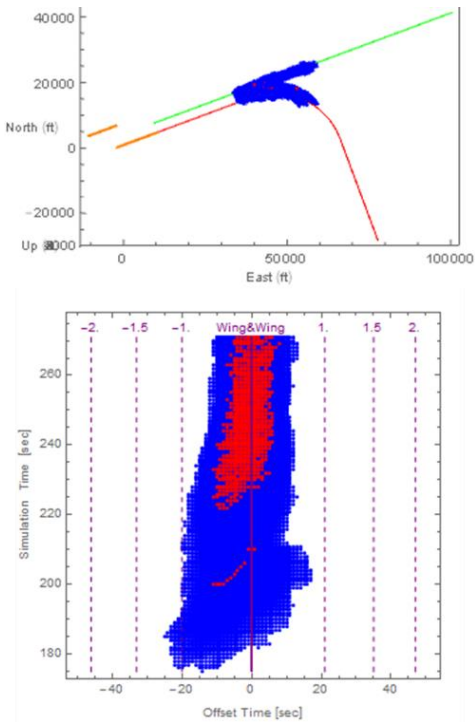


Figure C-22. 90-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.3.

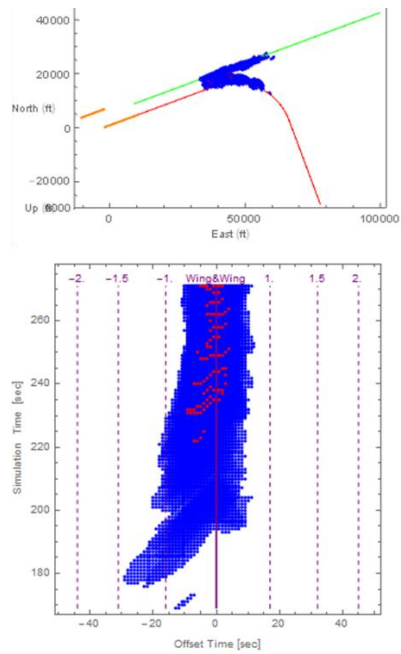


Figure C-24. 90-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.3.

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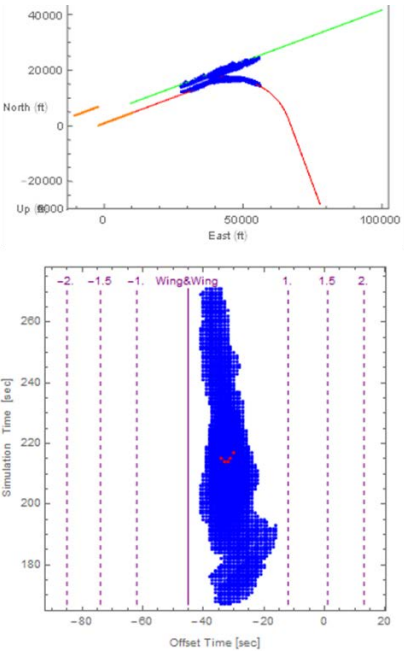


Figure C-25. 90-deg turn-on; 3400 ft runway spacing; speeds 170 kts; RNP 0.11.

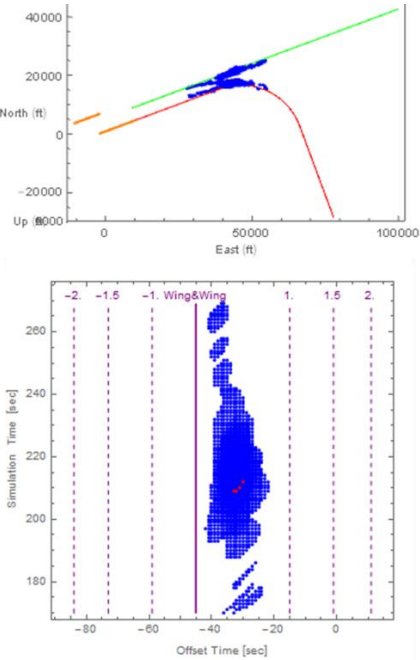


Figure C-26. 90-deg turn-on; 4300 ft runway spacing; speeds 170 kts; RNP 0.17.

C.3 180° turn-on cases

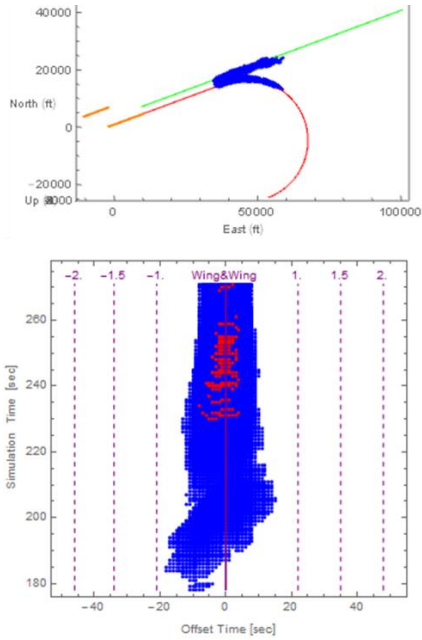


Figure C-27. 180-deg turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.1.

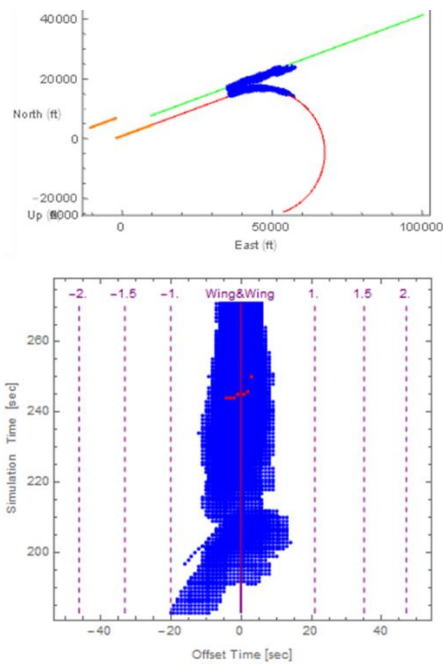


Figure C-28. 180-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.1.

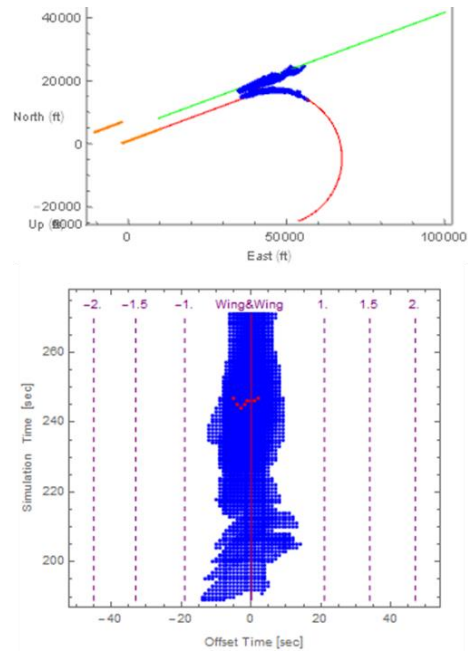


Figure C-29. 180-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.1.

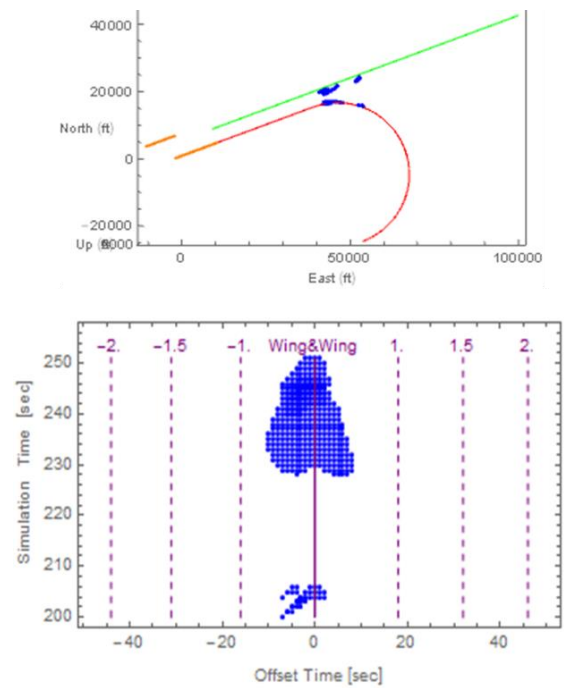


Figure C-30. 180-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.1.

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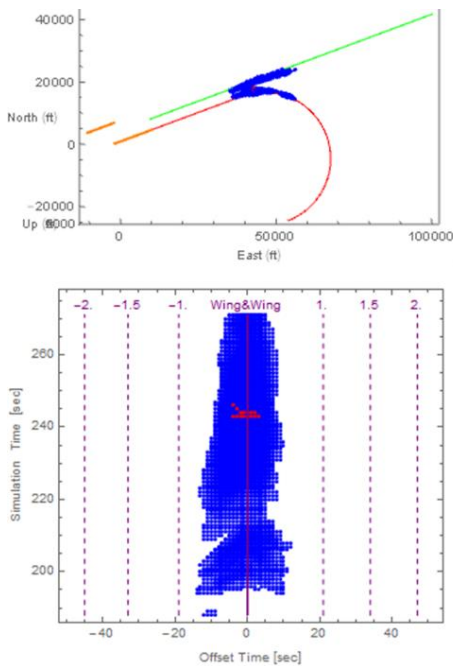


Figure C-31. 180-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.11.

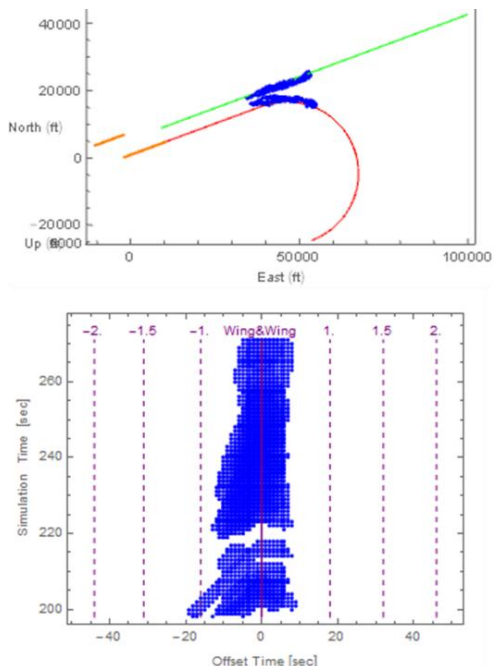


Figure C-33. 180-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.17.

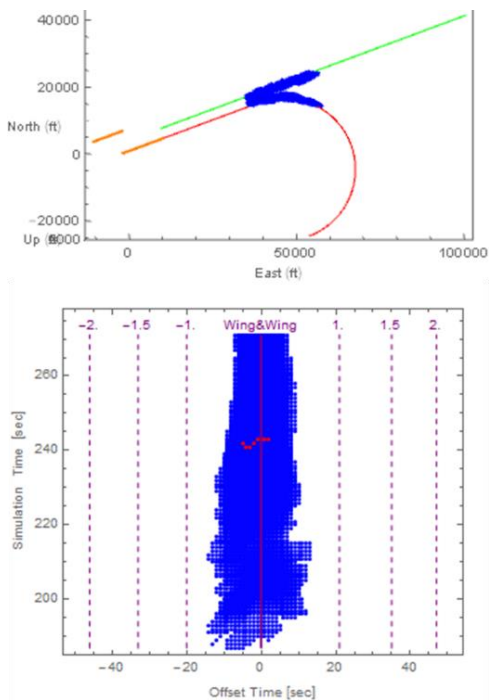


Figure C-32. 180-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.12.

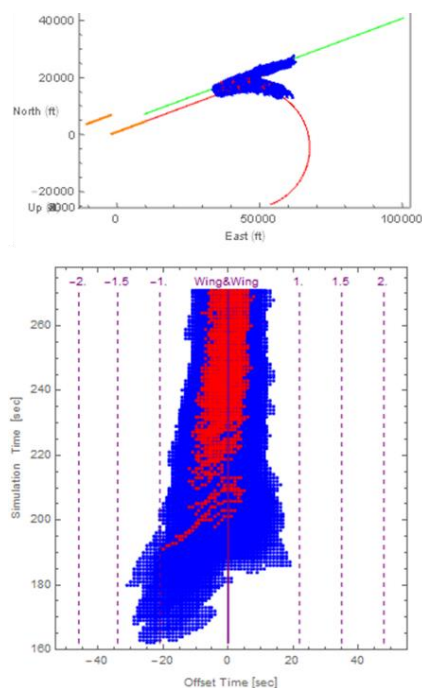


Figure C-34. 180-deg turn-on; 2500 ft runway spacing; speeds 150 kts; RNP 0.3.

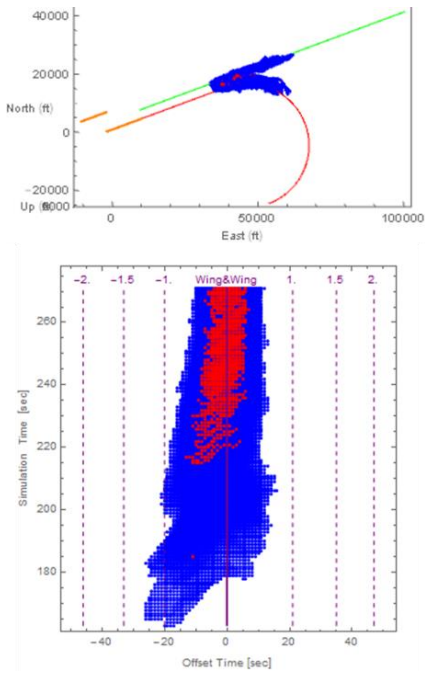


Figure C-35. 180-deg turn-on; 3000 ft runway spacing; speeds 150 kts; RNP 0.3.

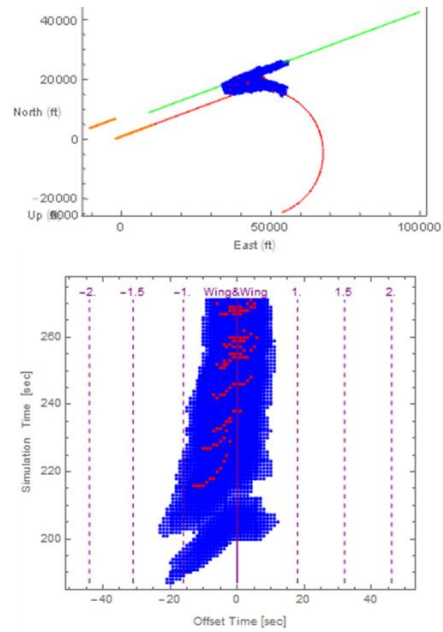


Figure C-37. 180-deg turn-on; 4300 ft runway spacing; speeds 150 kts; RNP 0.3.

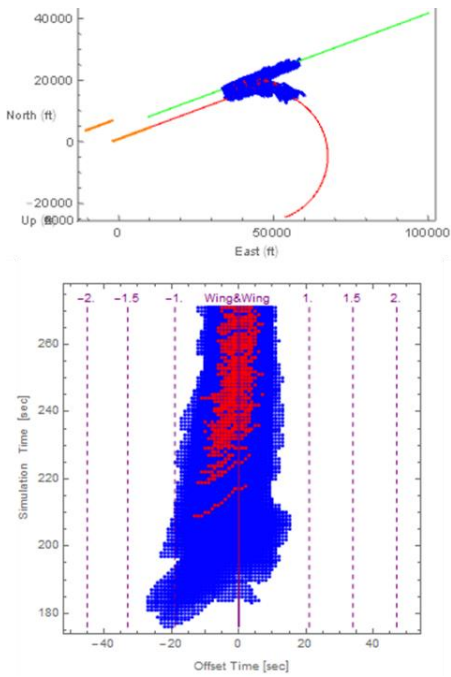


Figure C-36. 180-deg turn-on; 3400 ft runway spacing; speeds 150 kts; RNP 0.3.

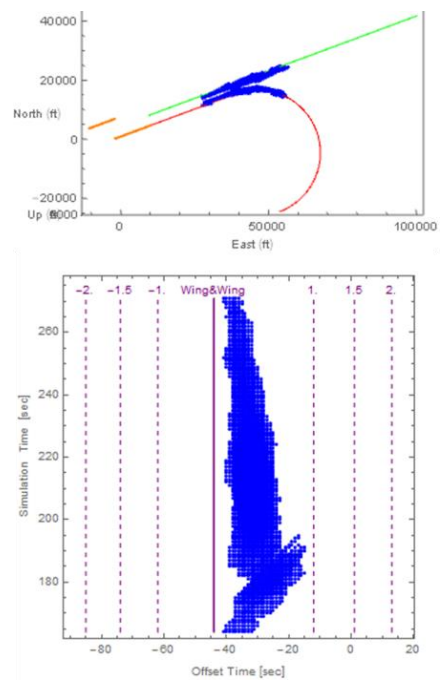


Figure C-38. 180-deg turn-on; 3400 ft runway spacing; speeds 170 kts; RNP 0.11.

AIRBORNE COLLISION AVOIDANCE CONSIDERATIONS FOR
SIMULTANEOUS PARALLEL APPROACH OPERATIONS

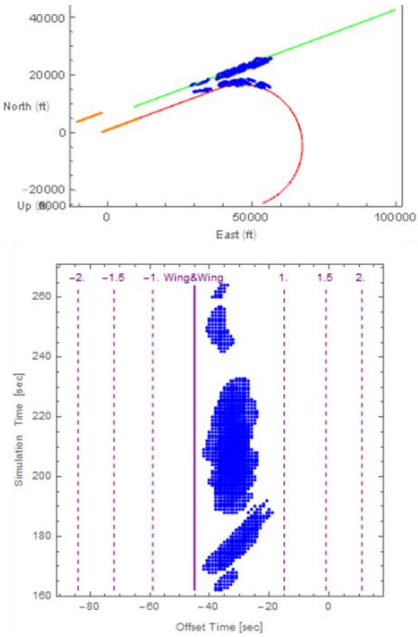


Figure C-39. 180-deg turn-on; 4300 ft runway spacing; speeds 170 kts; RNP 0.17.

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Date of Publication: 7/17/2016

Publisher: 30th Congress of the International Council of the Aeronautical Sciences ("Publisher")

Work Title: Airborne Collision Avoidance Considerations for Simultaneous Parallel Approach Operations ("Work")

Boeing Employee(s): Jeffery D Musiak

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