10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference
13 - 15 September 2010, Fort Worth, Texas

AIAA 2010-9334

Applications of Collision and TCAS Alerting Models in Parallel Runway Operations

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Collision and TCAS alerting models have been developed to analyze non-normal events and their mitigations during operations with two traffic streams on defined parallel tracks. Two particular events, i.e. deviations from path and not establishing on path during path turn-on, are emphasized in this paper. This paper will demonstrate how these collision and TCAS models can be used as tools for the design and development of parallel instrument approach operations. Extension of these models to general non-parallel traffic streams and operations with mitigation actions will also be discussed.

Nomenclature

ASRS	Aviation Safety Reporting System
DMOD	Distance Modification
FMS	Flight Management System
NTZ	Non-Transgression Zone
RNP	Required Navigation Performance
TCAS	Traffic Collision Avoidance System
CPA	Closest Point of Approach
FAF	Final Approach Fix
NMAC	Near Mid-Air Collision
RA	Resolution Advisory
TA	Traffic Advisory

I. Introduction

There are a number of efforts worldwide to develop operations which will enable efficient, environmentally-friendly, high-capacity access to parallel runways using simultaneous independent and dependent approach procedures[1 2]. These new operations, based in part on instrument approaches enabled by the appropriate level of RNP certification, rely on precise guidance and containment to maintain separation among participating aircraft. The safety afforded by lateral separation can be supplemented by a second layer of safety, such as controlling the relative along-track position of the aircraft, similar to today's dependent parallel approach operations. In the rare event that these primary modes of separation are somehow compromised, collision avoidance attributes are invoked, where the task becomes avoidance of another aircraft rather than maintaining ones' own deconflicted, prescribed path. Examples of collision avoidance considered for these procedures include air traffic controller intervention, where controllers issue escape maneuver instructions to prevent collision with other traffic, and TCAS (Traffic Alert and Collision Avoidance System), an on-board system certified to detect traffic conflicts and provide maneuvers to regain safe spacing. When designing new procedures enabled by RNP, the effectiveness of these collision mitigations must be considered, while at the same time being careful to minimize nuisance alerting and to avoid over-constraining system operations.

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In order to accomplish these goals, there is a need for a modeling approach (and associated tools) that

1. focuses on **non-normal** operational scenarios and the effectiveness of the relevant mitigations,
2. is capable of considering a wide range of non-normal events,
3. considers TCAS and its interactions with the procedure design,
4. bridges the gap between
    - mathematically complex approaches that may be difficult to implement, and
    - overly-simple implementations that may ignore key issues.

For example, the original Reich model[3] has been very effective in helping attain reduced lateral separations in oceanic routes, but is generally recognized as being difficult to apply easily to non-normal events and their mitigations by pilots and controllers. This shortcoming has been addressed, for example, by the generalized Reich model as developed at NLR[4]. However, this approach is mathematically complex and has not completely trickled down to common acceptance and usage as part of implementing parallel operations.

On the other hand, most of the existing (and simpler) methods rely on the infamous 30 degree deviation ("blunder") model[5], the principal basis of the safety assessment for parallel approaches today. These models have an advantage in their applicability and acceptance. But, not only does this modeling approach presuppose that the 30 degree deviation is "worst-case", but it focuses attention on the phase of the operation when the aircraft are already established on their guidance. However, the historical data of problems during parallel approaches points to issues stemming from the setup phase of the approach, which is the less-stable, and high-workload part of the approach. A quick survey of ASRS data show evidence of problems in this phase, such as failure to capture the ILS localizer or glideslope guidance in a timely fashion, a late runway or procedure change, or the effects of a latent error such as an incorrect navigational database entry or incorrect pilot FMS entry that goes un-noticed.

The purpose of this paper is to propose a simple but robust modeling approach for collision analysis of parallel approach operations that utilize lateral procedural separation. This approach can be used as part of a toolkit for the design and safety case assessment of procedures for parallel operations, perhaps in conjunction with methods aimed at assessing the effectivity of separation afforded by normal operations, and expert opinion of hazards and their mitigations. Additionally, this approach could be extended to the design of controller automation aids for parallel operations in the future.

The operational trials for parallel RNP approaches emerging worldwide share a common general concept of an RNP-guided turn to final, i.e. "turn-on". This protects both the aircraft in the turn and traffic established on guidance to a parallel runway by providing paths sufficiently separate from the other that they will not interfere. As shown in Fig. 1, one scenario being considered is when one aircraft (ownship) is already established on the runway centerline, while the other aircraft (intruder) approaches its corresponding runway centerline at a specified angle for a turn-on to the final, straight portion of the published procedure. At any time in the procedure, the intruder aircraft may fail to complete the turn-on, and subsequently *deviate* towards the other runway. Additionally, the model can explore the scenario when both aircraft are already established on their parallel tracks, and the intruder deviates from its initial track in the direction of the ownship, potentially threatening the traffic, akin to Massimini et al (Ref. 5). In this initial modeling effort, only along-track and cross-track motions are considered (as it is assumed that there is insufficient vertical separation), and wake vortex or wind effects are not considered.

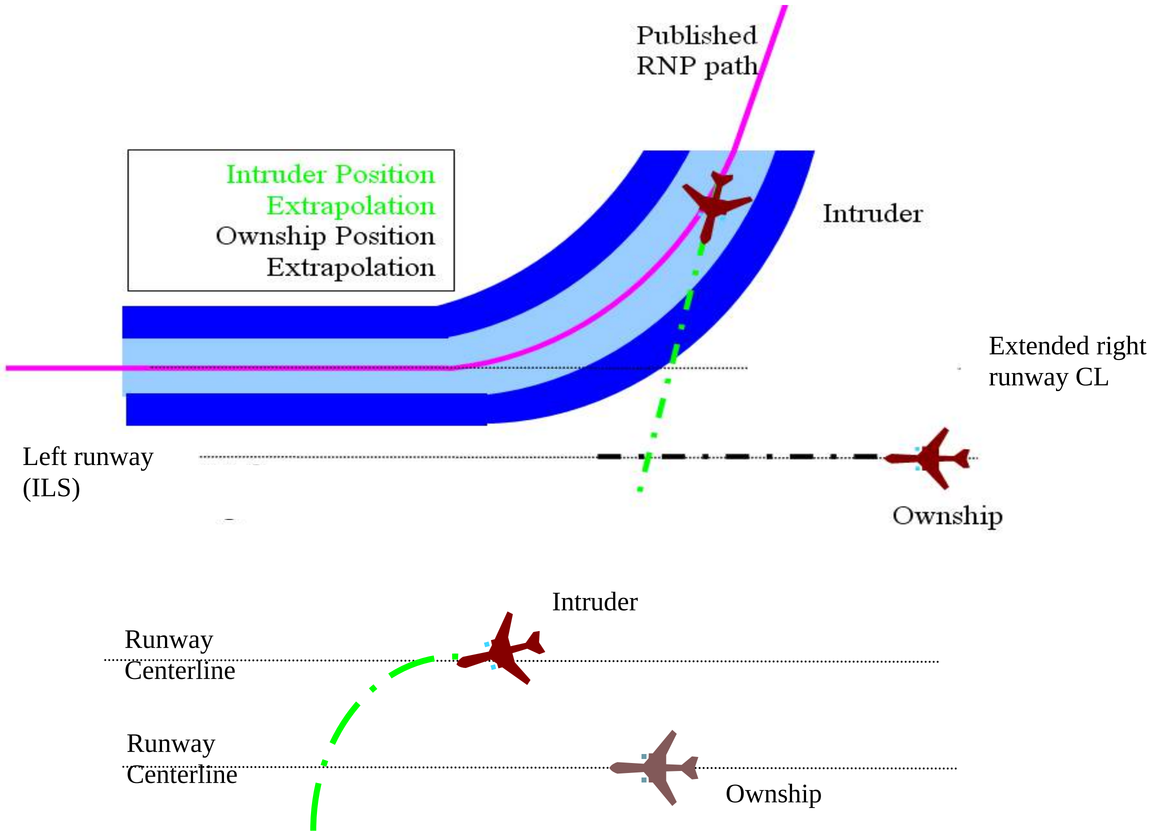

Figure 1. Deviation from Simultaneous, Parallel Arrivals
(e.g. RNP and ILS procedures to westerly runways as depicted)

These scenarios are the basis for two models and their associated analyses that are developed in this paper. The collision analysis models are used to explore minimum separations that may occur in the non-normal situation where the intruder aircraft deviates from its expected path. In Section II, the scenario is assumed to start just as the intruder deviates from its runway centerline (Figs. 2a and 2b), while in Section III, we extend this to the scenario where the intruder turns on to the runway centerline in a banked turn, and may or may not complete the turn successfully (Fig. 6). These models are exercised for both dependent and independent parallel operations. It is intended to help provide a basis for determination of separation standards for simultaneous approach procedures. We propose to do this through an exploration of the effects of varying approach parameters or combinations of parameters on the *remaining distance and/or remaining time to*, a Near Mid-Air Collision (NMAC, meaning a minimum miss distance of no more than 500 feet). Obviously, procedures should be designed to reduce the likelihood of an NMAC.

The simulation parameters include

- ground speeds of the ownship and intruder aircraft,
- turn-on angle and turn-off angle of the intruder (deviation angle = turn-on angle – turn-off angle),
- bank angle of intruder aircraft (during the turn-on),
- along-track distance of ownship from intruder aircraft, either ahead or behind, and
- runway separation.

In the presented results, these parameters remain constant over the course of any given simulation, but they can be chosen arbitrarily at the beginning of the simulation (within reasonable limits). Of course, in the real world, some of these parameters may vary over time (such as aircraft speeds).

This approach is also applied to a study of TCAS alerting (Section IV), and is used to identify those operational designs (geometry and procedures) which lead to a "nuisance" TCAS alert. Most modern aircraft are equipped with a TCAS system for collision avoidance. Since aircraft operating in these parallel approach operations are often in close proximity, a large number of TCAS alerts could be generated if not considered a priori. Therefore, in order to "design out" any geometrical configurations which might lead to an alert, it is necessary to understand those operational parameter ranges, or combination of parameter ranges, that could lead to a TCAS warning (either RA or TA). The operational parameters in this model are the same as in the collision analysis model, as described in the previous paragraph.

II. Collision Analysis Model

The initial setup for the collision analysis model is shown in Fig. 2a. This scenario involves two aircraft nominally on parallel approach paths (denoted by dotted green lines). In the example shown, the aircraft on the right runway (top) is deviating from its approach path by 30 degrees. Note that this is just an example scenario, and several of the parameters, such as deviation angle, aircraft speeds, and initial relative position, will be varied in this analysis.

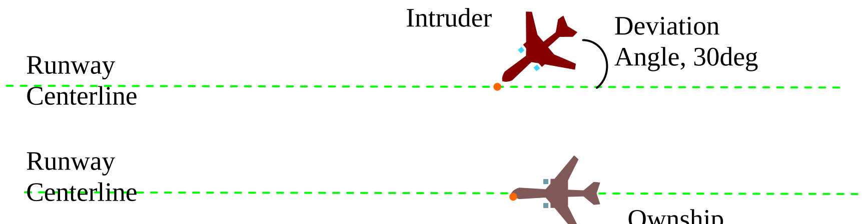

Figure 2a. Initial Condition (example only)

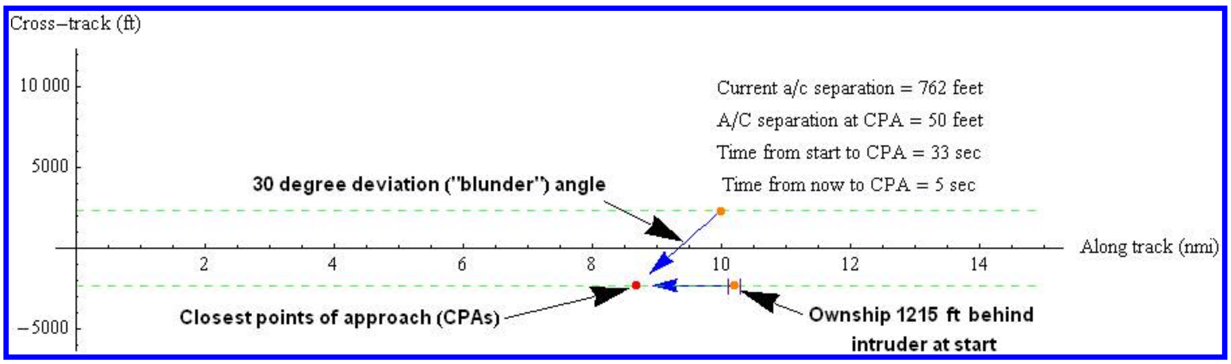

Figure 2b. The collision risk analysis model with instantaneous deviation (example only)

In Fig. 2b, the modeled version of this scenario, the x-axis is equidistant from the two runways, which in this case are 4642 feet apart. As shown, the aircraft fly from right to left until they reach the runway threshold, denoted by the y-axis. The aircraft on the right runway (top) is the "intruder" and the one on the left runway (bottom) is the "ownship". The aircraft trajectories are denoted by the blue lines, with the current positions of the aircraft represented by the tip of the arrowheads, and their initial position at the time the deviation began represented by the orange dots. In this particular snapshot, the notations in the upper right of the diagram indicate that at this particular point in the scenario, the aircraft are 762 feet apart and have 5 seconds to go before reaching their closest points of approach (CPAs), which are 50 feet apart. The CPAs are denoted by the two red dots, which in this instance are close enough together to appear to be one. Also, the time to CPA from the start of the scenario (orange dots) is 33 seconds.

Of particular interest in Fig. 2b are the vertical purple lines surrounding the starting point of the ownship on the left runway (bottom). Points in this interval are the *only starting points which can lead to an NMAC*, as long as all other parameters (such as aircraft ground speeds and intruder deviation angle) are kept constant. Note this interval is less than ¼ nmi long (about 1500 feet). Of course this interval will change in size and location if other parameters are changed, but this size is typical, except for very small deviation angles, a topic which will be discussed later.

Figures 3-5 show some results from this model. In Figs. 3 and 4, the runways are separated by 4642 ft., while in Fig 5, they are separated by 2500 ft. In Fig. 3, the x-axis represents the deviation angle of the intruder, with respect to the runway centerline. The y-axis represents the distance of the ownship ahead of (+) or behind (-) the intruder at the start of the scenario. The results are a family of pairs of curves for a specified set of intruder and ownship speeds (see legend).

For each pair of curves (same color and line type), the region *between* the curves in a given pair represents the combinations of intruder deviation angle (degrees) and ownship initial offset distance (nmi) from the intruder that lead to an NMAC. By implication, the region *outside* this pair of lines will *not* lead to an NMAC. This "threat" region (where an NMAC occurs) is consistent with the findings from other researchers, such as Pritchett[6]. The first speed in each pair in the legend is for the intruder and the second is for the ownship, and they all vary from 95 to 185 kts, and for each curve, the two speeds are either equal or have an absolute difference of 40 kts. Note that the "threat" regions are quite small compared to the complete parameter space of offsets and intruder deviation angles considered in the scenario of Fig. 2b.

For example, the two pairs of green curves with either solid or dotted curves are for the case where the intruder ground speed equals the ownship ground speed, and are on top of each other. This is because the "threat" region is independent of ground speed if both aircraft travel at the same speed. The two green pairings also show that regardless of the deviation angle, if the ownship is abeam or in front of the intruder, it is not threatened by collision. This may be intuitive, as without a speed differential, and a non-zero spacing between the two nominal paths, the deviating aircraft will never "catch" the other if they are wing-and-wing. Perhaps less intuitive is the shape of the total "threat" region for all the different deviation angles looked at as a single description of the potential threat from any deviation (i.e. not only 30 deg).

The analysis results also indicate that for small deviation angles, a larger section of the ownship path may be at a relatively higher collision risk. Consider for example the pairs of solid and dashed magenta lines (aircraft speeds are 95 and 135 kts), which start to widen at low blunder angles, thus increasing the size of the threat region. Of course, this additional collision risk is mitigated by the longer time to reach a hazardous condition near the minimum separation in the encounter process (see Fig. 4). If the deviation in these cases is detected, the hazard may be avoided by corrective action on the part of either aircraft or both.

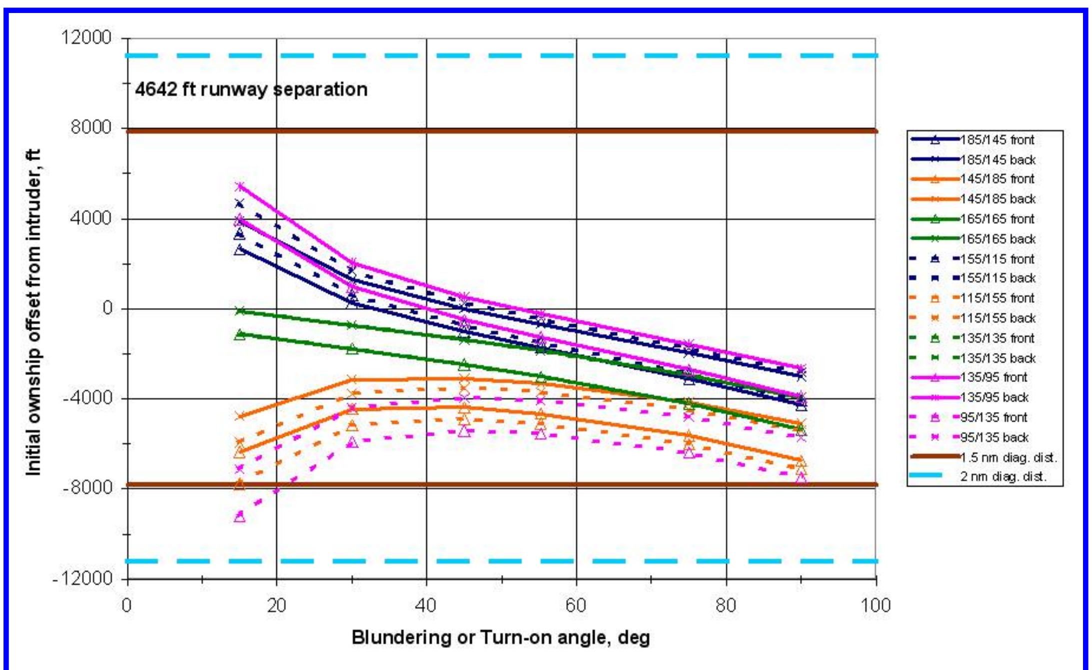

Figure 3. "Threat" regions as a function of intruder deviation angle and ownship along-track offset from intruder start point ("+" = "ahead" and "-" = "behind"), for various speed combinations (4642 ft runway separation)

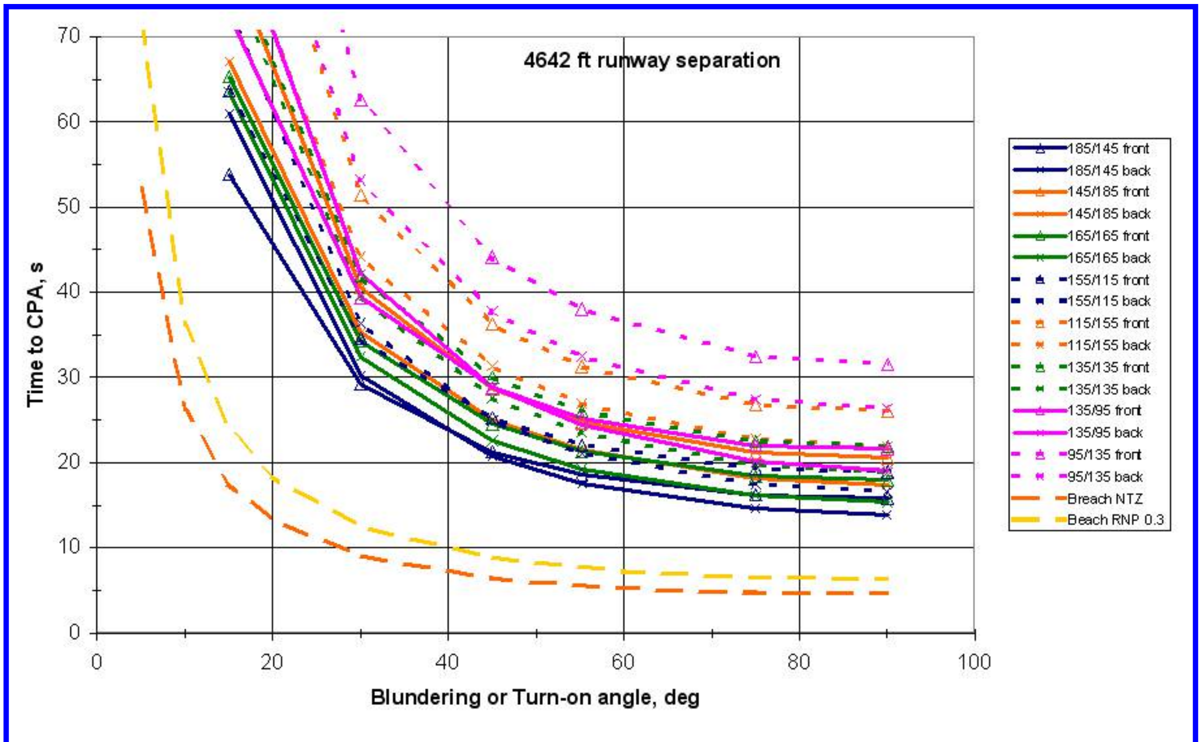

Figure 4. Time to CPA as a function of intruder deviation angle, for various speed combinations

Figure 4 shows the time to CPA corresponding to the data on the front and back of the initial along-track location for ownship (with respect to the intruder) shown in Fig. 3. Pairs of curves with the same color and line type in Figs. 3 and 4 have the same ground speed combinations. Of all the ground speed combinations considered, Fig. 4 shows that, at a given intruder deviation angle, the 185/145 velocity combination gives the smallest time to CPA.

Two additional curves are included in Fig. 4, one for the time when the deviating aircraft crosses into the Non Transgression Zone (NTZ) (dashed orange), a 2000 ft wide keep-out area centrally located between the two runways, and the other one for when the deviating aircraft crosses its own Required Navigation Performance (RNP) 0.3 boundary (dashed yellow). Both curves assume an ownship ground speed of 172 kts. These two curves are well below those from the collision model. This positive difference between these curves and the threat region indicates that there still be time for corrective action after the aircraft has breached the NTZ or RNP 0.3 boundary. This is especially true for small deviation angles by the intruder, where the time cushion is in excess of 30 sec.

This collision model has also been exercised for a 2,500 ft runway separation. Figure 5 shows results of this analysis, which can be compared directly to Fig. 3, since the only parameter that was changed is the runway separation. The threat regions in both Figs. 3 and 5 are very similar in shape and orientation, but in Fig. 5, these threat regions are narrower and more tightly clustered than in Fig. 3.

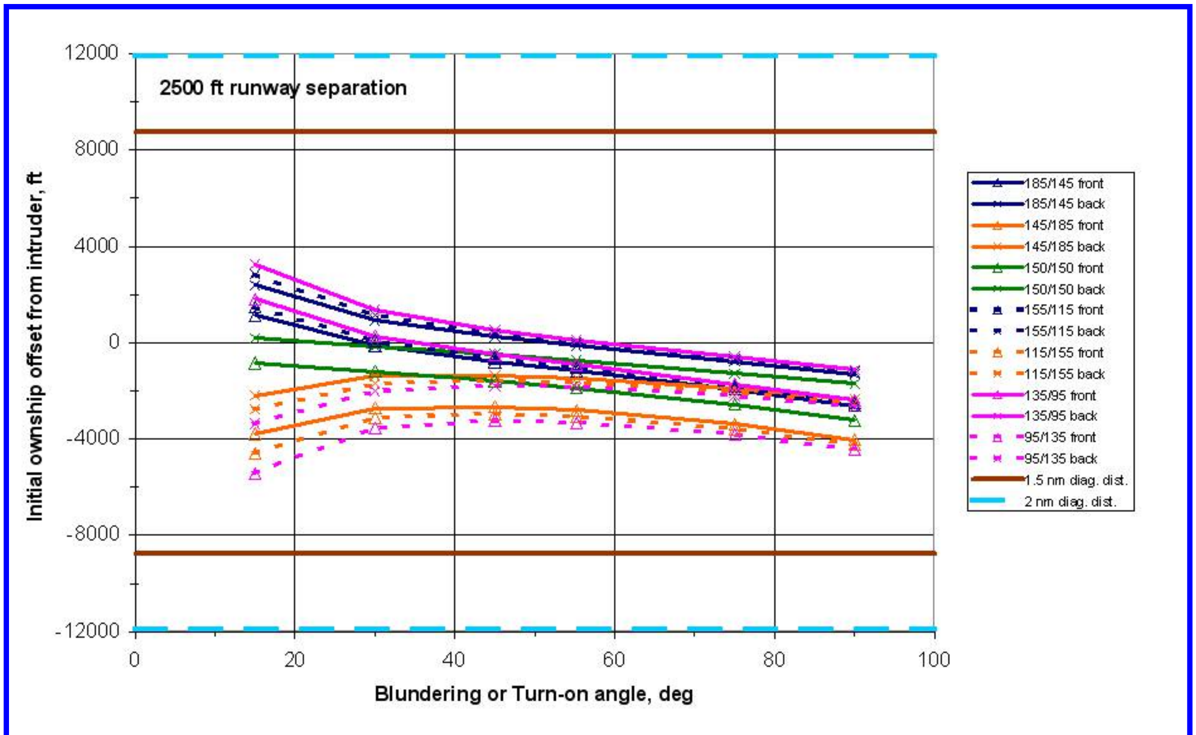

Figure 5. "Threat" regions as a function of intruder deviation angle and ownship along-track offset from intruder start point ("+" = "ahead" and "-" = "behind"), for various speed combinations (2500 ft runway separation)

For the speed combinations listed, and for intruder deviation angle between 15° and 90°, Fig. 3 shows that the window for initial along-track locations which may pose a threat are between 5,400 and -9,200 ft, while in Fig. 5 they are between 3,390 and -5,400 ft. In either case, if the ownship aircraft is placed outside the respective range of offsets, there is no potential collision regardless of the blundering angle (it is interesting that the range of available offsets for the ownship to be completely free of a potential NMAC is *greater* in the case of the 2500 ft runway separation than for the 4642 ft separation). This may be the basis for developing an ATC decision support tool to avoid placing aircraft inside the threatened region on the other parallel stream during a quasi-independent operation of the two parallel traffic streams (dependent operations require a specific spacing target, while a quasi-independent approach involves only the avoidance of a specified region). For the cases with intruder deviation angle less than 15°, the mitigation for collision could rely on the longer time for the potential hazardous situation to develop, as described earlier. These results indicate that an appropriate application of this model can be used as the basis for developing an ATC support tool for independent operations. One can imagine providing the controller with a simple, intuitive representation of developing "threat" regions, based on data shown in Figs. 3, 4 and 5, giving the controller the opportunity to adjust the aircraft spacing in order to head off a potential NMAC. This topic will be the subject of future work.

In both Figs. 3 and 5, horizontal lines are shown for the along-track distances corresponding to diagonal separations of 1.5 nmi (solid brown) and 2.0 nmi (dashed cyan) for the two cases where the ownship is initially ahead of or behind the intruder. These are standard separations in dependent parallel approach operations. This illustrates the inherent safety of dependent operations, since, except for a little overlap in Fig. 3 with the smaller diagonal offset of 1.5 nmi, the "threat" regions are completely inside the standard dependent diagonal offsets. This inherent safety is especially true for dependent operation with a 2 nmi diagonal distance.

Note the very important fact that, based on the scenario shown in Fig. 2b, in which the trajectories are straight line paths with known starting points, ground speeds, and deviation angle, it is straightforward to determine the time to, and hence the position of, the points on the two trajectories where the minimum separation occurs. The calculation can be done using basic calculus to determine the minimum of the distance between the two aircraft as a function of time. Of course, the scenario beginning and end points also become candidates for the points of minimum separation in case there is no zero derivative within the time interval under consideration. This can happen, for example, if the minimum occurs past the point where one or the other aircraft has already landed, or the trajectories are always diverging or always converging in the region of interest. The resulting closed-form formula for the time of closest approach is a function of aircraft ground speeds, intruder deviation angle, and initial offset of the ownship from the intruder, and this makes it very quick and easy to determine the sub-regions of the entire parameter space that can lead to an NMAC. No simulation is needed. Figures 3, 4, and 5 were produced by implementing this approach in an Excel spreadsheet, for example. The same situation exists for the TCAS alerting model of Section IV, namely, it is straightforward to compute the parameter of interest (so-called "range tau", to be described later) in closed form, in order to determine whether or not a TCAS alert will be issued during the course of a given scenario.

III. Collision Analysis Model Enhanced -- Curved Turn-On to Final

The extended collision risk analysis model, in which the intruder attempts to execute a curved turn-on to the runway centerline, is shown in Fig 6. Again, note that this is just an example scenario, for illustrative purposes only. Many other similar scenarios can be generated by variation of several parameters, as explained in the previous section.

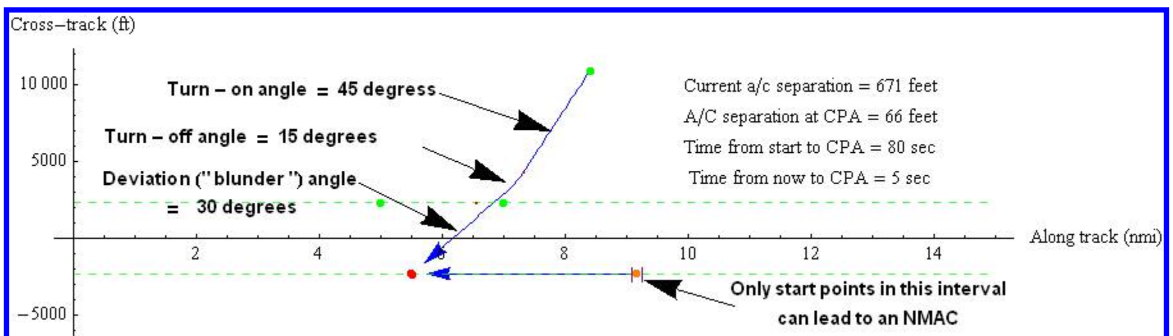

Figure 6. Collision risk analysis model with curved turn-on to final (example only)

Note that everything is the same in Fig. 6 as in Fig. 2b of the previous section, except for the intruder turn-on. Therefore, we limit the description to this aspect of Fig. 6. The large green dots (from right to left) on the right runway approach (top) denote the starting point, fly-by waypoint for the turn-on, and the FAF for the intruder aircraft. The two small red dots denote the *intended* beginning and end points for the intruder aircraft turn-on. Of course, in this particular scenario, the intruder failed to complete the turn, so it does not go through the turn end point, but deviates toward the other runway instead. The turn-on angle is 45 degrees, but the intruder only completes 15 degrees of this turn ("turn-off" angle), so the resulting deviation ("blunder") angle with respect to the runway centerline is 30 degrees. The ground speeds of both aircraft are 165 kts in this scenario.

The subspace of parameter combinations that lead to an NMAC are explored to determine the time from the start of the simulation to either the time of CPA or earliest NMAC occurrence, depending on the particular question being asked. It turns out that the set of parameter combinations for which the intruder comes close (i.e., within 500 feet) of the ownship, over the course of the simulation, is quite small. For example, in Fig. 6, consider the two vertical purple bars on the left runway (bottom) surrounding the ownship starting point (orange dot). It turns out that, if all other parameters are kept constant, *there cannot be an NMAC unless* the ownship starts within this "threat" interval, which is less than ¼ nmi wide (about 1500 feet). Of course, this interval for the ownship starting position will change in position and size as other model parameters are varied, but this limited interval length is typical, except for very low angles (< 15 degrees) between aircraft trajectories. Fortunately, this is compensated somewhat by the fact that the time to a conflict would be much greater.

Figure 7 shows some typical results from this model. The multi-colored surface represents the CPA distances between aircraft for *all combinations* of intruder turn-off angle (degrees) from the turn-on and the offset of the ownship start point from the intruder (ft). The horizontal plane at the 500 ft level at the bottom of the 3D-plot represents the minimum miss distance associated with an NMAC. The intersection between the two surfaces is the gray region in the center of the valley. This is the "threat" region, in that *only those parameter pairs in this region can lead to an NMAC* (given that the remaining parameters are kept constant).

In our terminology, the turn deviation angle (or "blunder" angle) = turn-on angle – turn-off angle. In this particular scenario, the turn-on angle is 30 degrees, so the intruder turn-off angle goes from 0 degrees to 30 degrees. At 0 degrees turn-off angle, the intruder simply misses the turn and blows straight through, resulting in a 30 degree deviation ("blunder"). At a 30 degree turn-off angle, the intruder aircraft completes the turn, merging perfectly onto the final course (no deviation).

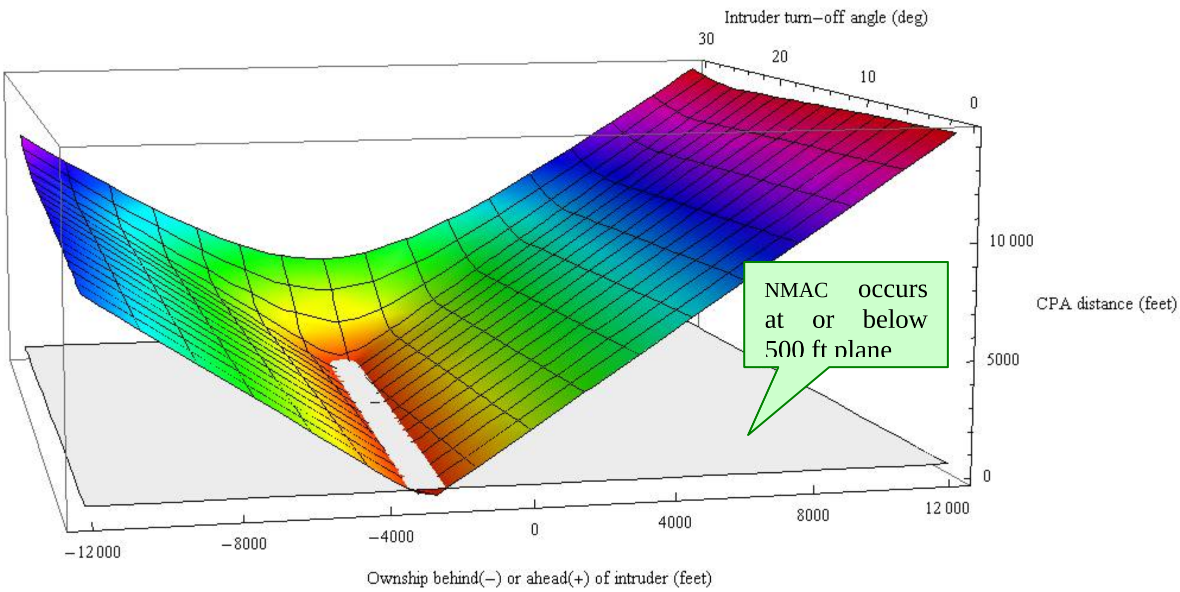

Figure 7. CPA distance as a function of intruder turn-off angle and offset of ownship start point from intruder. The gray region in the central "valley" contains all of the pairs of these two parameters which lead to an NMAC. Compares (roughly) to the region between the solid green lines in Figure 3. Runway sep =4642 ft, a/c speeds = 165 kts, intruder turn-on angle = 30 deg

In this particular example, the aircraft ground speeds are both set at 165 kts, and the runway separation is 4642 feet. Therefore, the gray "threat" region in Fig. 7 corresponds roughly to the threat region between the solid green lines in Fig. 3, at least between 0 and 30 degrees. The correspondence is not exact because the point where the intruder crosses the runway in the turn-on scenario will not be at exactly the same point of departure for the simpler scenario without a turn-on. However, it is clear that that the relative size and shape of the "threat" regions are similar.

Although the information provided in plots such as Fig. 7 is useful, *time to CPA* is also relevant to designing safety into the operation, because it gives insight into how to produce designs that have sufficient recovery times for the most likely non-normal scenarios . Therefore, in Fig 8a below we show a plot similar to Fig. 7, but the surface represents *time to CPA* rather than *CPA distance*. In other words, a point on this surface represents the time left to take evasive action before the two aircraft reach their CPA (if necessary). The aircraft ground speeds (165 kts) , turn-on angle (30 deg), and runway separation are the same as in Fig. 7.

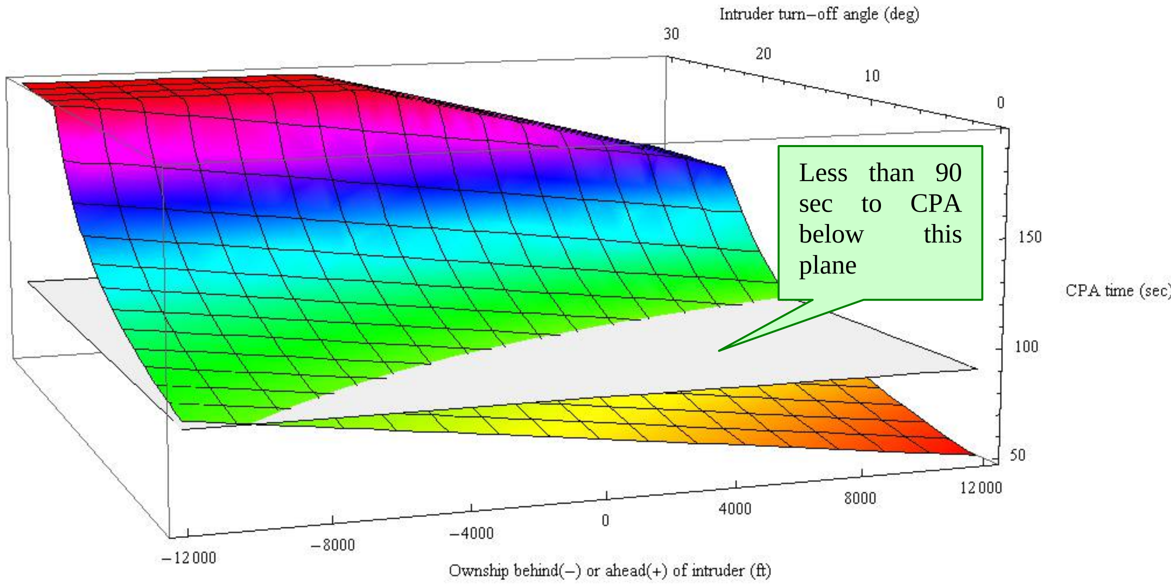

Figure 8a. Time to CPA as a function of intruder turn-off angle and offset of ownship start point from intruder. The gray plane denotes the 90 sec threshold. Thus, any point on the surface BELOW this plane indicates a combination of turn-off angle and ownship offset that leaves less than 90 sec for evasive action. Runway sep =4642 ft, a/c speeds = 165 kts, intruder turn-on angle = 30 deg.

However, what is most operationally relevant is the intersection of these two concepts, where both time to CPA is short, and CPA itself is small enough to be of concern: In Fig. 8b below, we show a plot indicating the region in the (turn-off angle, ownship offset)-parameter space for which *the time remaining to an NMAC is less than 90 seconds.*

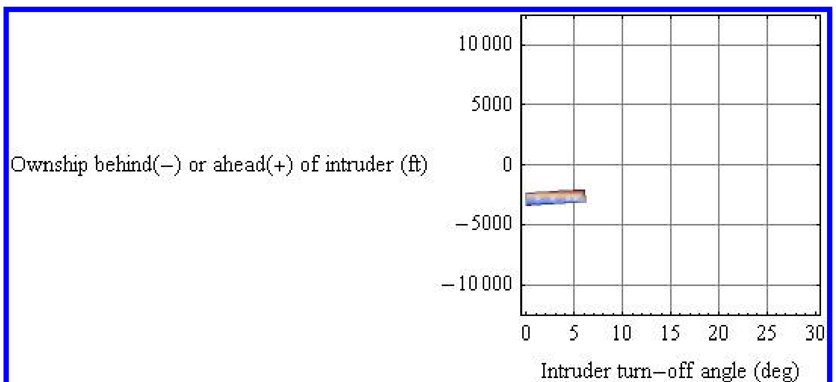

Figure 8b. Colored region indicates the only combinations of the two parameters which will lead to an NMAC in less than 90 sec. Other scenario parameters are the same as in Figs. 7 and 8a: 165 kt ground speeds, 30 deg turn-on angle, and 4642 ft runway separation.

IV. TCAS Alerting Model

Most modern aircraft are equipped with a TCAS system for collision avoidance. While TCAS provides a highly valuable service to aviation, it also introduces additional design and operational considerations, especially for operations that involve aircraft from different traffic streams operating in close proximity. TCAS could generate a large number of “nuisance” alerts if its alerting thresholds are not carefully avoided by the operational and procedure design. On the other hand, it is important that the expected interaction between traffic stemming from the new operation does not somehow suppress or delay TCAS alerts when they should indeed provide warning of imminent collision risk.

There are two types of TCAS alerts: The first is a Traffic Advisory (TA), which simply informs the aircrew that there is other traffic in the area that could potentially be a threat. The second, and more serious alert, is a Resolution Advisory (RA), which requires a response and potentially evasive maneuvers on the part of both aircraft involved in a sufficiently close encounter. A TA or RA will be issued when certain parameters are all in a defined range. These parameters are sensitivity level (SL), range tau, vertical tau , distance modification (DMOD), and altitude threshold.

The sensitivity level (SL) is a number which indicates a certain altitude range (in feet). Its purpose is to increase "sensitivity" as a function of altitude, that is, to lower the TA and RA tau thresholds as altitude decreases. The DMOD thresholds, measured in nmi, are designed to trigger an appropriate TCAS alert in those cases where the aircraft closing rate is zero or nearly zero, but the aircraft are still too close together for comfort, since any sudden deviation by either of them would leave insufficient time to recover. Finally, the altitude threshold is another check on whether an alert should be issued. Only if the aircraft are sufficiently close in altitude will the alert be generated. The altitude threshold is effectively a filter, determining the vertical range of aircraft considered a threat.

Table 1 below, based on the current TCAS system (TCAS II Version 7[7]), shows the conditions under which a TA or RA will be issued as a function of these parameters. First two tau values, with units of seconds, are calculated: a range tau and a vertical tau. The range tau, is simply the current slant range between the two aircraft divided by the closing rate (negative of the derivative of slant range as a function of time). In other words, range tau is an estimate of the time remaining (from the time when tau is calculated) until the two aircraft reach their closest points of approach, *assuming they both were to continue on a path from their current position at their current speeds in a direction indicated by their current velocity vectors*. (If the calculated tau is negative or infinity, obviously there is currently no danger of collision.) The vertical tau is correspondingly computed by dividing altitude difference by the negative of the rate of change of altitude with respect to time. Then these computed values are compared to the threshold tau values in Table 1, in order to decide if a TA or RA should be issued. BOTH computed values must be LESS than the relevant threshold in order for a TA or RA to be generated. An alert will NOT be generated if either one (or both) is above the relevant threshold. The relevant threshold is based on the values of the other parameters, namely SL, DMOD, and altitude threshold.

Table 1 Sensitivity Level Definition and Alarm Threshold in TCAS II Version 7

Own Altitude (feet)	SL	Tau (Seconds)		DMOD (nmi)		Altitude Threshold (feet)	
		TA	RA	TA	RA	TA	RA (ALIM)
< 1000	2	20	N/A	0.30	N/A	850	N/A
1000 - 2350	3	25	15	0.33	0.20	850	300
2350 – 5000	4	30	20	0.48	0.35	850	300
5000 – 10000	5	40	25	0.75	0.55	850	350
10000 – 20000	6	45	30	1.00	0.80	850	400
20000 – 42000	7	48	35	1.30	1.10	850	600
> 42000	7	48	35	1.30	1.10	1200	700

In this paper, we assume that the two aircraft will be flying parallel approaches with co-altitude vertical guidance during the encounter scenarios (Figs. 2a, 2b, and 6). Therefore we assume that both aircraft are at the same altitude, or at least that the aircraft are sufficiently close in altitude that vertical tau and altitude threshold conditions are met. Hence, the TCAS analysis that follows is based primarily on range tau computations for various combinations of the scenario parameters, just as the collision analysis in the previous section calculated "threat" regions for possible NMACs, based on various combinations of scenario parameters. Even though the particular analysis in this paper is for the case of turn-on to final in parallel runway operation, the tau computations that are performed and the visualizations shown are extensible to more general TCAS situations.

A. Independent Operation for Parallel Runways

In independent operations, the relative longitudinal position or offset of the aircraft on the two runways is not prescribed, hence it is of interest to determine range of longitudinal offsets of the ownship from the intruder that lead to TCAS alerts at a particular SL.

For example, if the runway separation is 4624 ft and the aircraft are within the range of speed covered in Figs. 3, 4 and 5, the range tau is at least 52 s for a 15° turn-on angle. Therefore neither the TA nor RA alert will be triggered regardless of the relative longitudinal location between aircraft nor the SL/altitude.

In Figs. 9a and 9b below, we show a family of relative range vs. closing rate histories (blue curves) as compared to selected relevant range tau thresholds (slanted straight lines emanating from the origin). The range tau thresholds are labeled according to the terminology in Table 1. For example, the top line is labeled “TA SL5”, which corresponds to the entry of Table 1 in the range tau TA column and the SL 5 row. In other words, this is a constant 40 sec line in the relative range/closing rate plane. The other range tau thresholds are similarly labeled. In order for a TCAS alert to be issued at some time during the scenario time history, a blue curve must dip down below at least one of the range tau thresholds. If a relative range/closing rate time history stays completely above all range tau thresholds, no alert will ever be issued (based on range tau alone).

In both Figs. 9a and 9b, the ownship initial longitudinal offset from the intruder varies from -10,000 ft to 10,000 ft in increments of 1000 ft, and the turn-on angle to the runway centerline is 15 deg. In Fig. 9a, the “intruder” completes the turn successfully, while in Fig. 9b, the intruder fails to make the turn at all and blows straight through. In the normal scenario of Fig. 9a, it is clear that an alert will not be generated under any circumstances, since the relative range/closing rate history stays well above all range tau thresholds throughout all scenarios. The red dots indicate those points in time at which the intruder crosses or first touches its own runway centerline.

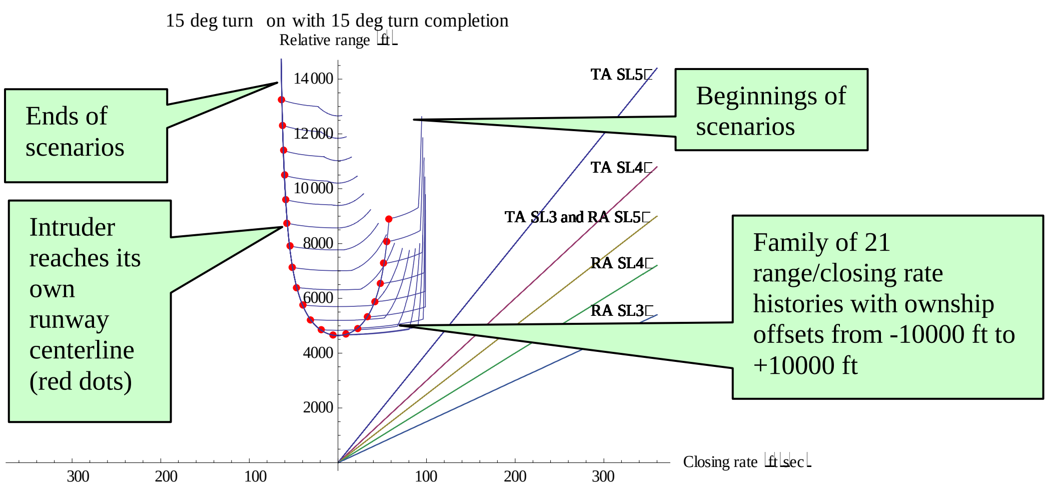

Figure 9a. The relative range/closing rate time histories (shown in blue) stay well above all of the range tau thresholds, so no alert will be generated under any circumstances (based on range tau alone). Turn-on angle = 15 deg, turn -off angle = 15 deg, and ownship offset varies from -10,000 ft to 10,000 ft in 1000 ft increments. Ownship ground speed = 145 kts and intruder ground speed = 185 kts.

However, in Fig. 9b, there are some range tau threshold crossings, although only for some of the offsets. Note that there would be no TCAS alerts (based on range tau alone) before crossing the runway centerline. Also note that only two of the scenarios considered will generate an RA if the turn to final is not completed. This small number of conditions that would cause a TCAS RA makes sense in the light of the small threat regions shown in the collision assessments in sections II and III.

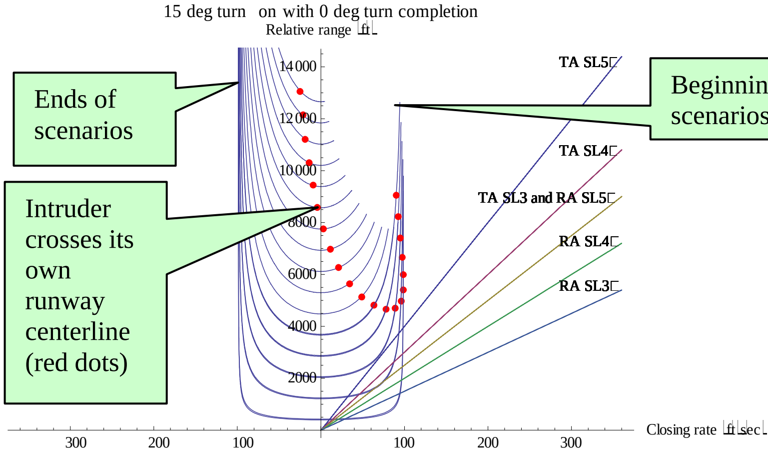

Figure 9b. Some range/closing rate time histories (shown in blue) cross below some range tau thresholds, so alerts could be generated in some cases. Turn-on angle = 15 deg, turn-off angle = 0 deg, and ownship offset varies from -10,000 ft to 10,000 ft in 1000 ft increments. Ownship ground speed = 145 kts and intruder ground speed = 185 kts.

When the turn-on angle is increased to 30°, then the range tau can become as low as 29 sec, which means a TA may be triggered for certain speed combinations and relative aircraft locations when the altitude is above 2,350 ft and an RA may be triggered above 10,000 ft. Families of relative range/closing rate time histories with a 30 deg turn-on are shown in Figs 10a and 10b below.

In Fig. 10a, note that the “trespass” into the topmost TA zone is very slight. This means that not only is there no danger of an RA being issued, but that even the TA could be avoided by judicious choices of the relevant procedure parameters.

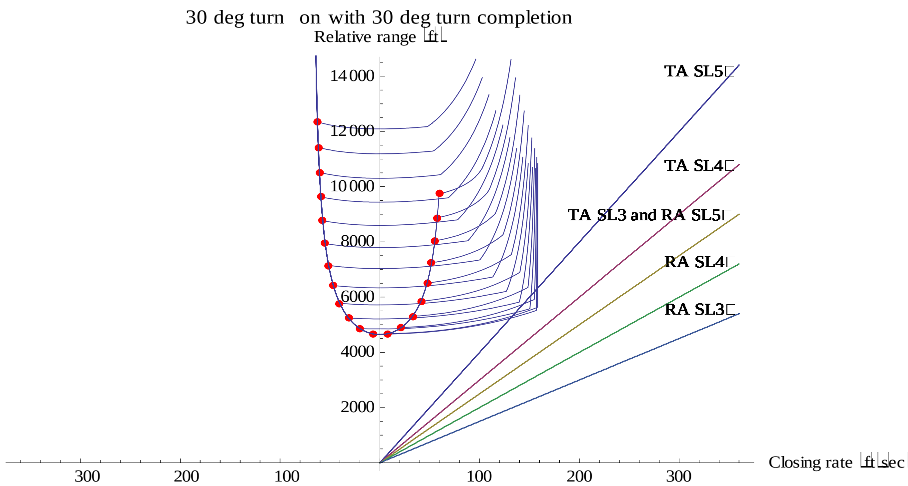

Figure 10a. Some relative range/closing rate time histories cross below some range tau thresholds, so alerts could be generated in some cases. Turn-on angle = 30 deg, turn-off angle = 30 deg, and ownship offset varies from -10,000 ft to 10,000 ft in 1000 ft increments. Ownship ground speed = 145 kts and intruder ground speed = 185 kts.

Note that in the case of successful turn completion (Fig. 10a), all of the potential alerts would occur before the intruder reaches its own runway centerline, whereas in the case where the intruder makes no attempt at the turn to final and blows through the centerline (Fig. 10b), there are a few cases where a TA alert would be issued after the intruder crosses its runway centerline.

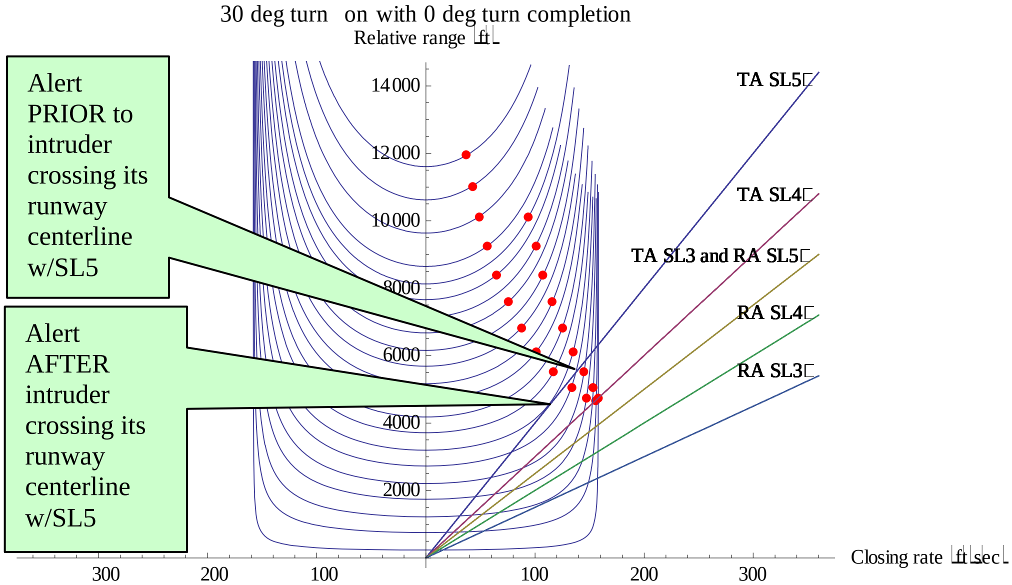

Figure 10b. Several relative range/closing rate time histories cross below some range tau thresholds, so alerts could be generated in several cases. Turn-on angle = 30 deg, turn-off angle = 0 deg, and ownship offset varies from -10,000 ft to 10,000 ft in 1000 ft increments. Ownship ground speed = 145 kts and intruder ground speed = 185 kts.

If the turn-on angle is increased to 45°, the range tau will then become as low as 21 s which means a TA may be triggered when the altitude is above 1,000 ft, and an RA may be triggered above 5,000 ft.

Figs. 11a and 11b again illustrate the differences between completing the turn-on successfully (as in Figs. 9a and 10a) or failing to turn at all (as in Figs. 9b and 10b), except in this case the turn-on angle is 45 degrees.

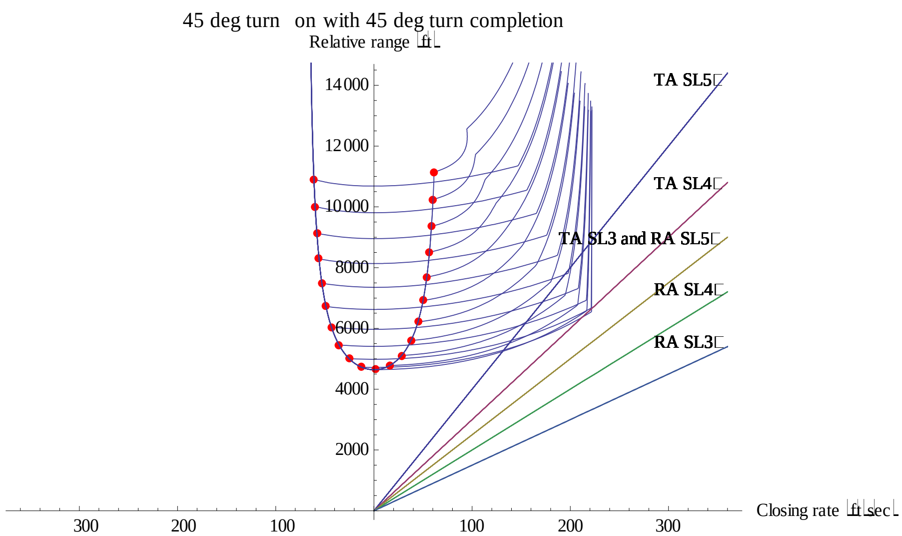

Figure 11a. Alerts could be generated in cases where relative range/closing rate time histories cross below range tau thresholds. Turn-on angle = 45 deg, turn-off angle = 45 deg, and ownship offset varies from -10,000 ft to 10,000 ft in 1000 ft increments. Ownship ground speed = 145 kts and intruder ground speed = 185 kt

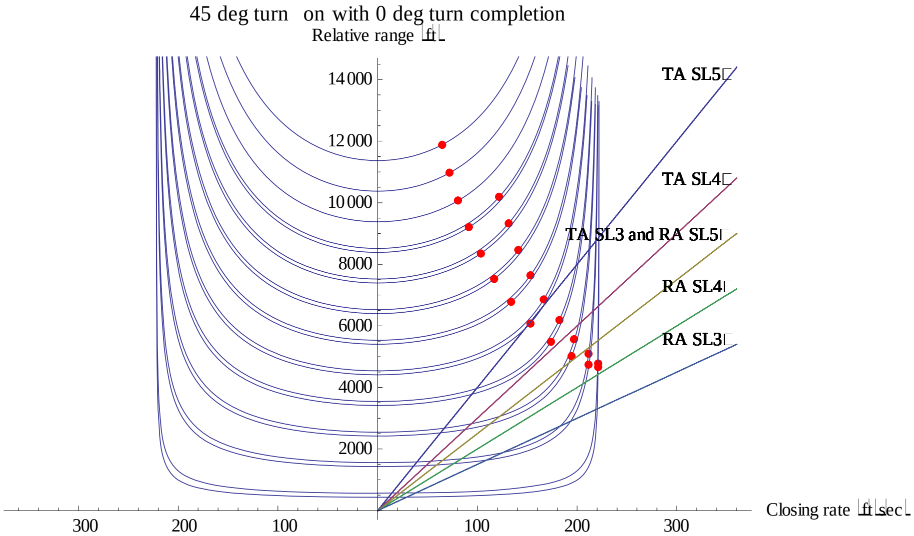

Figure 11b. Alerts could be generated in several cases where relative range/closing rate time histories cross below range tau thresholds. Turn-on angle = 45 deg, turn-off angle = 0 deg, ownship offset varies -10,000 ft/10,000 ft in 1000 ft increments. Ownship ground speed = 145 kts and intruder ground speed = 185 kts

These results indicate that, based on a runway separation of 4642 ft and ground speeds of 145 kts and 185 kts for the ownship and the intruder, respectively, a turn-on angle of 15° may ensure that neither a TA nor an RA will be triggered. However, for larger turn-on angles, the potential of a TA or RA being triggered needs to be addressed during procedure design. If the runway separation is reduced to 3,400 ft, results for a 15° turn-on angle show that a TA may be triggered above 5,000 ft and RA may not be triggered at all, and at larger turn-on angles, both a TA and an RA may be triggered above certain altitudes. Similarly, results for 2,500 ft runway separation show that with a 15° turn-on angle, a TA may be triggered at above 2,350 ft and an RA may be triggered at above 10,000 ft. Of course, it will be necessary to consider a range of relative speeds in any final designs. It seems that relative approach speeds and the aforementioned geometric parameters can be used as operational constraints to minimize unwanted alerting.

B. Dependent Operation for Parallel Runways

For the case of turn-on to final during dependent operations, potential TCAS alerts need to be considered for the aircraft performing the turn-on and its closing with the two nearest aircraft on the other parallel runway. Note, that in the dependent case, by definition, the slant range between the aircraft on the two different parallel runways is constant (or nearly so).

The same ranges of speed, turn on angle and runway separation as shown in Figs. 3, 4, and 5 were used for the dependent case TCAS analysis, but with a fixed 1.5 nmi diagonal separation. Results show that for runways separated by 4,642 ft, neither a TA nor an RA will be triggered for 15° or 30° turn-on angle. At a 45° turn-on angle, a TA may be triggered above 10,000 ft but an RA will not be triggered. Larger turn-on angles will lead to a potential TA at lower altitudes and even an RA may be triggered. If the runway separation is reduced to 2,500 ft with the same 1.5 nmi diagonal separation, the longitudinal distance between two aircraft on different parallel runways will be slightly increased, thus resulting in no TA or RA alerts up to a 45° turn-on angle.

In Fig. 12a and 12b, families of relative range/closing rate curves are shown for which the ownship offset from the intruder is fixed at 1.5 nmi and -1.5 nmi, respectively, but the turn-on angles vary from 5 deg to 45 deg (in 5 deg increments), plotted with the tau thresholds as before. Turn-off angle = turn-on angle in all cases. In Fig. 12a, the ownship is 1.5 nmi *ahead of* the intruder and in Fig. 12b, it is 1.5 nmi *behind* the intruder at the merge point (when the intruder is supposed to merge onto its own runway centerline). Note there is no chance of a TCAS alert (based on range tau), assuming both aircraft have 165 kt ground speeds. In the trailing case (Fig. 12b), the time histories come a little bit closer (but do not cross) the top range tau alert boundary. In all cases, the turn-on is assumed to be completed successfully.

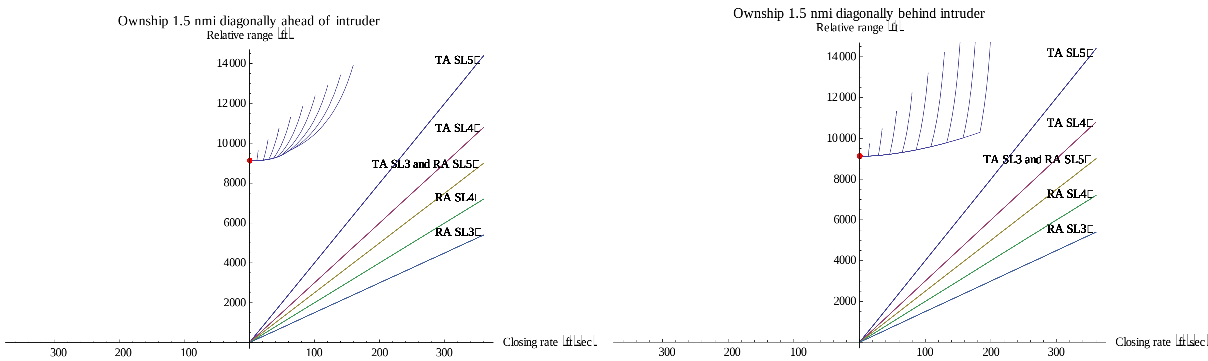

Figure 12a and 12b. On the left, the ownship is 1.5 nmi ahead of the intruder, and on the right, ownship is 1.5 nmi behind the intruder. In both cases, the turn-on angles vary from 5 deg to 45 deg in increments of 5 deg. Turn-off angle = turn-on angle in all cases. Aircraft ground speeds are both 165 kts.

In general, this model provides the potential constraints on operating altitude, aircraft speed, turn-on angle, and lateral separation based on TCAS alerting consideration.

V. Conclusions

When considering the safety of a new procedure, both the normal behavior of the system as well as non-normal behavior must be considered. As addressed in many Safety Management Systems, these considerations must account for both the frequency and severity of non-normal and rare-normal events. However, when all is said and done, if the normal and non-normal behavior of a safety-critical system cannot be assured to a degree of acceptable risk, additional mitigations, of both hazard causes and outcomes, must come into play. Moreover, one might argue that additional, independent checks on safety may afford resiliency to unknowns in an unproven system in which not all the non-normal events nor their frequency in practice are well understood. RNP AR procedures have proven themselves very reliable, and the operations that make use of them against real, 100% probability terrain hazards have been shown to be safe. Similarly, operations reliant on parallel ILS guidance establishment have proven to be safe. However, prudence suggests that as we introduce new operations which rely heavily on RNP containment for separation, particularly in a mixed equipage, surveilled environment, that we explore the next layer of safety beyond separation: collision avoidance. In addition, since TCAS is mandated equipment, the interaction between TCAS and any new operation, particularly one which purposely pulls aircraft close to one another, must be addressed.

The modeling techniques described herein have been shown to be an effective means of analysis for exploring a wide range of potential outcomes from the principal operational ‘hazard’ during parallel approaches: a traffic transgression which impinges on another aircraft’s path. These methods can explore the potential for one aircraft to deviate sufficiently from a planned approach to threaten another; where and when the threat is, and even where traffic should be to minimize the hazard of another’s potential transgression. These same techniques are shown to be useful in exploring the interaction between parallel approach designs and TCAS alerts. Using these techniques, the operations can be designed such that nuisance alerts are minimized, while the TCAS system is left unchanged. These analyses can also show the effectivity of dependent spacing, and how maneuvering aircraft on dependent tracks cannot physically cause an NMAC with properly-spaced traffic, based on a single “blunder” maneuver alone.

By design, RNP AR procedures, equipment requirements, training etc will mitigate many of the *causes* of a potential traffic transgression hazard. This in itself is a boon to safety, as some studies indicate that most traffic hazards that exist for parallel ILS approaches emanate from an earlier operational error which later precipitates a “blunder”. RNP procedures, and their comprehensive flight guidance path including the turn-on to the final course, provide an excellent means of separation. Because of the nature of the high-density, mixed-equipage, radar-controlled environment where these parallel operations are likely to operate, we must go beyond separation to consider collision avoidance. The models described herein provide some tools to do so.

Though the models described here are in the same horizontal plane, use straight intercept vs. curved courses, and assume constant ground speeds, the technical basis behind these models makes them extensible to other trajectory-based control scenarios. The method could easily be extended to manage three dimensional trajectories and varying speed.

Both the NextGen and SESAR visions are based on trajectory control. It follows that both will need to develop trajectory-based separation standards to other trajectories, vectored traffic, and even designated airspace regions. While there are a number of ways to explore the necessary nominal requirements, time-based methods for collision risk management and the models described herein can be used to develop a richer, deeper safety declaration. These methods, which use aircraft state extrapolated to a host of plausible path transgression scenarios (rather than one, e.g. a 30° "blunder"), can help developers explore robust design criteria and system requirements for a wide range of trajectory-based control.

VI. Acknowledgements

The authors would like to thank Boeing Commercial Airplane and Boeing Research and Technology for their support for these activities.

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