NEAR-TERM SOLUTION FOR EFFICIENT MERGING OF AIRCRAFT ON UNCOORDINATED TERMINAL RNAV ROUTES

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Abstract

It is anticipated that controllers will continue to vector traffic for spacing in the near-term where there are Required Navigation Performance (RNP) Area Navigation (RNAV) routes that merge prior to the final approach or on the final approach. Under moderate to heavy demand, this will negate many of the efficiency, throughput, and predictability benefits of keeping aircraft on the RNP RNAV routes.

Given the current level of metering and aircraft equipage, existing decision support automation and avionics capabilities can be used to keep aircraft on the routes and maintain benefits. In an earlier paper, we presented a suite of tools and concepts that address the merging and spacing problems arising from structured RNAV and RNP routes in the terminal environment. This suite of tools and concepts is referred to as Spacing of Performance-based Arrivals on Converging Routes (SPACR). The initial set of tools and concepts addressed the near-term merging and spacing problem, relying on existing cockpit and ground automation capabilities. In this paper, the tools and concepts are extended to the mid-term, requiring modest modifications of existing capabilities. SPACR includes applications of cockpit capabilities such as Flight Management System (FMS) Offsets and Required Time of Arrival (RTA) and ground automation functionalities such as the embedded ghosting function in the Automated Radar Terminal System (ARTS), Standard Terminal Automation Replacement System (STARS), and new STARS Graphical User Interface (GUI) functionalities. The previous paper presented an operational concept along with analytic and human-in-the-loop experiments for SPACR based upon the Converging Runway Display Aid (CRDA), a ground-based decision support tool, and the Lateral Offset capability in the cockpit.

In this paper, we extend SPACR to include a potential use of RTA and present an operational concept using it in conjunction with Lateral Offsets and CRDA. We present analytic results related to ground computation of RTA and matching that with the airborne computation. Results of human-in-the-loop experiments related to using SPACR to manage the final merge using only CRDA are reported. The paper concludes with a discussion of issues.

Introduction

No near-term solutions have been proposed that take advantage of existing ground and cockpit automation to address uncoordinated terminal merges except the RNAV route design tried by German Air Traffic Control (DFS) at Frankfurt. This design included charting a series of waypoints for turning the aircraft from downwind onto final [1]. The concept did not provide any controller tools to decide which waypoint should be selected nor any tools for monitoring aircraft conformance. This paper integrates existing technology and outlines a path for transitioning to future technologies and capabilities within current economic constraints, equipage and operations.

Background

With the introduction of more RNAV arrival and departure procedures, there is a potential benefit of reducing the need to vector aircraft and reducing the required air/ground communication. Maintaining and increasing these benefits will require controllers to keep aircraft on the planned routes [2].

Current terminal operations are already changing as more terminal RNAV routes are defined that aircraft are expected to fly. Previously, aircraft arriving on a Standard Terminal Arrival Route (STAR) were given vectors to guide them to the runway when the aircraft transitions from the STAR and enters the terminal area. There are, however, efforts underway to extend these STARs as overlays of the current traffic patterns. The Federal Aviation Administration's (FAA) Operational Evolution Plan (OEP) [3] indicates that there are many RNP STAR procedures scheduled for implementation at the top 35 airports within the next three years. Europe mandated basic (B-RNAV) in 1998 and has conducted benefits analyses and operational concepts for moving towards precision (P-RNAV) non-mandated terminal applications in 2005 [4].

As these terminal routes are implemented in the near-term and with a limited number of control techniques available to the terminal area controller in such a route-oriented environment, obtaining the full benefit of systems or terminal networks of these routes is a concern. The FAA's *Roadmap for Performance-Based Navigation* [5] indicates that the FAA will need to implement an appropriate merging and spacing decision support system which will be essential to achieving full benefits of RNAV and RNP procedures in a TRACON environment. Additionally, in the "Concept for Implementing a Performance-Based National Airspace System," which describes a mid-term set of operational capabilities in a performance-based NAS [6], the authors point out that to achieve desired capacity and efficiency benefits, merging and spacing capabilities will be needed. In Europe, it is also recognized that obtaining full benefits of terminal RNP RNAV will require additional controller tools [7].

In a previous paper [8] the authors introduced a suite of tools and concepts called SPACR. In that paper the near-term concept of using Lateral Offset in conjunction with the Converging Route Display Aid (CRDA) [9] was developed. This version of SPACR was near-term since the capabilities of the tools being utilized are already available in the cockpit and in the National Airspace System (NAS). This paper further develops this concept and adds the integration of the RTA function. The RTA function can be introduced into the near-to-mid-term time frame provided that a population of adequately equipped aircraft exists and minor algorithmic enhancements are made to CRDA.

Concept of Operations

Terminal operations around the world are now in the midst of change due to the introduction of RNAV and RNP arrival routes. With these routes and aircraft equipped to fly them, aircraft predictability improves significantly as long as aircraft can remain on the procedure. In moderate-to-high-demand terminal areas, it is recognized that in the near-term operational environment that does not benefit from time-based metering provided by tools such as Traffic Management Advisor (TMA) [10], controllers and pilots will need tools to manage the currently uncoordinated terminal merges. SPACR addresses this problem with a solution that utilizes existing air (Lateral Offset) and ground capabilities (CRDA). CRDA is used by the ground to identify a spacing problem soon enough to either resolve it with speed control or to use a Lateral Offset, which retains predictability and takes advantage of airborne automation. CRDA used in conjunction with the Lateral Offset allows the ground to easily monitor evolving relative spacing situation.

For a discussion of SPACR and how CRDA works and the parameters associated with the application, see [8] and references cited there. CRDA is currently implemented in the ARTS systems (IIA, IIIA and IIIE) as well as STARS in the United States. For the STARS implementation, there is Pre-Planned Product Improvement Initiative (P^3I) in place for enhancing CRDA. CRDA can be used with the Lateral Offset to manage merges prior to the merge on final provided there is adequate airspace available for executing the Lateral Offset. Given that the current environment supports vectoring aircraft, adequate airspace is not a significant issue considering that the magnitude of most Lateral Offsets would be in the range of 3-6 nm to the left or right of the centerline.[1]

The RTA function can be introduced into the operation as a method for managing the speed control needed to obtain proper spacing at the merge for a pair of aircraft identified as having a spacing problem by CRDA. With aircraft assigned to fly routes with altitude and speed constraints, the ground can predict soon enough whether a merge will work out with speed management or will need a Lateral Offset to achieve proper spacing. Additional information in the aircraft data block of the ghost will indicate either an RTA or a Lateral

[1] In the en route environment, the Lateral Offset can be used as a tool to manage congestion caused by the bunching of fast aircraft behind slow aircraft [11]. In this instance, a significant amount of airspace is required to accommodate aircraft passing with typical en route and transition speed differentials.

Offset for the target aircraft which the controller issues via voice for the pilot to meet. The workload for the pilot to respond is minimal for Lateral Offset [12]. Discussions with pilots and experimentation with emulations of actual RTA functionality indicates the same is true for RTA. The ground automation does not have to predict exactly when the aircraft should execute a speed change; this is taken care of by the cockpit automation. The controller can use CRDA to monitor the RTA execution. The pilot enters the RTA and the airborne automation manages the speed of the aircraft subject to procedure altitude and speed constraints to get the aircraft to the merge point at the desired time. The RTA accuracy of current systems that can apply an RTA in the terminal area is within seconds for shorter flight segment.[2]

The ground must be able to predict accurately enough what range of RTAs each aircraft can execute. An open question is whether the controller will be able to estimate the RTA accurately enough using SPACR with ghosting[3] alone or whether an RTA needs to be computed and provided to the controller. In the analysis section, we discuss what kind of ground algorithms will be required to predict accurately enough the flight time of the aircraft over these segments in the terminal.

SPACR will be able to improve the merge on final in a similar manner as the pre-merges. Two streams will be coordinated by SPACR, such as the downstream merge with a straight-in-stream. Aircraft from the straight-in-stream will be ghosted onto the downstream traffic. This will allow the controller to mitigate the merge through extension of the downwind in the near-term. Current CRDA can support this type of application. With the introduction of Radius-to-Fix (RF) legs for RNP procedures, modification of the projection algorithm used for projecting the ghost to take a path closer to the actual flight path (circular arcs), will improve the spacing information provided the controller and reduce the size of protection buffers. As SPACR migrates to a mid-term concept, the ground algorithms can be augmented to provide an estimate of the RTA required to merge the streams. Finally, the algorithm could be augmented to compute an RTA based upon proper wake vortex separation at the runway and allow for discrete path extension of the downwind to achieve proper spacing.

SPACR attempts to solve the terminal arrival spacing problem by solving each merge on a pair-wise basis. Early merges in the terminal area are coordinated or coupled with downstream merges, such as the merge on final, through a spacing buffer. The role of the buffer is to prevent the streams from being so closely spaced that there will not be any room for additional aircraft to merge into the coordinated stream without having to manipulate each aircraft extensively or by resorting to extended downwinds to create adequate spacing. SPACR differs from other concepts that solve the terminal merge in the following ways. The Final Approach Spacing Tool (FAST), passive version, focused on assigning a sequence to perform runway balancing. FAST was not coupled to the en route metering tool Traffic Management Advisory (TMA) when computing its schedule. Active FAST (the version that would provide active speed and heading advisories to controllers) did not assume that aircraft would still be flying coded procedures much further into the terminal environment nor did it take advantage of the RNAV Lateral Offset capability or the RTA functionality. In the near-term operational environment, SPACR does not provide active heading or speed advisories to controllers; in the mid-term, SPACR provides an indication of whether a merge could be solved using RTA versus Lateral Offset. SPACR does not attempt to solve the entire terminal merging problem. Rather, the terminal merging is solved in a more tactical manner taking advantage of RNAV routes and aircraft automation.

Future Extensions to the Concept

In a previous paper [13], the authors discussed a far-term concept that took advantage of terminal routes to improve planning and predictability called

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[2] Flight trials were conducted by Smiths and Scandinavian Airlines for B737 NG aircraft. The flight trials found that a flight time accuracy of 21 seconds could be achieved from takeoff to the landing runway. For more details, see “Flight Trials: “Runway-to-Runway” Required Time of Arrival Evaluations for Time-Based ATM Environment” by Keith D. Wichman, Goran Carlsson, and Lars Lindberg presented at the 20th DASC Conference.

[3] In the CRDA automation tool the position of the aircraft is projected to another location on the controller’s display. That projected position is referred to as a “ghost”.

Terminal Routing Using Speed Control Techniques (TRUST). This concept introduced ground automation that was able to compute a landing schedule for all aircraft in the terminal area based upon conflict free routes. The ground automation would monitor the schedule of aircraft and maintain the schedule of the arriving aircraft using speed control. The ground automation would compute the needed speed adjustment for each aircraft and issue a speed advisory to the controller. The concept assumed a time-based metering operational environment (if time-based metering did not exist, the concept provided its own metering function). The TRUST concept did include a feedback loop between the terminal metering function and the en route metering. The terminal metering function would attempt to pass along any needed delays in excess of what could be absorbed with speed control, back to the en route. The feasibility of this depends upon the accuracy of the flight planning information and the adherence of aircraft to executing the plan. In cases where aircraft delay could not be taken in the en route and it exceeds the amount available through speed control, limited path extension was (through coded procedures) included.

SPACR builds upon the current airspace design that is underway in the U.S. RNAV STAR extensions that are based upon overlays of current vectored traffic patterns. Merging of different en route streams occurs regularly within 60 nm of the runway inside the terminal area. SPACR provides a mechanism for maintaining benefits of RNP RNAV routes incrementally. Through enhancements to CRDA, SPACR should be able to provide improved spacing and monitoring for all merges in the terminal. Time-based metering will further improve the operation of SPACR. SPACR may be able to optimize the full terminal merging problem by progressing to more sophisticated ground automation that coordinates more precisely the loosely coupled schedules of the pair-wise merges with a global schedule. SPACR would also improve with the introduction of Automatic Dependent Surveillance-Broadcast (ADS-B) mode with the ground algorithms also implemented in the cockpit, providing the pilot with the same relevant situational awareness as the controller. The introduction of a data link (e.g., Controller Pilot Data Link Communication [CPDLC], ADS-B, Aircraft Communications Addressing and Reporting System [ACARS]) would also improve the information available to the ground system of the aircraft capabilities.

SPACR delineates a transition strategy from the near-term to more automated solutions. It lends itself well to taking advantage of future technology and moving towards a more distributed air-ground decision support system.

Analytic Results

Estimate of Time to Merge Point

If an RTA is to be used in conjunction with CRDA and Lateral Offset, the ground automation system needs to be able to estimate the time of arrival of an aircraft at the merge fix. In the current system the information that is known about the aircraft by the ground automation is data that is in the tracker tables such as the identity of the aircraft, its altitude, position, and an estimate of its groundspeed and direction. The question is how much information is needed to make an accurate estimate of the arrival time of the aircraft at the merge fix.

Three methods of making this estimate have been hypothesized for this analysis. In Method I only the distance to the merge point and the current ground speed are used to make the estimate. This method will obviously make early estimates because aircraft tend to slow down as they get nearer to the airport. In Method II the indicated airspeed is estimated at the current altitude (ignoring the wind) and the assumption is made that the aircraft will sustain that airspeed to the merge point which is at a lower altitude. The average groundspeed is calculated and used in the estimate. This estimate will also tend to be early because aircraft are likely to slow their indicated airspeed as they approach the airport. In Method III assumptions are made concerning the nominal airspeed assignments at the current point and the merge point. From these assumptions a crude estimate of the headwind is made and applied to make the estimated time of arrival. This estimate should be somewhat better than the other two estimates.

To illustrate the magnitude of the accuracy of the estimate, we have chosen the same route geometry that was used in our previous paper [8]. As shown in Figure 1, the BOJID One Arrival RNAV procedure passes over the Lancaster VORTAC at 10,000 feet at 250 KIAS. By BUNTS the aircraft will be at 8000 ft and by SCOOL it will be at 6000 ft and 220 KIAS. There are several combinations of descents and decelerations that can meet these constraints, yielding an earliest time and a latest time at BOJID. If we compare our estimates using the methods proposed above to the earliest time we get the results shown in Figures 2 and 3 for Methods I and II respectively. In each analysis the distances between the fixes have been scaled from 70% to 120% to show the effect of the length of the distance to fly to the merge point. The true length of the path is about 40 nm. The result is that the error in the estimate is roughly cut in half with the added information that the groundspeed of the aircraft will slow prior to reaching the merge point.

In Method III enough assumptions have been made to place the estimate within the range of the earliest and latest times that the aircraft can actually fly to the merge point. In Figure 4, the percentage of the interval referenced to the earliest time is shown. As one can see, the estimate still tends to be in the early part of the window. For a 40 nm distance to the merge point, the window is between 57 and 100 seconds wide with an average of 76 seconds and a standard deviation of 8 seconds. (This variation is due to variations in wind speed and directions and variations in deceleration rates.)

Effectiveness of an RTA Merge

Based upon the previous analysis, the ground model used to estimate RTA must incorporate at least altitude and speed changes, and the effect of wind. To evaluate the sensitivity of determining an achievable RTA, an analytic model was constructed that takes into account all of the above factors. It was run for the case of a merge at the same altitude.

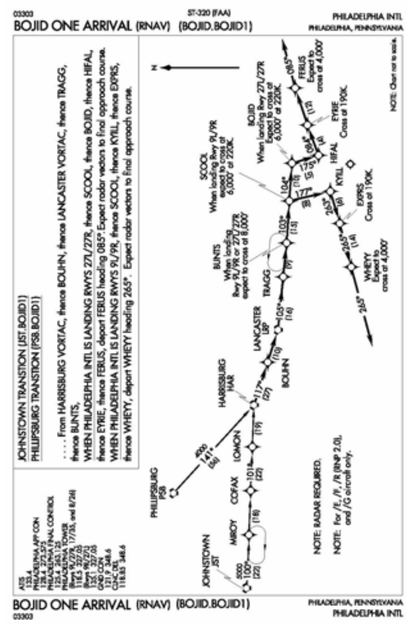

Figure 1. BOJID One Arrival

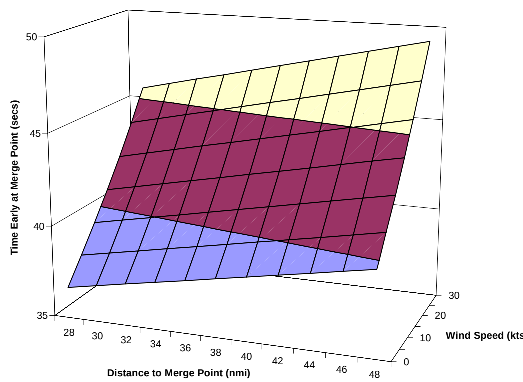

Figure 2. Method I Maximum Time Early at Merge Point

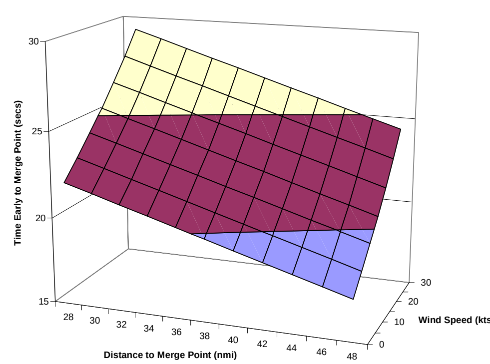

Figure 3. Method II Maximum Time Early at Merge Point

The model assumes that the aircraft performs a discrete speed change over the segment and does not allow speed change and altitude change simultaneously. A constant along track headwind/ tailwind is also assumed. The parameters of the model include initial and final airspeed, the initial and final altitude, the constant wind vector, the lateral path segments defining the merge, the separation distance desired at the merge, and the deceleration based upon aircraft type (small, large, and heavy).

If these algorithms were to be implemented in STARS or ARTS, then these systems would need to be modified to extract lateral path based upon the waypoints and Aeronautical Radio Incorporated (ARINC) coding and speed and altitude constraints from the coded procedure. It may be feasible to enter this information as adaptation data, but this option needs further exploration. The wind information would be obtained from a weather feed such as Integrated Terminal Weather System (ITWS) or perhaps entered by the controller. The deceleration values and the merge separation distance to use would be adaptation data. We now describe how the analytic model for the ground was used to assess the feasibility of an RTA.

The ground automation predicts, given current aircraft ground speed and the speed and altitude restrictions of the route, when each aircraft will arrive at the merge. The ground automation examines the two cases based upon whether Aircraft A arrives before or at the same time as B or whether B arrives before A. Without loss of generality, assume Aircraft A is predicted to arrive before B, then the ground estimates what the predicted separation of the aircraft pair is when A arrives at the merge point, P. If the predicted separation is less than the required separation D (which is nominally 5 nm) and a buffer (B), then three choices are evaluated: 1) expedite Aircraft A as much as possible and check if that solves the merge, 2) delay B as much as possible and check if that solves the merge, and 3) expedite A as much as possible and delay B (up to the maximum amount) and check if that solves the merge. If none of these solve the merge, then a Lateral Offset is executed by one of the aircraft to achieve the proper spacing. If a recommended RTA is determined, then the RTA is displayed in the data block of the aircraft.

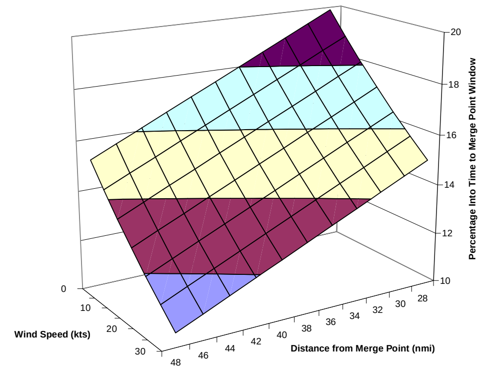

Figure 4. Minimum Percentage into the Flight Time Window

The controller verbally issues the RTA and the pilot enters the desired value into the FMS. As the aircraft executes the RTA, the controller can monitor the result using CRDA.

If the two streams merging are at the same initial and final altitude and speed, then the RTA function may not be useful since the aircraft RTA automation will manage its speed while not violating any speed constraints associated with the procedure. Unless there is a significant wind differential and substantial existing spacing between the aircraft pair, there will not be adequate speed control to create proper spacing at the merge.

The ground function must be able to predict whether an RTA is achievable based upon not violating coded speed constraints. As stated above, this implies that the ground automation knows what the coded speed constraints are and takes them into account when predicting an RTA. If the spacing cannot be achieved with an RTA, then the ground automation would compute an appropriate Lateral Offset to use or just indicate that an RTA is not achievable. Either of these options would be indicated in the aircraft data block with a voice clearance by the controller.

For the merge on final, the ground prediction algorithm must model the flying time taking into account that the aircraft is turning from a tailwind into a headwind and decelerating from around 180 kts to an approach speed of 160 kts (for a B767). The aircraft's RTA function can be used to get the aircraft to the initial approach fix at a desired time. The ground automation algorithm accounts for the continued compression of leading/trailing aircraft and accounts for the proper wake vortex separation at the runway threshold in arriving at the RTA to issue. With use of Radius-to-Fix (RF) legs, all aircraft equipped to fly these legs types will execute the same circular arc ground path which will improve the quality of the ground prediction algorithm. Speed constraints and the ARINC coding of the final approach procedure must be made available to the STARS and ARTS systems in the same manner as for the arrival procedure.

The ground algorithm computes the estimated landing time. The ordered times indicate the landing sequence. For the given sequence, the wake vortex separation at the threshold is checked for the leading/trailing pair of aircraft and the time to arrive at the threshold is computed based on this separation. This time is propagated back to the merge on final point and tested for desired lateral and longitudinal separation using a constant deceleration model.

Aircraft on the downwind possess an additional degree of freedom, the length of the downwind before being turned onto final which can be used to achieve proper spacing. Again, the proposed operational environment does not include time-based metering to the runway threshold. The previous uncoordinated terminal merges are producing smoother flows for handoff to the final. Theses merges are loosely coupled to the merge on final through a buffer that is part of the separation distance desired at the earlier merges. We consider the case of allowing three different downwind extensions; the expedite (turn early), the nominal, and the delay (turning later). Allowing only one turn location will make it very difficult for the controller to make the merge work out even with the assistance of CRDA. Since the ground automation knows about the coded procedure, it will know which aircraft are on the downwind legs and select them as candidates for path changing. The ground algorithm will try to solve the merge with RTA keeping aircraft on the nominal downwind turns. If proper separation cannot be achieved by speed control based upon the nominal turn from downwind to base, then the ground will seek a solution based upon either expediting or delaying aircraft on the downwind. Lateral Offsets can not be used in this region of the terminal area. The ground automation makes this determination when the aircraft are on the initial phase of the downwind segment to allow time for pilots to select a different approach transition.

We now present some results of running the analytic model for the merging of two streams at the same altitude. Figure 5 shows the feasibility of achieving proper spacing based upon a range winds applied to one segment. In this run of the model, aircraft are showing up at the same distance from the merge with the same initial speed and altitude. The result indicates that RTAs are feasible only for the larger wind values. The three rows of ones above the flying times indicates when an RTA is not feasible. The bottom row is the case where the earlier aircraft is expedited, the second row is the case where the later aircraft is delayed more, and the third (top) row is the case where the earlier aircraft is expedited as much as possible. Similar runs were made for the deceleration values and the starting distance of the aircraft.

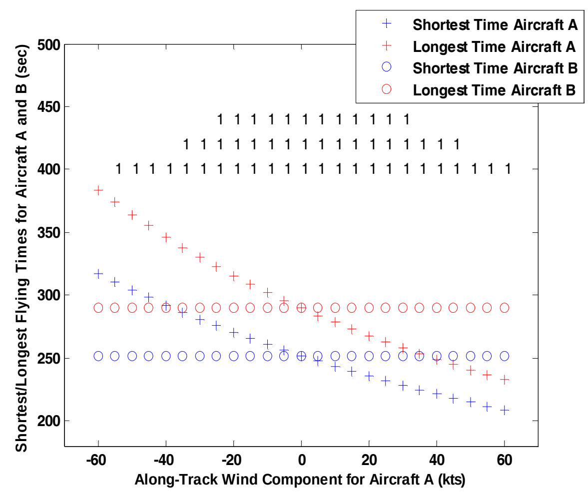

Figure 5. Flying Times as a Function of Wind

Table 1 summarizes the results for of RTA feasibility for 1000 runs with merge separation distance of 5 nm where wind, acceleration, and starting distance are all varied within some range randomly, two of the three parameters are varied, and only one parameter is varied randomly. The table lists the number of number of cases out of 1000 where RTA is feasible, a Lateral Offset is required, or there was no spacing action required. From the table we see that difference in segment lengths (equivalent to different Miles-in-Trail [MIT] spacing at the entry fix) and wind, have the most impact on the feasibility of RTA.

Table 1. Summary of RTA Feasibility

Parameter	RTA Feasible	Lateral Offset Required	No Spacing Action Required
Segment Length (L)	671	133	196
Decel (a)	1000	0	0
Wind (vw)	956	42	2
L and a	674	112	214
L and vw	618	100	282
Vw and a	957	40	3
L, a, and vw	610	110	280

Controller-in-the-Loop Simulations

Following our previous paper [5] we have continued the investigation of the use of CRDA with Lateral Offset, focusing on the merge-to-final problem. (It was previously demonstrated that a merge of two RNAV routes in the Terminal Radar Approach Control [TRACON] can be facilitated via the SPACR concept [5].) The merge-to-final is common at virtually all TRACONs. Whether or not aircraft have merged in the TRACON, there will inevitably be a common path required on final approach. During periods of sufficient traffic this naturally leads to a need to merge aircraft efficiently towards the final approach fix. The controller typically tries to turn the aircraft onto final just outside the “final approach gate” which is 3 nm from the Outer Marker. However, due to conflicting traffic, the downwind path of some aircraft is often extended.

In our initial investigations of the merge-to-final with two independent RNAV arrival flows (see Figure 6), we found that ghost aircraft could be generated using existing CRDA. Ghosting regions are created for straight segments of the route originating from CLARR that can be “mapped” to appropriate sections of the LUXOR route. Using the projection algorithms in CRDA, the appropriate ghost aircraft are drawn onto the approach from LUXOR. CRDA allows the option of introducing a Fixed Offset in the projection distance of the drawn ghost aircraft. In this rather dramatic application of coordinating aircraft from opposite-direction flows, the ghost aircraft are projected so that when a parent aircraft (on the CLARR approach) is at the turn to final point selected for this demonstration (just opposite BAKRR) the ghost is positioned at BAKRR. If then, the controller on LUXOR has managed to control his/her aircraft so that they are near the respective ghost targets, then a safe and efficient spacing will be achieved on final.

In experimentation, we found that the controller was not comfortable using the Lateral Offset maneuver on the LUXOR approach since the aircraft were typically approaching relatively fast and there is not very much space along the LUXOR route to allow the offset. In fact, the controller mostly used speed control to achieve his matching with the ghosts. In cases where speed control was not sufficient, he would typically allow his aircraft to fly south to intercept the extended centerline farther to the east than BAKKR. However, the simulations showed that the ghost aircraft allowed him to see the developing problem and mitigate last minute spacing problems on final. This is not unlike the technique used today, except that CRDA allows the controller to monitor the relative spacing sooner and make adjustments accordingly.

This initial experiment also attempted to see if keeping only one downwind path for the turn on final was feasible with ghosting. In this experiment the turn-to-final on the CLARR route was held fixed. This removes a degree of freedom from the final controller. Perhaps a more realistic situation would be to allow the turn-to-final to be more flexible as described in the previous section. Using CRDA it should be possible to control the two arrival flows to merge onto final efficiently, with the downwind extension of the CLARR route used as an additional control technique. The hypothesis is that there will be a net shorter downwind using the SPACR concept in such configurations where there are two RNAV routes pushing aircraft into the final approach regime. We would expect the downwind segment of the CLARR aircraft to be shorter (less tromboning) and hence more efficient. Experimentation is now under way to examine this hypothesis.

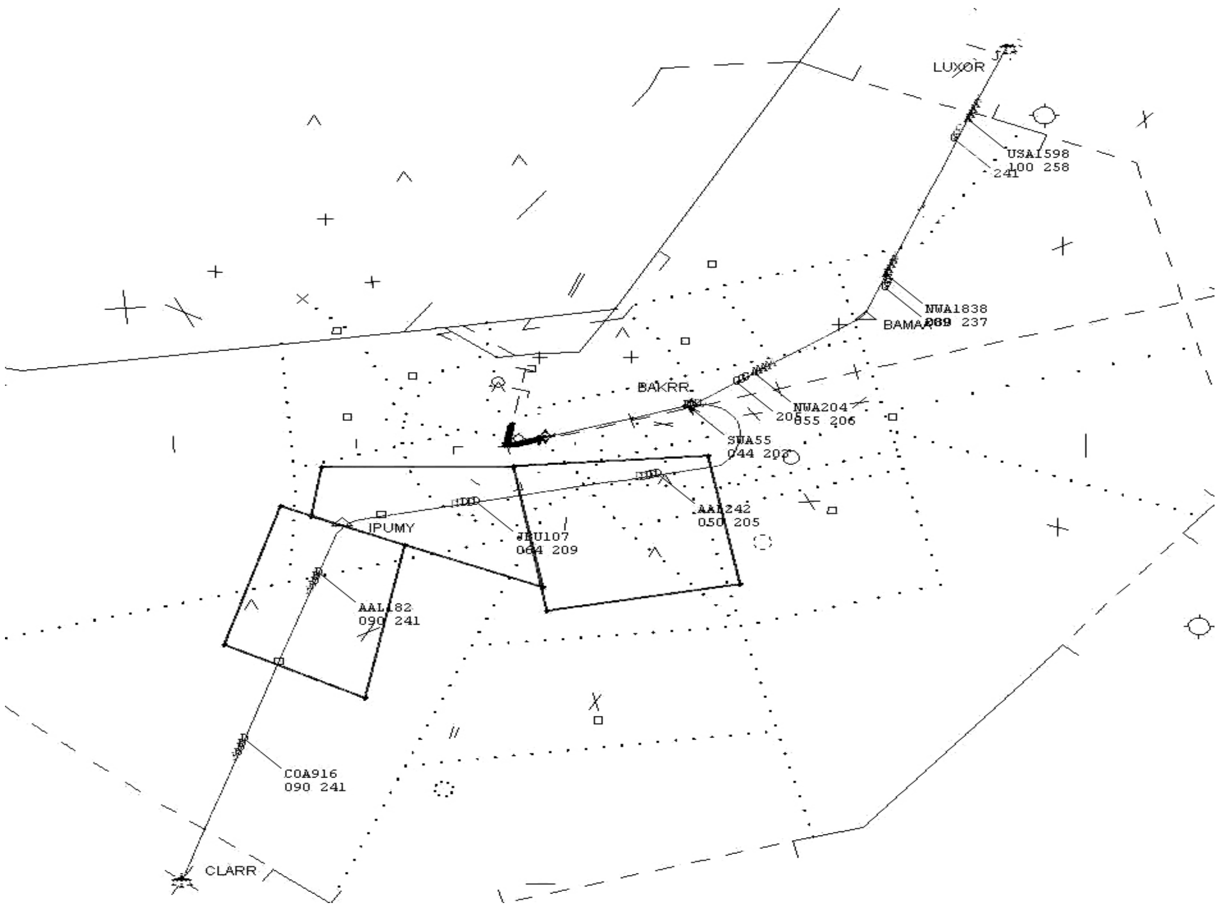

Figure 6. CRDA Application for Final Merge

Pilot's Point of View

During approach on an RNAV route, in general, the pilot will note the waypoints on his Flight Management Computer (FMC) as the aircraft progresses with respect to them and they are sequenced. In most cases in the SPACR concept, the aircraft stays on the nominal route. The pilot may receive speed instructions which he will execute in a timely manner. Under the aegis of the FMS, the aircraft will still meet its constraints (if any) at subsequent waypoints.

For the case of the pilot receiving an ATC request for a Lateral Offset, the pilot selects "R" "5" "EXEC" from the FMC keypad to initiate, e.g., a 5 nm Lateral Offset to the Right. See Figure 7 for an example which indicates a Lateral Offset maneuver (from a different experiment) on the CLARR to IPUMY segment of the geometry shown in Figure 7. The map display in the FMS will typically show the expected offset path. The actual rendition of the display may differ somewhat between different manufacturers, implementations and aircraft types.

Figure 7. Pilot View of Lateral Offset Example

Phraseology

As maneuvers such as the Lateral Offset become employed in concepts such as SPACR, there may be a need to refine the ATC phraseology. For example, if the controller requests a Lateral Offset and intends the aircraft to return to the nominal route, he could say "*Offset 5 Right and Return*." This would further relieve the controller's workload—the aircraft will perform the offset and effect the desired spacing, while returning at the pilot's initiative. Ideally the FMS will note the subsequent waypoint restrictions (such as speed and altitude) and meet them while on the offset.

FMS Mixed Equipage

There are differences in the implementation of the FMS suite of possible functions. As addressed in a previous paper [14], there may be arriving aircraft that have no RNAV route-following capability at all. For some applications, this condition can be tolerated up to a certain percentage of "unequipped" aircraft in the stream.

More likely, for concepts like SPACR, the issue will be implementation differences in FMS functions themselves, which vary by manufacturer. For example, Honeywell FMS does not allow for a Lateral Offset while on Navigation Database (NDB), SIDs or STARs. Most Boeing aircraft (except the B737) have Honeywell FMSs. On the other hand virtually all B737s are equipped with Smiths' FMSs which allow Lateral Offset. Some Airbus aircraft are equipped with a mix of Honeywell and Smiths FMSs, and the Honeywell FMSs have apparently been modified to act more like a Smiths box. Similar statements are true for the RTA functionality and other aircraft such as regional jets.

Some harmonization of functionality is desired. Perhaps the advent of concepts such as SPACR and the requirement to efficiently use RNAV routes, including merges, will act in a "carrot and stick" fashion to lead FMS manufacturers to improve and standardized their offerings.

In addition, some thought needs to be given as to how to indicate to the controller the level of equipage for a given aircraft to participate in concepts such as SPACR. Should the equipage level be announced by the pilot upon contacting the radar controller? Should the Automated Terminal Information Service (ATIS) indicate equipage expected for arrivals on flows to be merged? Current plans for the "/?" notation in the NAS cannot accommodate the necessary information to indicate to the controller the aircraft capabilities with respect to Lateral Offset or RTA. The controller could ask the pilot about the aircraft's navigational capability, but that would present additional communications workload which is antithetical to the RNAV concept

Therefore, it would make sense to test the SPACR concept in an air traffic environment where there is a fleet mix that will allow sufficient similar FMS functionality so that the controller can effectively achieve desired spacing of aircraft on merging RNAV routes.

Conclusions

In this paper we have discussed the SPACR concept for merging arriving aircraft assigned to RNAV routes in the terminal area. The original concept (involving the use of CRDA to recognize potential spacing problems, with speed control and/or Lateral Offset to resolve spacing problems) has been expanded in this paper to include the possibility of using the RTA function of the FMS-equipped aircraft as a means of achieving necessary speed control. SPACR combines existing (or slightly enhanced ground automation) with existing airborne FMS capabilities to maintain efficient use of RNAV routes without introducing undue workload either on the pilot or controller. The enhancement of the existing ground automation functionality to indicate the appropriate RTAs for aircraft on pair-wise basis to ensure efficient merging can be addressed via the STARS P^3I activity. Initial analytic studies indicate that the use of RTA will require assumptions about the speed and altitude profile of the route(s) and estimates of the wind.

The merge to/on final approach is not different in principle from the case of route merging as currently done in the TRACON, however, currently the merge on final is typically more tactical and challenging due to concentration and compression of traffic. SPACR can also be used in this regime with an appropriate use of CRDA, possibly augmented with final approach-specific dynamics of the aircraft. Routes defined to the final via RF legs could improve predictability and repeatability making the merges on final more efficient and minimizing the downwind extension (tromboning) typically used when vectoring for spacing in the final approach regime. Controller-in-the-loop simulations show encouraging results to date.

The use of FMS capabilities to facilitate SPACR begs for more harmonization in the implementation of FMS functions such as RTA and Lateral Offset. The issue of how the controller (or ground automation) understands the FMS capabilities of a given aircraft is acknowledged and should be addressed. The ideal test bed for the SPACR suite of tools would be in a TRACON where there are merge problem(s) and a sufficiently homogenous fleet mix of equipped aircraft to explore the efficacy of the solution. Given a success of a concept such as SPACR, there will be additional incentives for aircraft FMS manufacturers to harmonize their offerings, and for carriers to equip their fleets. However, there are very likely to be benefits of using SPACR in the near term, even in lieu of ideal conditions.

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