CNS Requirements for Precision Flight in Advanced Terminal Airspace

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Abstract—The capacity of the United States' National Airspace System (NAS) must double to handle the passenger demands that are projected over the next 25 years. NASA initiated the Virtual Airspace Modeling and Simulation (VAMS) Project in 2002 with participants, including members from industry, government, and academia to develop and share ideas on revolutionary concepts to meet the future demand. [1][2]

The constraints in the Terminal Area domain are the focus of Raytheon's VAMS concept, Terminal Area Capacity Enhancement Concept (TACEC). TACEC envisions a high level of automation and synchronization, generating optimized 4D flight profiles to land/depart multiple aircraft "simultaneously" on closely spaced parallel runways. Implementation requires infrastructure improvements such as highly automated guidance and scheduling systems, timely data link, improved surveillance, and improved on-board navigation systems. This paper discusses the guidance and scheduling systems required to pair the aircraft for simultaneous landing. Performance required by the autopilot/navigation system to maintain control necessary for formation flight onto closely spaced parallel runways, data link and surveillance requirements are also addressed.

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1. Introduction

This paper addresses the automation as well as the Communication, Navigation, and Surveillance (CNS) requirements of the VAMS Terminal Area Capacity Enhancement Concept proposed by Raytheon, We start with an overview of TACEC including a summary of the TACEC modes of operation (Initial Approach and Final Approach). The automation system required for pairing the aircraft and the performance required by the autopilot/navigation system to maintain control necessary for formation flight onto closely spaced parallel runways are discussed. The projected traffic within the TACEC terminal environment and associated data link and surveillance requirements are also addressed.

2. TACEC Overview

NASA's VAMS Program is addressing the challenge of increasing the future NAS capacity by developing new approaches to air traffic management. Raytheon's TACEC concept addresses the constraints in the terminal airspace. A preliminary concept evaluation showed that additional runways will be required to meet the 2 to 3x demand growth [1].

Today's procedures require 4300 feet between runways without Precision Runway Monitor (PRM) and when PRM is in use, the separation can be reduced to 3000 feet. Improvements in navigation and surveillance may reduce this separation, but wake vortex becomes the limiting issue with separation distance less than 2500 ft. Adding more independent runways would require almost two square miles of land, impossible for many urban airports that are likely to see the bulk of the capacity growth. Since land will not be available to build many more independent runways, another solution is needed.

The fundamental limit on the number of aircraft that can operate from a runway according to today's procedures is their "in trail" spacing used to protect from the vortex wakes generated at the lead aircraft's wing

Clearly wake vortex constrains today's operations on dependent runways, and for flights landing on the same runway. TACEC addresses the wake vortex hazard by utilizing the Flight Corridor concept proposed by NASA's Rossow [2]. The Flight Corridor is a defined region in space wherein the hazardous vortex rolling moment can induce no more than 5 degrees of unplanned roll.

[2] IEEEAC paper #1034, Version 8, Updated December 16, 2004

TACEC can significantly increase the airport's arrival (and departure) rate by using the Flight Corridors to land multiple aircraft on parallel runways, with separation distance as close as 750 feet. Houk [3] has shown that runway separation distances of 750 feet require rapid reaction times of 2 to 3 seconds to detect and respond to blunders. Such minimal separation distance will require a very quick reaction time to detect and respond to blunders. The quick reaction times as well as the need to provide increased capacity in Instrument Meteorological Conditions (IMC) are the primary drivers behind auto-land operation.

The TACEC approach to Flight Corridor/wake hazard avoidance also adopts the notion of a "protection zone" suggested by R. Bone [4]. The forward boundary of the protection zone provides protection from blunder, while the aft boundary guards the following aircraft from the wake of the lead. The forward boundary is nominally placed at 750 feet behind the lead. The aft boundary prevents the follower from drifting more than 30 seconds behind the lead [2]. For a B747 operating at near minimum terminal speed of 150 knots, this equates to an aft boundary at 7600 ft. The nominal position of the following aircraft is defined in the middle of the protection-zone, or 4200 ft behind the lead. Of course the ability of each aircraft to meet its Required Time of Arrival (RTA) will put an error about this nominal position, as discussed in Section 3.5.

3. INITIAL APPROACH

Analysis conducted in 2003 using the NASA VAMS Airspace Concept Evaluation System (ACES) simulator doubled the May 17, 2002 traffic arriving and departing at 24 candidate closely-spaced parallel runways (CSPR). This analysis indicates that TACEC could achieve a doubling of airport capacity, as shown in Figure 1.

TACEC's objective is to land/depart multiple aircraft "simultaneously" on closely spaced parallel runways. This requires the ability to stage the aircraft upon entering the Terminal airspace. While TACEC assumes no control authority until aircraft pass the Arrival Meter Fix, knowledge of actual and intended trajectory profile is available before this event. TACEC will establish a unique track for each flight as it approaches and will maintain this track as it passes through the Terminal Airspace. Automatic Dependent Surveillance – Broadcast (ADS-B) is the preferred surveillance source and will be used for equipped aircraft. Traffic Information System – Broadcast (TIS-B) will provide the trajectory profiles of non-equipped aircraft.

After track is established, aircraft are evaluated to determine if they can be paired with other aircraft and 4D (lat, lon, alt, time) flight paths are generated. The 4D flight paths are calculated in two steps. The first step determines whether it is possible to bring the two aircraft to the final wake vortex

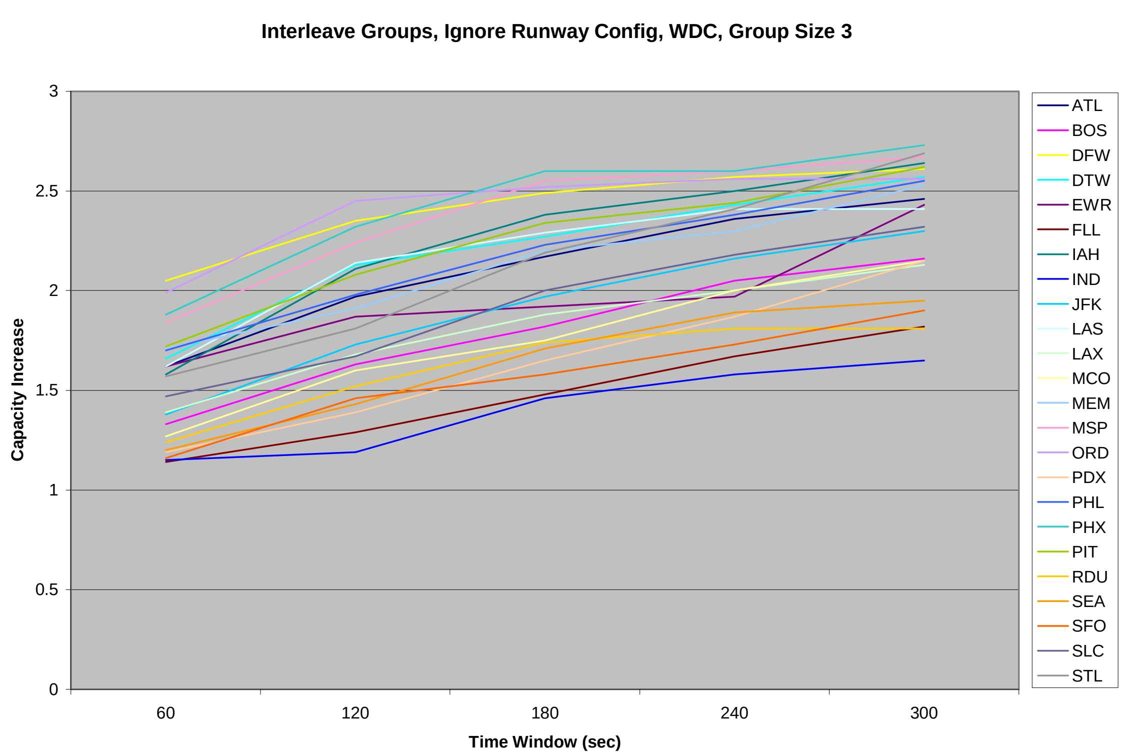


Figure 1 - TACEC Capacity Growth Potential using Closely Spaced Parallel Runways

approach meter fix nearly simultaneously, without regard to considerations. Aircraft pairs that do not meet this requirement are eliminated from further consideration. The second step determines how the flight paths must be modified for wake avoidance.

Initial Path Calculation, No Wake Avoidance

The first step begins by attempting to group aircraft which have "similar" flight characteristics and arrive at the approach meter fix within a specified threshold, nominally 2 minutes. The most important flight characteristic considered is airspeed, because the two aircraft must enter the final approach simultaneously and must also land simultaneously. Table 1 shows how aircraft might be grouped in this manner.

Table 1 shows three groups of aircraft that have similar flight speeds (compare columns ("Min Speed" and "Max TRACON Speed"). Only aircraft in the same group are considered for pairing.

The next part of the calculation is to determine the aircraft flight paths. We begin by determining the time window that can be obtained through varying the speed of each aircraft, keeping in mind the fact that we require a two minute window as discussed previously. This calculation requires a "minimum speed" and a "maximum speed" for the entire group. Figure 2 shows how to calculate these values. The minimum speed for the group must represent the worst case minimum, i.e. the largest of all the aircraft minimum speeds in the group. Similarly, the group maximum represents the smallest maximum speed of all the aircraft in the group.

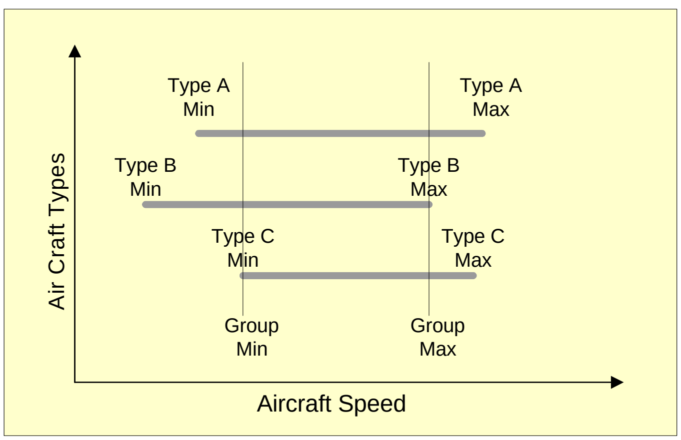


Figure 2 – Determination of Min, Max Group Speeds

The initial time window is calculated by considering the length of the current flight paths used in Chicago O'Hare Airport (ORD). Figure 3 shows the current paths, taken from STAR data as given in "U.S Terminal Airspace Procedures" handbook, EC Volume 3, 19 Feb. 2004.

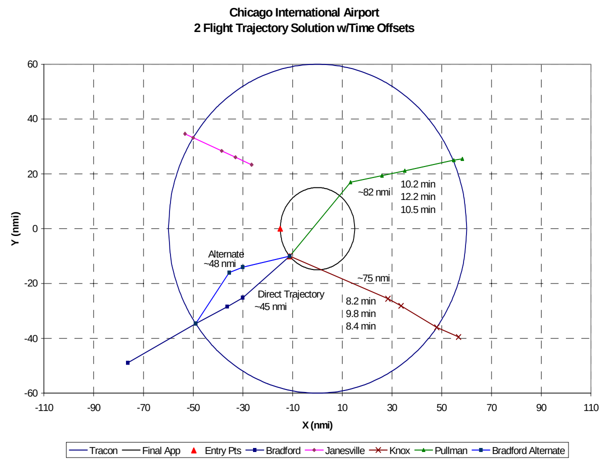
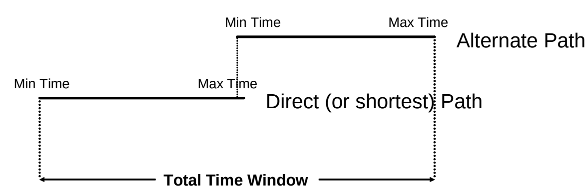


Figure 3 - ORD Terminal Airspace Flight Paths

If we consider the shortest flight path (Bradford), its length of 45 nautical miles (nmi) only allows a worst-case time window of 1.2 minutes. This falls far short of the required 2 minutes, so it becomes necessary to add an alternate flight path, which is slightly longer (48 nmi). The two paths taken together make it possible to obtain a two-minute window for aircraft that arrive at the southwest meter fix.

The alternate flight path must be chosen so that the time windows of the two paths overlap each other. The total time window must also yield the two minute requirement (see Figure 4). The "Direct Path" line segment represents the difference between the minimum and maximum aircraft traversal times for the direct path. The length of this segment depends upon the length of the direct path, and upon the minimum and maximum allowed aircraft speeds. Similarly, the "Alternate Path" line segment represents the difference between the minimum and maximum traversal times for the alternate path. The overlap mentioned above occurs if the minimum time for the alternate path is less than the maximum time for the direct path. The "Total Time Window" is the difference between the minimum time for the direct path and the maximum time for the alternate path. This must be at least two minutes. These are conflicting requirements, and it may not be possible to satisfy this for all types of aircraft. If this happens, it may become necessary to add a third flight path.



- **There must be overlap between time intervals**
- **Total Time Window >= 2 minutes**

Figure 4 – Alternate Path Calculation

Table 1 – Aircraft Grouping

AC_Type	Min Speed Capable (kts)	Max Speed Capable (kts)	Max Speed TRACON (kts)	min time (min)	max time (min)	Window (minutes)
A306	200	280	226.667	11.912	13.500	1.588
A310	200	280	226.667	11.912	13.500	1.588
A319	200	280	226.667	11.912	13.500	1.588
A320	200	280	226.667	11.912	13.500	1.588
B712	200	280	226.667	11.912	13.500	1.588
B722	200	280	226.667	11.912	13.500	1.588
B732	200	280	226.667	11.912	13.500	1.588
B733	200	280	226.667	11.912	13.500	1.588
B734	200	280	226.667	11.912	13.500	1.588
B735	200	280	226.667	11.912	13.500	1.588
B737	200	280	226.667	11.912	13.500	1.588
B738	200	280	226.667	11.912	13.500	1.588
B742	200	260	220.000	12.273	13.500	1.227
B744	200	260	220.000	12.273	13.500	1.227
B752	200	280	226.667	11.912	13.500	1.588
B762	200	260	220.000	12.273	13.500	1.227
B763	200	260	220.000	12.273	13.500	1.227
B772	200	260	220.000	12.273	13.500	1.227
DC10	200	260	220.000	12.273	13.500	1.227
DC8Q	200	260	220.000	12.273	13.500	1.227
DC93	200	280	226.667	11.912	13.500	1.588
MD11	200	260	220.000	12.273	13.500	1.227
MD81	200	280	226.667	11.912	13.500	1.588
MD82	200	280	226.667	11.912	13.500	1.588
MD83	200	280	226.667	11.912	13.500	1.588
MD90	200	280	226.667	11.912	13.500	1.588
AT72	150	250	183.333	14.727	18.000	3.273
CL60	180	280	213.333	12.656	15.000	2.344
CRJ1	180	280	213.333	12.656	15.000	2.344
CRJ2	180	280	213.333	12.656	15.000	2.344
CRJ7	180	280	213.333	12.656	15.000	2.344
E145	180	280	213.333	12.656	15.000	2.344
F100	180	280	213.333	12.656	15.000	2.344
GLF3	180	280	213.333	12.656	15.000	2.344
GLF4	180	280	213.333	12.656	15.000	2.344

For the other flight paths (Janesville, Knox, Pullman) the current path length of 75 nmi or greater can provide the required two minute window. No alternate flight paths are needed.

Wake Avoidance

The calculated 4D paths from step 1 are unacceptable from the standpoint of wake avoidance. The trailing aircraft would fly through the leading aircraft's wake before it could catch up to the leading aircraft.

It is therefore necessary to modify the trailing aircraft's flight path that was calculated in step 1, so that the leading aircraft's wake is avoided. Figure 5 shows this modification.

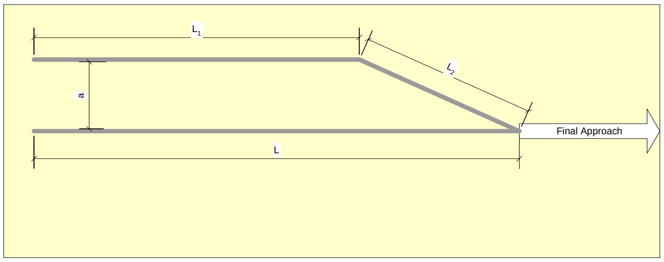


Figure 5 – Wake Avoidance Calculation

The original flight path of the aircraft is represented by the straight line of length "L". This is the path to be modified. The modification is accomplished by calculating appropriate values for "L1" and "a". The distance "a" represents the horizontal separation between the two aircraft.

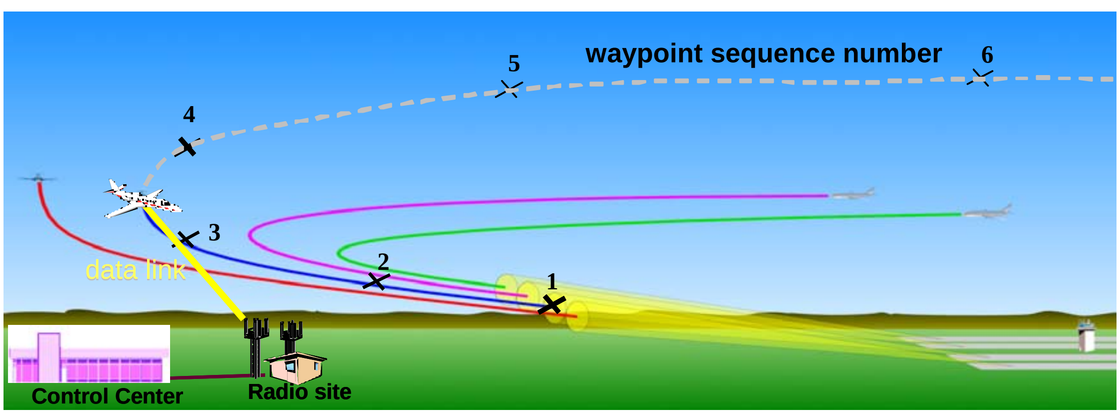
This modification does not appreciably change the overall flight path for reasonable values of "a", such as 0.5 nmi [2]. This is shown in Table 2, where the sum "L1 + L2" is calculated. The result is only slightly longer than the original length of 45 nmi. It is therefore anticipated that the small perturbation introduced by this path modification can easily be compensated for by adjusting the aircraft speeds.

Table 2 – Flight Path Modification for Wake Avoidance

L_1	L_2	L_w
0.000	45.003	45.003
5.000	40.003	45.003
10.000	35.004	45.004
15.000	30.004	45.004
20.000	25.005	45.005
25.000	20.006	45.006
30.000	15.008	45.008

The flight paths calculated above are then uplinked using a data link discussed in Section 3.4 to the aircraft, and the aircraft's flight management system will follow the path requested (See Figure 6). Since multiple aircraft are flying interrelated flight paths with variable error performance and with variable and unpredictable wind or other flight conditions, the waypoints not yet flown through may well need to be updated. The duration of this flight regime, in initial approach, is approximately 20 minutes. Therefore a waypoint will be passed approximately every one to three minutes. Based upon initial analysis, it appears the error budget will not be exceeded if the waypoints are updated approximately every minute. If upon further analysis, additional waypoints are needed minor waypoints could be defined that could be as close as at 20 second intervals.

Controlled Flight Path



- **Each aircraft fly a controlled flight path during terminal area approach/departure**
  - Defined by waypoints for each aircraft
  - Dynamic number of waypoints contingent upon traffic conditions, weather, etc.
  - 4-D waypoints (X/Y position, altitude & time) dynamically computed
  - Waypoint values uplinked every minute to each aircraft's flight control system

Figure 6 - Flight Path Definition During Initial Approach/Final Departure

Arrivals at Different Meter Fixes

The discussion so far has centered upon pairing aircraft that arrive at the same TRACON boundary meter fix. When aircraft arrive at different meter fixes, the problem is different because of the (potential) large difference in flight path lengths. For example, flights that arrive at southwest meter fix at ORD (Bradford) have only 45 nmi travel distance to the final approach meter fix, whereas flights arriving at southeast meter fix (Janesville) need to travel 75 nmi to reach the same final approach point.

This is handled by calculating an offset time "t_{off}" which represents the difference between the minimum times required for the aircraft to fly each path. This offset is depicted in Figure 7. The line segments labeled "Direct Path' and "Alternate Path" are the same as shown in Figure 4. The "SE Meter Fix" line represents the minimum and maximum times to traverse the path from the SE meter fix to the final approach fix. This path is much longer than the other two so there is no overlap with those paths. The offset time, t_{off} is the difference between the SE meter fix minimum time and the direct path minimum time.

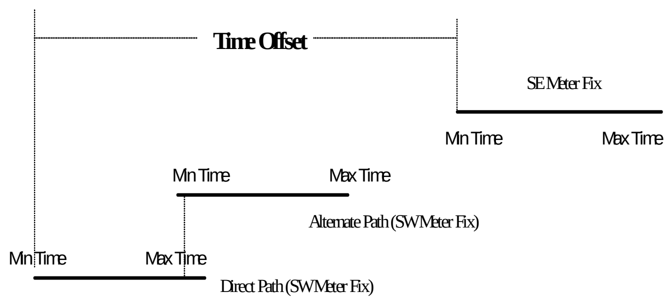


Figure 7 – Time Offset for Arrivals at Different Meter Fixes

Any aircraft that arrives at the southeast meter fix at time t can be paired with an aircraft of the same group that arrives at the southwest meter fix at time $t + t_{off} \pm t_{win}$, where t_{win} is the required two minute window. Note that the case where both aircraft arrive at the same meter fix is simply a sub-case of this, where t_{off} is equal to zero.

Since this process will use a data link to reach the aircraft that are arriving and departing, one concern is whether the aircraft can or will be equipped with the necessary avionics. One approach that has been defined by the International Civil Aviation Organization (ICAO) and the certification of the necessary avionics supported by the FAA is VHF Data Link Mode 3 (VDL Mode3). We have evaluated in [5] whether a system having characteristics similar to VDL

Mode 3 could support this application. The essential features of VDL Mode 3 are the time division multiple access protocol providing four subchannels for user information and a separate management channel. The subchannels can be used in several modes. For analysis we selected a mode that provides two separate user groups each having a shared voice and data network all transmitted on one 25 kHz bandwidth frequency. Other similar time division link level protocols have been defined and provide similar capabilities.

VDL Mode 3 at the link layer is a ground station controlled process. The link layer is managed by the ground station accepting requests for data transfer from both mobile users and the ground with 4 levels of priority. The ground system schedules the use of each data burst and assigns it to either the ground or a specific mobile user. However, it must be recognized that the ground system has the ultimate power to decide who gets to send what data. This allows the ground station to schedule waypoint position updates as necessary and with a maximum delay to the next opportunity of 120 msec. There is also a built-in acknowledgement scheme at the link level where the mobile user acknowledges correct reception of a message transfer in a separate sub-channel.

Within one VDL Mode 3 2V2D user group consisting of 1 voice and 1 data slot with up to 120 users, there is an opportunity for the ground system to send up to 62 bytes of information addressed to any one mobile user every 120 msec and one voice conversation between the approach controller providing a human monitor of the situation and the pilots in the approach pattern. Using 9 bytes per waypoint as established in [5]. The 62 bytes provide for the next 6 major waypoints to be sent to the aircraft. These 6 waypoints could define the aircraft position for the next 6 minutes or a waypoint every minute of flight. Or if appropriate a much shorter interval can be used. For instance, the next 6 waypoints could be provided for 20 second intervals with a projection into the future of 2 minutes. With an update rate of 1 per minute, up to 500 updates can be transmitted using the full capacity of the network. Using the full addressable capacity of a VDL Mode 3 user group, recently upgraded by the RTCA Special Committee 172 in the draft of a B version of DO-224A [4] to 120 users in a single 2V2D group (or 240 per frequency), sending one uplink burst for each of 120 aircraft once per minute would use 24% of the available capacity of the network. This leaves a reasonable capacity for other possible uses, such as broadcast of current weather conditions and general alerts. With a total capacity of 600 airport operations/hour and a 20 minute approach period for each aircraft, an average capacity of 200 aircraft at any time is necessary. This can be achieved using both user groups available on one VDL Mode 3 frequency, which provides a total capacity of up to 240 users with a 20% margin for imbalance in arrivals vs. departures or peaking of traffic.

Transition to Final Approach

During initial approach the aircraft are maneuvered to deliver the following aircraft within the protection-zone behind the lead. During this phase, each aircraft follows its own 4D flight path, therefore each is affected independently by RTA errors. RTA flight trials conducted with a Boeing 737 in the spring of 2001 [6] have shown that RTA errors at waypoints at the top of the Standard Arrival procedures had a error of 4.8 seconds (1-sigma), and the error increased to 12.7 seconds (1-sigma) at the runway threshold. Final approach occurs approximately half way between these two end-points, so the error lies somewhere in the middle. If the aircraft remain independently controlled during final approach the error can be assumed to be an average or 8.75 seconds (1-sigma). This equates to a position error of about 2400 ft. In this case the follower could overtake the leader as notionally depicted in Figure 8.

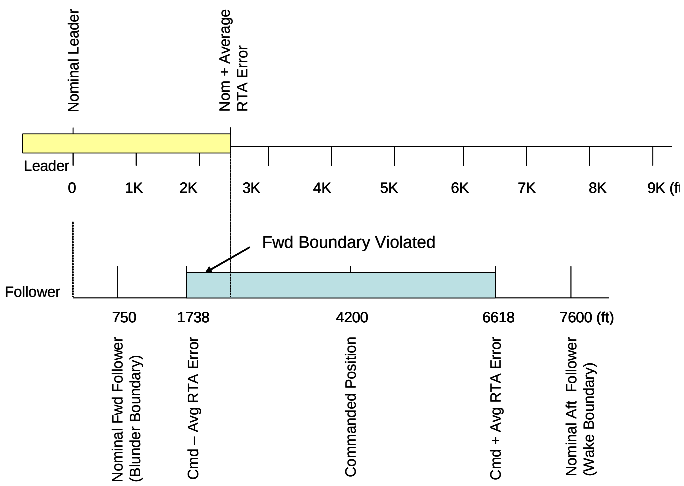


Figure 8 - Position Error with Independent Control During Initial and Final Approach

An alternate approach would be control of the follower relative to the leader after the pair begins final approach. The effective RTA error would be reduced to about 6.7 seconds (1-sigma). This produces a position error of about 1900 ft, and in this case the follower remains behind the lead by at least 400 ft as depicted in Figure 9.

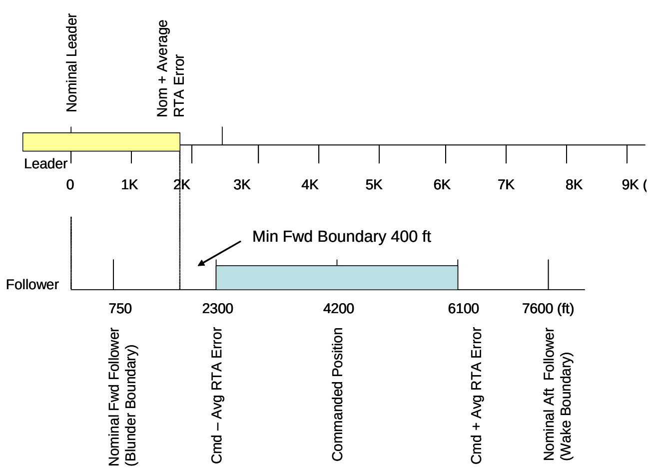


Figure 9 - Position Error with Coupled Control During Final Approach

4. FINAL APPROACH OVERVIEW

The aircraft transitions into Final Approach, entering the TACEC Flight Corridors, approximately four minutes from the airport. Close-control during Final Approach is achieved by using differential GPS landing aids in conjunction with auto-land avionics. This will require a Total System Error (TSE) smaller than available today. TSE is composed of Navigation Sensor Error (NSE) and Flight Technical Error (FTE), and defines how well an aircraft can accurately follow a pre-defined path in the sky. Differential GPS systems such as the Wide Augmentation System (WAAS) and the Local Area Augmentation System (LAAS) significantly reduce NSE compared to radar sensors such as Instrument Landing System (ILS). However, Hammer [7] and Houk [8] have shown that flight management systems and cock-pit displays in today's fleet preclude the system from taking advantage of the reduced NSE. Due to the existing avionics, the system even with WAAS/LAAS, produces a TSE roughly equivalent to existing ILS.

The promise of improving airport capacity by utilizing IMC approaches onto closely spaced parallel runways can not be attained without a change to the avionics. Since TACEC uses auto-land, modifying the avionics to include tunnel-in-the sky displays may not be required. Instead, a lower-cost and relatively simple tuning of the autopilot interface may suffice. We plan to investigate this issue in the near future, possibly through the use of hardware-in-the-loop (HIL) simulations.

Final Approach Data Link

The Local Area Augmentation System (LAAS) includes an internal data link with capacity to support close control of the aircraft. LAAS operates on a VHF broadcast data link known as VDB. VDB is a TDMA based scheme with 28.4 Kbps application data. While the datalink bandwidth allows for 95 unique Final Approach Segment (FAS) blocks, the actual number is limited to 48 by the number of unique Reference Path Data Selector (RPDS codes). Thus, LAAS can support up to 48 aircraft during Final Approach/Initial Departure. The differential corrections are uplinked in Type 1 messages at 2Hz. The differential reference points and FAS are uplinked in Type 2 and 4 messages, respectively, every 10 seconds. The LAAS VDB coverage is depicted in Figure 10.

Alternative approaches are also being considered should LAAS not be available. Under these conditions the lead aircraft would use whatever the approved approach procedure is for the weather conditions. The trailing aircraft would position itself with reference to the lead aircraft using its ADS-B data. While ADS-B may not provide extremely accurate absolute position, if both aircraft are navigating in the same area using the same augmentation from either LAAS or WAAS the relative positions will be very

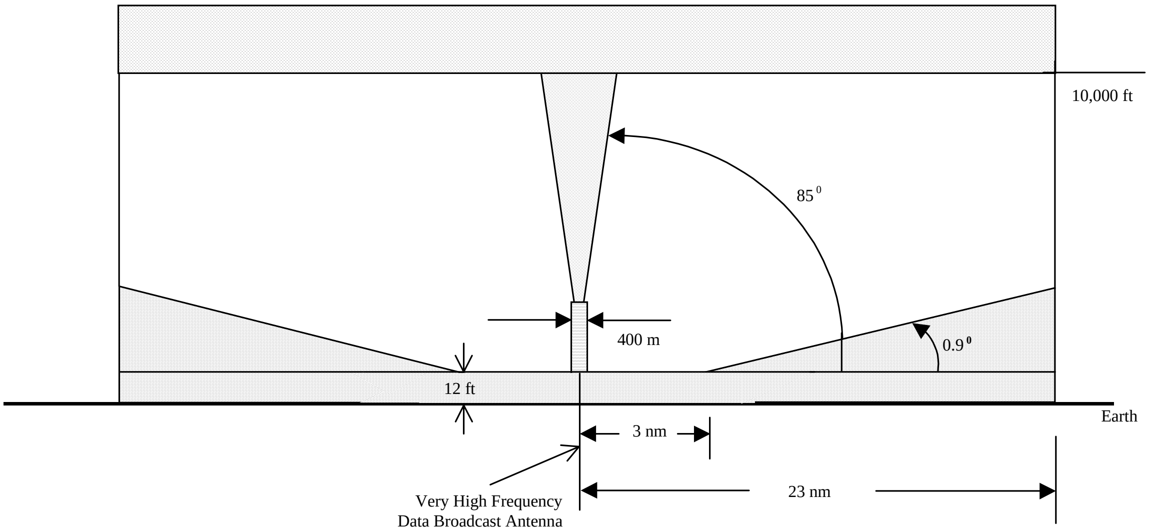


Figure 10 - LAAS VDB Coverage

accurate. As was pointed out in earlier papers by Houk [3] under these conditions the potential for the lead aircraft to blunder into the following aircraft's flight path is the major concern. Knowledge of the roll and roll-rate of the lead aircraft appears to be the most sensitive indicator of a turn toward the follower. As few as two bits of information indicating the following 4 states might be sufficient:

1. Rolling away
2. Normal level flight
3. Moderate roll toward following
4. Severe roll toward following.

There does not appear to be space within the existing ADS-B message structure to support this information transfer, but a simple direct data link between the aircraft might be the solution. As these two aircraft are well separated from all other aircraft and the ground an adaptation of the same data links used or proposed for use on the surface might be appropriate.

5. TRAFFIC LOADING

Grouping aircraft improves performance, but the spacing between groups onto and off of the same runway must adhere to today's wake vortex separation requirements. For arrivals, assuming a typical terminal airspace velocity of 140 knots, a group of Large aircraft would need to follow another Large group by 1:04, while a Large group following a Heavy group would require a spacing of 2:08. Assuming a worst case (with respect to communication loading) of one minute separation between arriving groups, with two aircraft per group, the maximum number of arrivals per hour onto one set of parallel runways would be 120 arrivals/hour. For departures, according to FAA 7110.65M the Category III groups must be separated by 6000 ft, or approximately 40 seconds. When the group is taking off behind a heavy jet or B757 the groups must be separated by 2 minutes. Again we will use the worst case assumption of 40 seconds for communication loading. With two aircraft per group, the maximum number of departures per hour off of one set of parallel runways would be 180 departures/hour. The 120 arrivals/hour and 180 departures/hour represent the busiest hours, however averaged throughout the day the number of arrivals and departures will even out. An airport can be equipped with multiple sets of closely spaced runways, some used exclusively for arrivals and others for departures. Assume two sets are dedicated to arrivals with each handling 120 arrivals/hour. Two other sets will each handle 180 departures/hour. The total airport operations could therefore be 600 operations/hour. This is slightly higher than the 546 operations/hour that would be required at DFW if its capacity were to double and so is a reasonable worst-case across the NAS. The number of aircraft controlled by TACEC, during a 20 minute Initial Approach mode, will be 200 (80 arriving and 120 departing). As was noted above, up to 120 aircraft can be handled at any one time supporting the two 180 departure operations/hour runway pairs with a 20 minute departure window.

There will be 40 aircraft during the four minute Final Approach/Initial Departure, bringing the total number of aircraft controlled in a 24 minute TACEC Terminal Airspace to 240. An additional 100 aircraft in the terminal area representing GA or otherwise non-equipped are included in the link analysis.

Communication Loading

In addition to flight plans, TACEC also requires that surveillance data be transmitted between the ground and aircraft. ADS-B will provide surveillance of equipped aircraft, those under TACEC control. Surveillance of non-equipped aircraft will be available via TIS-B to the ground based operational algorithms and TACEC aircraft for pilot situational awareness. Accurate knowledge of the wind field is required by the ground based operational algorithms, and this information will be available at the ground station through the Integrated Terminal Weather System (ITWS) Gridded Winds Product – Terminal Winds. TACEC also allows for transmission of voice, to be carried on VDL Mode-3 using the 2V/2D mode. The previous communication loading analysis [5] indicate that 4D Flight Plan message utilize approximate 30% of the VDL Mode 3 data link. The other links are also significantly below their limits.

6. Conclusion

This paper has demonstrated that the TACEC approach to Terminal Area traffic flow can provide a significant improvement to the arrival and departure capacity of the terminal area. Implementation will require that avionics be modified in order to take advantage of the increased navigation accuracy available through WAAS/LAAS. A low-cost approach to this modification is under investigation. TACEC also requires a digital communications infrastructure much of which is anticipated to be in operation, especially on the aircraft, when TACEC would be implemented. If VDL Mode 3 is not implemented, a similar system with similar capabilities is anticipated.

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BIOGRAPHY

Mary Ellen Miller *is Senior Principal Engineer for Raytheon Company. She has over 20 years of experience in Systems Engineering, program and technical management. Experienced in the design, development, and integration of complex systems, she strives to maximize system effectiveness and customer value. Mary Ellen has participated in and led teams in many technical domains, including Air Traffic Management, Object-Oriented Distributed Simulation, Satellite Communication, and Missile Systems. Mary Ellen holds a BSAE from the University of Michigan and a MSSE from the University of Massachusetts.*

Steven Dougherty*, Senior Principal Engineer, leads Raytheon's systems engineering on the NEXCOM program. Steve has been involved in the system design of communication systems to support Air Traffic Management and Air Defense Systems for the last 30 years. Steve participates in RTCA Inc. committees SC-172 VHF Air/Ground (A/G) Communication and SC-198 Next Generation A/G Communication. Steve holds a BSEE from Rutgers University, along with a MS and an Engineer Degree in EE from Stanford University.*

Pavan Reddy is a Senior Systems Engineer for the Raytheon Company; where he is involved in the design and analysis of communication systems for various programs. Prior to Raytheon he has worked at Cisco Systems. In his five years of experience Pavan has worked on problems in, improving QoS of wireless packet networks, RF system design and designing high availability software systems. Pavan holds a BS and MS in Electrical Engineering both from the Worcester Polytechnic Institute.

Joe Stella *is a Principal Engineer for Raytheon Company. He has 24 years of Engineering experience, and is especially experienced in the use of simulation and mathematical analysis in performing complex system analysis and tradeoff studies. He holds a BS degree in Physics and a MSEE, from the University of Massachusetts*