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Cockpit Display of Traffic and Wake Information for Closely Spaced Parallel Approaches

Gordon H. Hardy * and Emily K. Lewis†
Northrop Grumman Information Technology, Moffett Field, CA 94035

A preliminary study of a Cockpit Display of Traffic and Wake Information for closely spaced parallel approaches was conducted at the NASA Ames Research Center. With the advent of the navigational precision of the Global Position System, data-link, and the operational procedures of Required Navigational Performance, the possibility exists for simultaneous instrument operations to runways with separations approaching those used for simultaneous visual operations. In addition, new algorithms for predicting wake vortex movement may allow these instrument operations to be conducted with greater safety than for present visual operations. The study developed a cockpit display for traffic and wake information and developed operational procedures for a mix of conventional and runway independent aircraft to closely spaced landing areas. Results showed that very small Total System Errors were obtained using pursuit displays and manual flight control. For aircraft with different approach speeds, a small increase in paired aircraft approach spacing was found to be necessary for wake separation over that for aircraft with similar approach speeds. Performance at decision height was compatible with CAT II/IIIA operations.

Nomenclature

b_f	wingspan of the following aircraft, feet
b_g	wingspan of the wake generating aircraft, feet
b'	effective wing vortex span, feet
B_g	wake width for the generating aircraft, feet
c.g.	center of gravity
KT	knots
NM	nautical miles
S_F	distance from GSI to the start of final, feet
S_{MS}	distance from GSI to the point of minimum runway separation for unrestricted operation, feet
t	time, seconds
t_d	time for wake dissipation, seconds
t_E	extra pair separation time for aircraft with different approach speeds, seconds
T	exponential trajectory convergence time constant for the PFD pursuit displays, seconds
Δt_F	difference in arrival time at the start of final, seconds
Δt_{GSI}	difference in arrival time at GSI, seconds
Δt_{MS}	difference in arrival time at the distance S_{MS}, seconds
$(t_{MS})_O$	time for Ownship to travel the distance S_{MS}, seconds
$(t_{MS})_T$	time for Traffic to travel the distance S_{MS}, seconds
V	free stream airspeed, feet per second
W	weight, pounds

* Senior Simulation Engineer, Technical Services, Mail Stop 243-6, NASA Ames Research Center, AIAA Member.
† Simulation Engineer, Technical Services, Mail Stop 243-6, NASA Ames Research Center, AIAA Member.

ρ	air density, slugs per cubic feet
AVOSS	Aircraft VOrtex Spacing System
CDTI	Cockpit Display of Traffic Information
CDTWI	Cockpit Display of Traffic and Wake Information
CSPA	Closely Spaced Parallel Approach
CTOL	Conventional Take-Off and Landing
FTE	Flight Technical Error
GSI	Glide-Slope Intercept with runway surface
IMC	Instrument Meteorological Conditions
LDI	Lateral Deviation Indicator
NAV	NAVigation Display
PFD	Primary Flight Display
RIA	Runway Independent Aircraft
RMS	Root Mean Square
RNP	Required Navigation Performance
TSE	Total System Error
VDI	Vertical Deviation Indicator
VMC	Visual Meteorological Conditions

I. Introduction

One of the primary constraints on the capacity of the nation's air transportation system is the landing capacity of its largest airports. Capacity will continue to be constrained at many of these large, hub airports during some periods of the day, even in Visual Meteorological Conditions, VMC. The problem is exacerbated when the weather goes below VMC, requiring a large increase in the minimum allowable spacing between parallel runways for simultaneous use in Instrument Meteorological Conditions, IMC. New runways with the required lateral spacing are the best solution, but these are not easily implemented for a number of reasons, not the least of which are cost and community acceptance. Possible solutions are 1) to improve navigation accuracy and reduce Total System Error, TSE, to allow simultaneous operations to runways with reduced lateral separation, and 2) to move smaller commuter aircraft off the primary runways to allow more passengers per landing on the primary runways by simultaneously serving Runway Independent Aircraft, RIA, on new, shorter runways through STOL operations, or tilt-rotors and helicopters at verti-ports.

The present requirement for simultaneous independent landings in IMC is at least 4300 feet of lateral runway spacing (as close as 3000 feet for runways with a Precision Runway Monitor). Operations in VMC only require a lateral runway spacing greater than 750 feet. With the advanced navigation and data-link communication systems imminent in the National Airspace System, all aircraft should know, almost instantaneously, the location and state of all other equipped traffic in the area. The Global Positioning System, GPS, with suitable local augmentation has demonstrated a lateral accuracy of only a few meters. In addition, new algorithms for predicting wake vortex movement may allow avoidance of this hazard. If traffic position and velocity information can be conveyed to the pilot (and controller) on a suitable display in real time, there should be no reason why parallel approach separation in IMC could not be similar to that presently used for VMC. The shorter runway lengths required for Runway Independent Aircraft operations, combined with reduced runway spacing due to better navigation and displays, could be combined to further increase the number of available landing areas. Not only would this use of new airspace management and flight deck technology support increased airspace system capacity, but runway expansion projects could become smaller, less expensive, and less intrusive on the environment.

NASA[1-2] has sponsored Cockpit Display of Traffic Information, CDTI, studies for the en-route and terminal phases which provide intent and prediction information on the Navigation Display. These displays have included spacing tools to provide greater efficiency in sequencing aircraft into the final approach queue. NASA Langley[3-6] and NASA Ames[7] have sponsored the development of the Airborne Information for Lateral Spacing, AILS, system. The goal of this work was to enable Closely Spaced Parallel Approaches, CSPA, to runways spaced as close as 2500 feet using specific AILS cautions and alerts. The FAA has sponsored studies at Stanford University[8] using synthetic vision displays of traffic with similar approach speeds for CSPA using intent information based on traffic aircraft state information. The Mitre Corporation[9-10] studied simultaneous Category I instrument operations to the San Francisco Airport for aircraft with similar approach speeds where the primary instrument runways are spaced 750 feet. Presently, airport capacity at the San Francisco airport is reduced from about 60 arrivals per hour in visual conditions to 30 in instrument conditions. The report by Cotton[11] for the San Francisco International Airport Runway Reconfiguration Project also supports the concept of simultaneous paired approaches in instrument conditions to preserve airport arrival capacity. NASA Langley[12–13] has developed the Aircraft VOrtex Spacing System, AVOSS, for wake prediction and spacing. Rossow[14–15] of NASA Ames has studied wake prediction algorithms extensively. Holforty[16] used Rossow's algorithms to predict wake location for addition to the Stanford University synthetic vision Primary Flight Display, PFD.

The FAA's "Roadmap for Performance - Based Navigation"[17] provides a framework to tie the technologies discussed above into a workable solution to increase the capacity of Closely Spaced Parallel Approaches, CSPA, in instrument conditions. Key parts of this performance-based system include communications, navigation, and surveillance. The concept of Required Navigation Performance, RNP[18–20], provides the strategies necessary for this performance-based navigation system.

The goal of the present study was to integrate and extend these studies and concepts in lateral traffic separation, longitudinal station keeping, wake prediction, wake display, and the concepts of RNP into a system concept for CSPA. The preliminary concept which was developed, presented traffic and wake information on the NAVigation Display, NAV, and developed operational procedures for a mix of conventional and Runway Independent Aircraft with different approach speeds for approaches to Closely Spaced Parallel Runways.

II. Concept

The most challenging situation for instrument condition CSPA is to runways separated by 750 feet, the minimum used for visual traffic. Runways 28L & 28R at San Francisco International Airport, SFO, were chosen as an example for study as they meet this requirement and suffer a serious traffic acceptance penalty in instrument conditions. Figure 1 shows the airport diagram at SFO and Fig. 2 shows one example of the Cockpit Display of Traffic and Wake Information, CDTWI, on the NAV display for two heavy conventional (B747) class aircraft developed during this study for a typical proposed CSPA. Ownship is the filled icon approaching runway 28L and the paired Traffic is

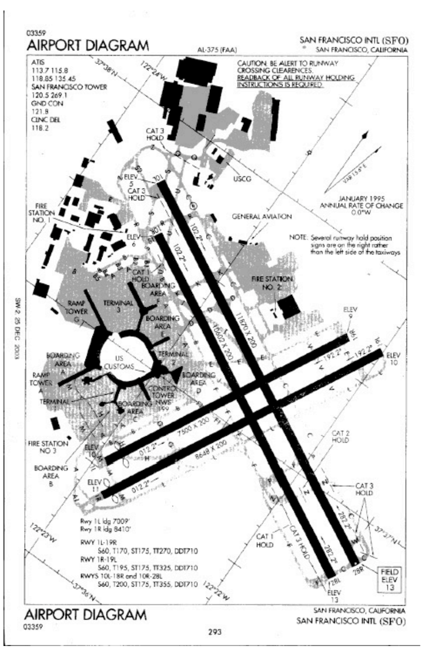


Figure 1. San Francisco International Airport Diagram

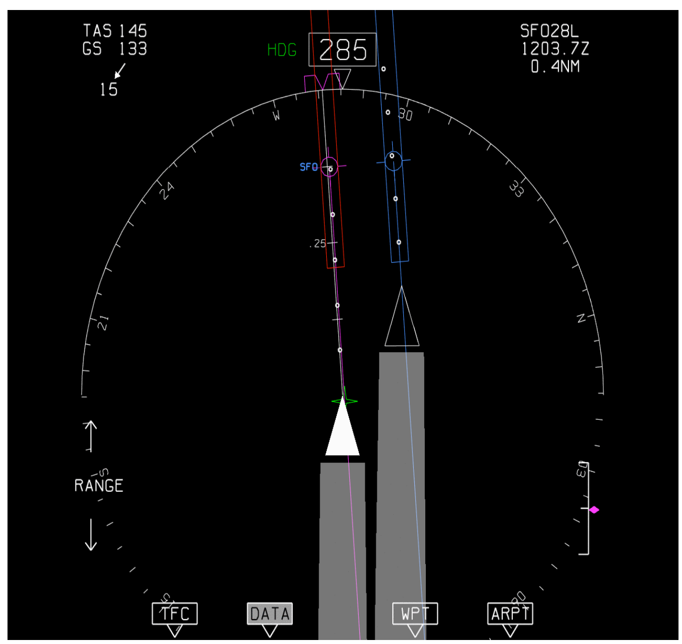


Figure 2. Typical CDTWI for the Approach of Two Conventional (B747) Aircraft to Runways 28L/28R at SFO

the open icon approaching runway 28R. Five two second position predictor circles and the wakes are shown for each aircraft. A 15 kt right quartering crosswind is shown in the upper left of the display which causes the wakes to drift to the left. Figure 3 shows another example of a typical approach for a heavy conventional on a straight in to runway 28R with a heavy RIA on a downwind approach for 28L. It was assumed that the wake of a heavy RIA could be hazardous for a heavy conventional. A short turn-in and rollout onto final at 500 feet altitude (about 1.5NM for a three degree approach) was used by the RIA to minimize the exposure to traffic and wakes. The RIA is at 140 knots on downwind and decelerates to 70 knots at rollout for the three degree final approach. The three degree glide slope capture from the 1500 foot level downwind is shown approximately abeam the runway threshold. The downwind leg abeam distance (one NM for this example) was chosen to give a small roll angle (approximately 5 degrees) at the 70 kt rollout onto final such that a go-around to the left can still be easily accomplished. The CTOL is on a three degree final from 1500 feet at 140 knots. The CTOL is shown in amber in Fig.3, as his lateral deviation is more than one dot (120 feet at this point in the approach) to the left of the desired path.

More details on the displays will be given later. The paths flown by the two aircraft and the procedures used are:

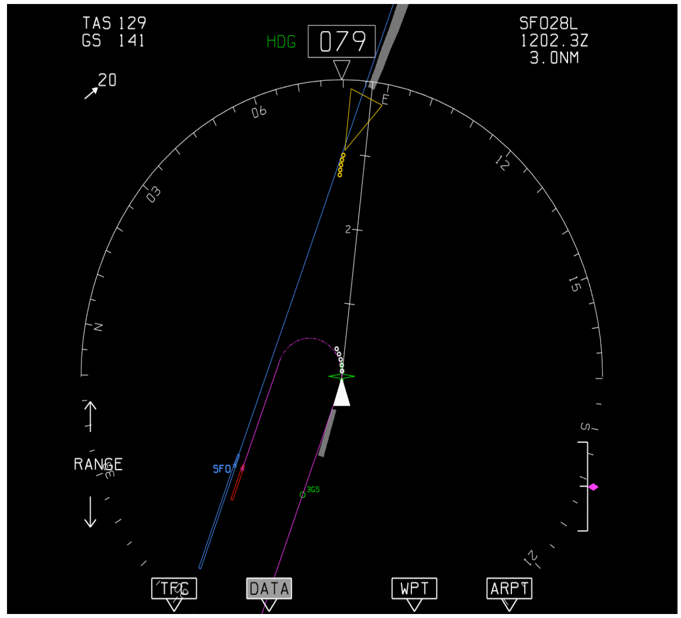


Figure 3. Profile Used for a CSPA of a B747 Class Aircraft on a Straight-in and a Heavy RIA on a Downwind Approach

1. En-route and terminal area traffic control pair the two aircraft, Ownship and Traffic, as they enter the terminal area and space them such that at some point in the approach, the separation and wake avoidance responsibility will be turned over to the Ownship.
2. Terminal control calculates (with backwards integration) an airspeed profile for both aircraft for a prescribed lateral path and a prescribed altitude profile using predicted winds, wake characteristics, and nominal approach airspeeds. Figure 4 shows an example of these profiles for the two aircraft. Ownship is at 140 kt equivalent airspeed, Ve, on the downwind and decelerates at one kt/sec to rollout on final at 70 kt. The traffic aircraft is at 240 kts and decelerates at one kt/sec to capture the glide slope at 140 kts. For this example, both aircraft captured the three degree glide slope at 1500 feet.
3. The respective lateral paths and the altitude and airspeed profiles are then data-linked to the two aircraft. A profile of separation distance on the Traffic aircraft is also data-linked to Ownship. This is obtained from the distance profiles for the two aircraft from the backwards integration in step 2 which are shown in Fig. 5. Distance to Glide-Slope Intercept, GSI, is the distance to the point where the nominal glide-slope intercepts the runway surface. Figure 6 shows the nominal difference in distance from the profiles shown in Fig. 5. For aircraft with different approach speeds this profile is not a constant distance.
4. The lead, or Traffic aircraft, accepts his clearance and follows the altitude and airspeed profile as data-linked.
5. Ownship accepts his clearance and assumes separation responsibility on the Traffic aircraft.
6. Ownship uses the data-linked lateral and vertical profile to generate pursuit display information[21] on the PFD for lateral and vertical separation. Figure 7 shows an example of Ownship's PFD. The PFD was patterned after conventional CTOL PFDs with the exception of the flight path centered symbology in the central area of the display. A flight path marker (white with large open center) is used in conjunction with the leader (green perspective delta winged aircraft with small circular tailpipe) for pursuit guidance. The leader is flying a perfect trajectory T seconds ahead of Ownship. The pilot's task is to place the flight path marker on the

Figure 4. Nominal Equivalent Airspeed Profiles

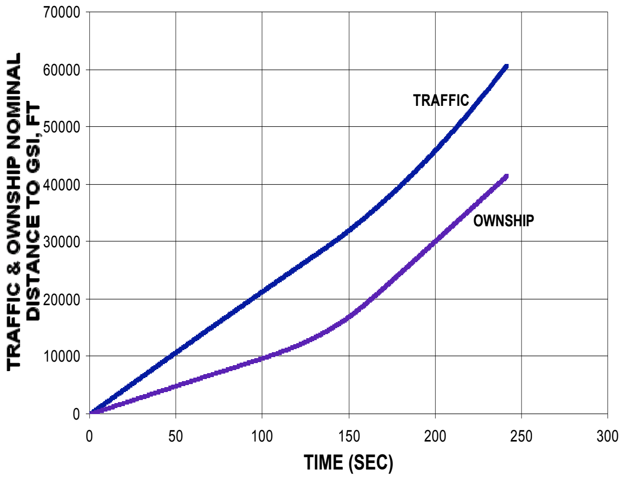


Figure 5. Nominal Distance Profiles From the Backwards Integration

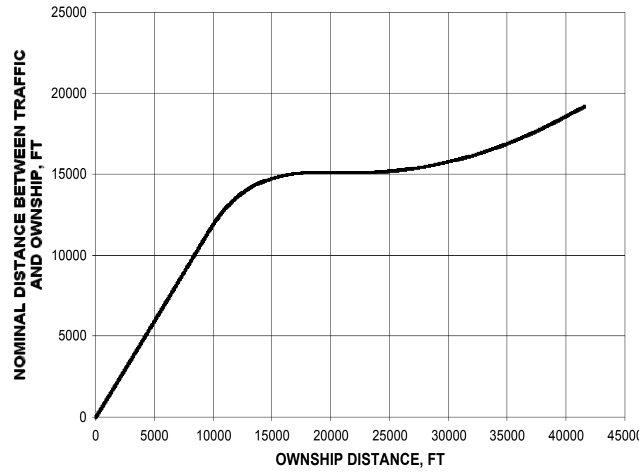


Figure 6. Nominal Distance Between Traffic and Ownship

leader. This will converge his path on the desired trajectory exponentially with a time constant of T seconds. An airspeed rate caret and an airspeed error tape are shown on the left wing of the flight path marker. Power and pitch commands are shown with the bicycle grip handle on the left wing for power and the pitch caret off the right wing of the flight path marker.

7. Ownship uses data-linked actual Traffic location to control to the specified along-track separation distance, shown in Fig. 6, using the airspeed and command information on the PFD shown in Fig. 7. This compensates for errors in the predicted wind, Traffic aircraft speed errors, and errors in the data-linked profiles, and provides the desired wake separation. The algorithm used for commanded speed was:

$$V_C = V_{NOMINAL} - \frac{1}{\tau_D}\left(\Delta S_{ACTUAL} - \Delta S_{NOMINAL}\right) \quad (1)$$

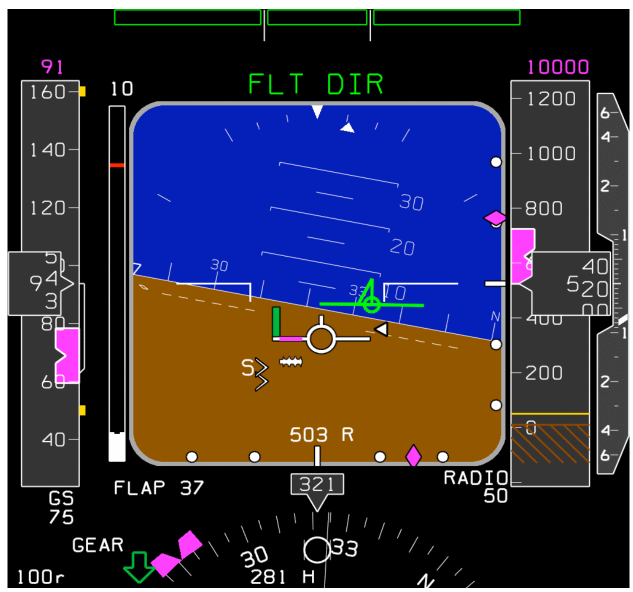


Figure 7. Typical Primary Flight Display for a Runway Independent Aircraft on Final Approach

where ΔS_{ACTUAL} is the separation distance based on actual Traffic location with respect to Ownship and $\Delta S_{NOMINAL}$ is the up-linked value in Ownship's clearance (Fig. 6). τ_D is the approximate convergence time constant for distance errors. A value of 60 seconds was used.

8. Both Ownship and Traffic use their NAV display to monitor separation and wakes. This procedure helps eliminate the dispersion tails on lateral separation and also supports wake avoidance by the crew if necessary.

As can be seen, there are two critical problems in solving the CSPA problem in instrument conditions, traffic separation and wake avoidance. Typical traffic profiles flown have been shown in Figs. 2 and 3. A brief description of the vehicle simulated will be given next followed by a discussion of traffic separation and then details on wake avoidance.

III. Vehicle Simulated

An existing simulation of a Civil Tilt Rotor[21] was used as the simulated vehicle. It was a vehicle with a 50,000 pound gross weight, 250KT cruise speed, and the capability of tilting the thrust vector (rotors) through 90 degrees. The CTOL Traffic aircraft was simulated with the thrust vector at zero degrees (aligned with respect to the fuselage) which gave conventional aircraft flight characteristics. The RIA Ownships were simulated with the thrust vector at 80 degrees from the fuselage centerline giving powered lift aircraft flight characteristics. For the calculation of wake characteristics discussed later, it was assumed the heavy conventional aircraft had a 200 ft wingspan and approach weight of 450,000 pounds. The heavy RIA was assumed to have a 100 ft wingspan and an approach weight of 100,000 pounds.

The CTOL Traffic trajectories were flown first on the simulation and then stored. During the simulated RIA Ownship flights, the stored Traffic flights were then used to simulate the Traffic. The stored Traffic flights had small intentional path and speed deviations.

The control system used was Rate Command/Attitude Hold in the pitch and roll axes with yaw turn coordination.

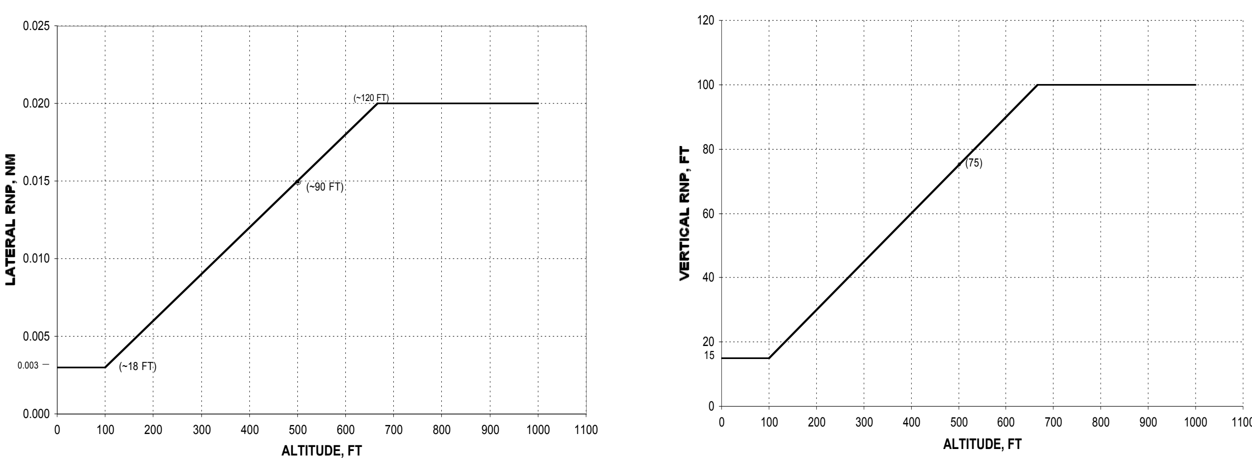
IV. Lateral Traffic Separation

Recommendations from the FAA's Advisory Circular AC120-29A[20] addressing Category I and II weather minima for approach, and Advisory Circular AC120-28D[19] addressing Category III weather minima for takeoff, landing, and approach, were used to construct bounds on lateral and vertical error. These documents specify RNP Levels for various phases of approach, Initial, Intermediate, and Final.

The concept of RNP specifies the performance of the system to maintain the aircraft within a defined boundary 95% of the time. This 95% value is defined by the FAA to be 1xRNP. A value of 2xRNP is termed the containment limit.

The errors were displayed to the pilot as deflections of the lateral deviation indicator (LDI) and vertical deviation indicator (VDI). The LDI and VDI are shown on the PFD of Fig. 7 as the magenta diamonds on the bottom and right edges of the PFD. The PFD LDI/VDI scaling used was 1xRNP corresponding to one-dot, and 2xRNP "containment" corresponding to two-dots. The 1xRNP values are shown in Fig. 8. RNP values used at 100 ft altitude and below were 0.003 NM (18 ft) laterally and 15 ft vertically. FAA Advisory Circular AC120-29A suggests that these values support Category I/II/III minima. Based on experience with this display format in the civil tilt rotor simulation reported by the author[21], values for RNP for the initial approach segment of the profile were selected to be 0.02 NM (120 ft) laterally and 100 ft vertically. These values are tighter than the AC120-29A Initial/Baro-Vertical approach RNP Levels. These values were held constant above 667 feet. Between 100 ft and 667 ft the RNP values were proportional to altitude.

From Fig. 8, the value of lateral 1xRNP on the Closely Spaced Parallel Approach is 0.015NM (90 feet) at the 500 ft altitude rollout point. If we assume 3xRNP containment for each aircraft and a 750 ft runway separation, there are 210 feet left over for the sum of wing semi-spans (approximately the B747 wingspan). For Gaussian distribution, 3xRNP gives a probability of being more than 270 feet towards the other runway for each aircraft of about $2x10^{-9}$. The joint probability of both aircraft being off laterally towards the other runway more than 270 feet at the same distance from touchdown (GSI) and at the same time is much less than 10^{-9}. With a good display of



a), Lateral b), Vertical

Figure 8. One-Dot (1xRNP) Values

traffic information and rigid two pilot cockpit procedures, manually controlled errors should have shorter dispersion tails than Gaussian distributions. With this level of confidence in cross-track protection, it is believed that specific blunder protection algorithms to provide protection from the other aircraft may not be necessary.

V. Wake Prediction Algorithms

The wake prediction algorithms of Reference 15, predicted winds, and aircraft characteristics were used for predicting wake position. These wake predictions were used by traffic control for generating the up-linked clearance trajectories and also in real time for the NAV display wake depiction. They are shown on the NAV display for two example scenarios in Figs. 2 and 3. If the center of gravity, c.g., of the Ownship (apex of the solid triangle) in Fig.2, for example, is kept out of the wake area for the Traffic, then Ownship has a high probability of not encountering any hazardous wake-vortex-induced rolling moments. From Ref. 15, if the wing span, b_f, of the following aircraft is less than 0.5 the wingspan, b_g, of the lead or generating aircraft, the initial width of the lead's hazardous wake area is twice its wingspan. If $b_f / b_g \geq 0.5$, the initial wake width, B_g, of the generating aircraft is:

$$B_g = \left[2 + \left(b_f / b_g - 0.5\right)\right] b_g \tag{2}$$

Since both heavy CTOL aircraft in Fig. 2 were assumed to have wingspans of 200 feet, the initial width of both wakes is 500 feet. The aircraft icon wingspan was kept proportional to the actual wingspans, but was constant for all map scales. At the 0.25NM range scale of Fig. 2 the icon wingspan is twice that of the actual aircraft or 400 feet.

For large times behind the wake generating aircraft, the wake expands as:

$$B_g = 0.5 b_g \sqrt{t} \tag{3}$$

where t is time in seconds behind the generating aircraft. For the example of Fig. 2, the time-dependent wake characteristic is smaller than the initial constant width characteristic for $t < 25$ seconds. In addition, the lateral spread of both wake segments is increased by an amount equal to the ability to predict the wind, and this accounts for the slight spread in the wakes seen in the Fig. 2. A value of two knots was assumed for the uncertainty in wind prediction for two aircraft on Closely Spaced Parallel Approaches. Once the upper boundary of the hazardous area of the wake of the generating aircraft has drifted down below the following aircraft, the wake was no longer shown on the NAV display. Vertical spread of the wake was predicted[15] similar to the lateral and its sink rate, w, was calculated[16] using:

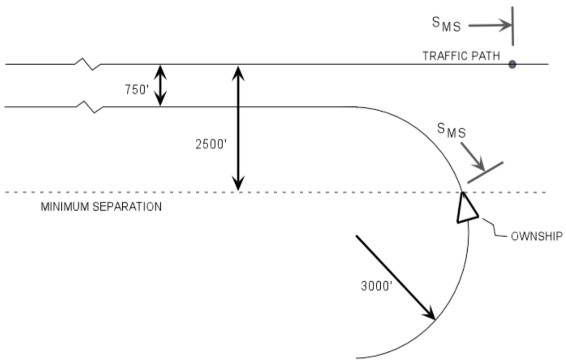
$$w = \frac{W}{2\pi\rho V b'^2} \tag{4}$$

where W is the aircraft weight, ρ is air density, V is free-stream airspeed, and b' is the effective vortex span.

VI. Approach Scenarios

A. Traffic Spacing with Different Approach Speeds

Once a means for the prediction of the wake locations is assumed, algorithms for optimal along-track spacing for achieving maximum dual runway airport acceptance rates for a mix of light RIA, heavy RIA, and conventional aircraft can be determined. Figure 9 shows the geometry for a typical scenario at the start of the CSPA where the Ownship's separation on the Traffic aircraft's wake on base turn first goes below the minimum lateral runway separation allowable for unrestricted operation. The current value[22] of 2500 feet was used. S_{MS} is the distance to the initial point (start of the CSPA) for this minimum separation for Ownship (distance measured from GSI). The Traffic aircraft is assumed to first encounter the point for minimum separation on Ownship's wake at the same distance, S_{MS}, as shown in Fig. 9. Figure 10 conceptually shows the distance to GSI time histories for two pair of



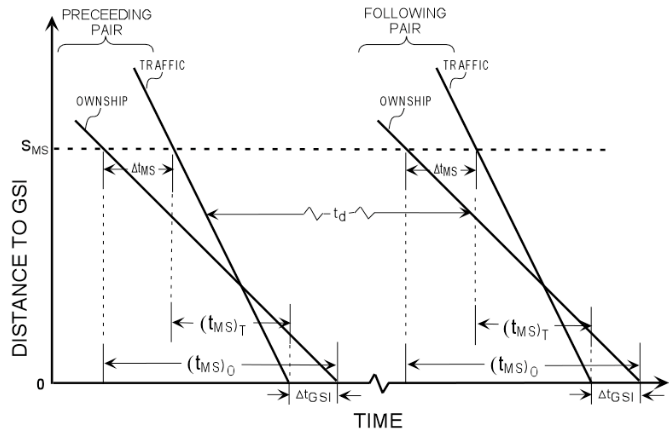


Figure 9. Ownship First Encounters the 2500 Foot Minimum Runway Separation on Traffic

Figure 10. Spacing for Traffic Pairs

aircraft on Closely Spaced Parallel Approaches. Each pair has a high speed Traffic (CTOL) and a lower speed Ownship (RIA). The abscissa is time (increasing to the right) with the difference in GSI arrival times, Δt_{GSI}, and the difference in times, Δt_{MS}, for first going below the allowable lateral runway separation needed for unrestricted operation at distance S_{MS} shown. Since distance is measured from the GSI, the slopes (velocities) in Fig. 10 are negative for approach. Each aircraft in the following pair must have enough time separation from either aircraft in the preceding pair for their wakes to dissipate. This separation time, t_d (minimum of 2-3 minutes[15]), is shown at a typical distance in Fig. 10. For the scenario shown, the Traffic aircraft passes Ownship on the final approach. It can be seen that the following Ownship aircraft has minimum time separation on the preceding Traffic at S_{MS} and the following Traffic has minimum time separation on the preceding Ownship at GSI. From Fig. 10 it can also be seen that for a given value of t_d, the time interval between successive Traffics to runway 28R or successive Ownships to runway 28L is the larger of $t_d + \Delta t_{GSI}$ or $t_d + \Delta t_{MS}$. From either pair of aircraft in Fig.10:

$$\Delta t_{GSI} + \Delta t_{MS} = \left(t_{MS}\right)_O - \left(t_{MS}\right)_T \tag{5}$$

where $\left(t_{MS}\right)_{O,T}$ are the times for Ownship, Traffic to travel from the initial wake minimum separation point, S_{MS}, to GSI. From the geometry in Fig. 10, the minimum extra separation time, t_E, over the time for wake dissipation, t_d, for aircraft pairs with different speeds occurs when $\Delta t_{GSI} = \Delta t_{MS} = t_E$. This of course gives the maximum airport acceptance rates. From Eq. (5) then, the minimum extra time between pairs of aircraft with different approach speeds is:

$$t_E = \frac{\left(t_{MS}\right)_O - \left(t_{MS}\right)_T}{2} \tag{6}$$

which becomes zero for aircraft with the same approach speeds (or times). This does require that the faster aircraft pass the slower on final approach. For a typical no-wind example of Traffic at 140 knots and Ownship at 70 knots and a distance, S_{MS}, of 12964 feet (for a 3000 foot base turn radius), $t_E = 27.4$ seconds. For this example and a typical minimum time, t_d, for wake dissipation of two minutes, gives an acceptance rate for two runways of 48.8 aircraft per hour versus 60 per hour for aircraft with equal speeds on two runways or 30 per hour for single runway IMC operation. Again for this example from Fig. 10, Ownship is 27.4 seconds ahead of Traffic at the initial wake minimum separation point, S_{MS}, and 27.4 seconds behind at GSI. If a significant crosswind is present, this could allow Ownship's wake to drift onto Traffic at the initial wake minimum separation point or the Traffic wake to drift onto Ownship at GSI. For these cases, different procedures are required and these are discussed next.

1. Right Cross-Wind

For a very strong right cross-wind, or for complete Ownship wake protection, if both aircraft arrive at the GSI at the same time ($\Delta t_{GS} = 0$ in Fig. 10) the Traffic aircraft in each pair will always be behind its paired Ownship. This gives the Ownship complete wake protection, and Ownship's wake is not a factor for Traffic because of the right crosswind. Figure 11 shows the NAV display for an example of this scenario with a 10KT right crosswind component. From Fig. 10, this doubles the time penalty, t_E, between paired aircraft and reduces the two runway acceptance rate to 41.2 per hour.

To help alleviate this penalty, we can let the Traffic pass on final such that Ownship is following Traffic at GSI. For a right crosswind, the Traffic's wake will drift toward Ownship with the critical point being as Ownship approaches the GSI with the Traffic ahead on the rollout. It is assumed that the Traffic's wake is no longer generated after touchdown and Ownship must therefore be close enough to the Traffic such that Traffic's wake at touchdown (GSI) doesn't drift onto Ownship as it approaches GSI. The trajectory clearances that are up-linked to both aircraft predict the wake drift and space the aircraft appropriately. To determine, for this case, the maximum time that Ownship can safely follow the Traffic at GSI, a worst case was assumed with both Traffic and Ownship 2xRNP (36 feet each from Fig.8) lateral error towards each other approaching GSI. For a 10 KT right crosswind, zero headwind, and a 2 KT wind measurement error allowance example, the maximum time, Δt_{GS}, a RIA Ownship can follow the heavy CTOL Traffic without encountering the Traffic's hazardous wake area is 21.9 seconds. This is less than the 27.4 seconds for equal Δt_{GSI} and Δt_{MS} from the earlier light crosswind example and from Eq. (5), $t_E = 32.9$ and the two runway acceptance rate reduces to 47.1 per hour. This is a small penalty over the 48.8 per hour for light cross-winds. Figure 12 shows the NAV display for this example, and it can be seen that Ownship's c.g. is well clear of the Traffic's hazardous wake area. It was assumed that Ownship has the present local winds, the Traffic's size, weight, and position history such that Traffic's wake location can be predicted in real time using the algorithms given earlier. This allows the Ownship to monitor the Traffic wake to accommodate any unforecast deviations in winds or flight paths from those predicted.

Figure 11. Heavy RIA/Heavy Conventional Approaching Touchdown with Complete Wake Protection for a Right Crosswind

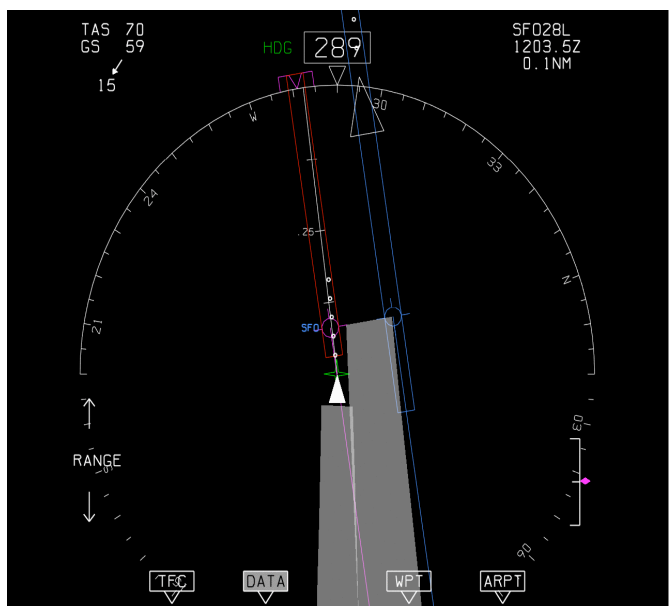


Figure 12. Heavy RIA Approaching GSI after Being Overtaken by a Heavy Conventional on Final with a 10KT Cross-Wind Component

2. Left Cross-Wind

For a very strong left cross-wind, or for complete Traffic wake protection, if both aircraft arrive at the distance, S_{MS}, for the start of the CSPA at the same time ($\Delta t_{MS} = 0$ in Fig. 10) the Ownship aircraft in each pair will always be behind its paired Traffic. This gives Traffic complete wake protection and Traffic's wake is not a factor for Ownship because of the left crosswind. From Fig. 10, this again doubles the time penalty, t_E, between paired aircraft and reduces the two runway acceptance rate to 41.2 per hour.

To help alleviate this penalty, we can let the Traffic pass on final such that Traffic is following Ownship at the initiation of the CSPA. For a left crosswind, Ownship's wake will drift toward Traffic with the critical point being when Traffic approaches the distance where Ownship starts final, S_F, as for larger Ownship distances (as seen in Fig. 9), the lateral distance for the wake to drift is greater. This would not be true for large crosswinds but is an acceptable assumption for reasonable crosswinds. Traffic must therefore be close enough to the Ownship such that Ownship's wake doesn't drift onto Traffic as Traffic approaches S_F. The up-linked trajectory clearances predict the wake drift and space the aircraft appropriately. To determine, for this case, the maximum time that Traffic can safely follow Ownship at S_F, a worst case was assumed with both Traffic and Ownship 2xRNP (180 feet each from Fig.8 for a 500 foot altitude) lateral error towards each other. For a 10 KT left crosswind, zero headwind, and a 2 KT wind measurement error allowance example, the maximum time, Δt_F, a heavy CTOL Traffic can follow a heavy RIA Ownship at the start of Ownship's final without encountering Ownship's hazardous wake area is 10.6 seconds. The start of a final from 500 feet altitude and for a three degree glide-slope is a distance, S_F, of 9541 feet. For the no headwind example with $\Delta t_F = 10.6$ seconds, this gives a time, Δt_{MS}, of 25.0 seconds at $S_{MS} = 12964$ feet. This is less than 27.4 seconds for equal Δt_{GSI} and Δt_{MS} for the light crosswind example and from Eq. (5), $t_E = 29.8$, and the two runway acceptance rate goes to 48.1 per hour. Again, this is a small penalty over the 48.8 per hour for light cross-winds. Figure 13 shows the NAV display for this example and it can be seen that Traffic's c.g. is well clear of Ownship's hazardous wake area. It was assumed that Traffic has the present local winds, Ownship size, weight, and position history such that Ownship's wake location can be predicted in real time using the algorithms given earlier. This allows the Traffic to monitor the Ownship wake to accommodate any unforecast deviations in winds or flight paths from those predicted.

Figure 13. Heavy RIA/Conventional at Start of CSPA with a 10 KT Left Crosswind

3. Summary for Different Approach Speeds

For aircraft with different approach speeds and the approach scenarios considered so far for the development of the spacing algorithms, the results are summarized in Fig. 14. Again the examples considered had zero headwind, 70KT RIA final approach speed, 140KT CTOL final approach speed, 120 second wake dissipation time, 2KT wind measurement uncertainty, and the CTOL Traffic was allowed to pass the RIA Ownship on final. For varying winds and varying approach speeds, the distance profiles from the backward integration (Fig. 5) need to be used for determining the predicted allowable separation times but the procedure is similar. An example for the nominal right crosswind spacing scenario is shown in Fig. 15.

The results show that even when there is a factor of two difference in approach speeds (and times on approach), a large percentage of the VMC airport acceptance rate for identical approach speeds can be recovered in IMC conditions. Although not shown in Fig. 14, for the strong crosswind cases discussed earlier with complete wake protection (no passing on final) the airport acceptance rate is 41.2 aircraft per hour. This is almost 70% of the VMC rate and is a significant improvement over the present day 50% IMC rate. As mentioned earlier, for equal approach speeds there is no airport acceptance rate penalty in IMC conditions.

B. Additional Nominal Approach Scenarios

In addition to the approach scenarios discussed previously, two additional nominal scenarios were examined. Light RIA/Heavy Conventional and Two Heavy Conventionals. These are discussed next.

1. Light RIA / Heavy Conventional

Figure 16 shows the NAV display for this scenario. The light STOL RIA is on a six degree approach with the heavy conventional on a three degree approach. It was assumed that the wake of the light RIA has a negligible effect on the heavy conventional. If the light RIA is kept ahead of the heavy conventional (both assumed to land at the same time in Fig.16) and is above the heavy conventional wake, there is wake protection for the light RIA. Since both aircraft have wake protection and can touch down at the same time, there is no time penalty on the presently used VMC airport acceptance rate.

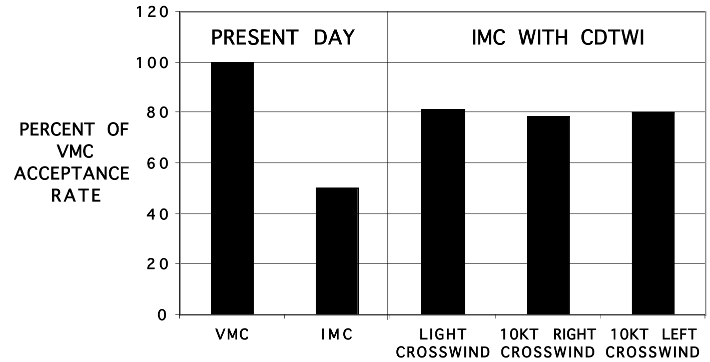


Figure 14. Example Airport Acceptance Rates for Aircraft with Different Approach Speeds

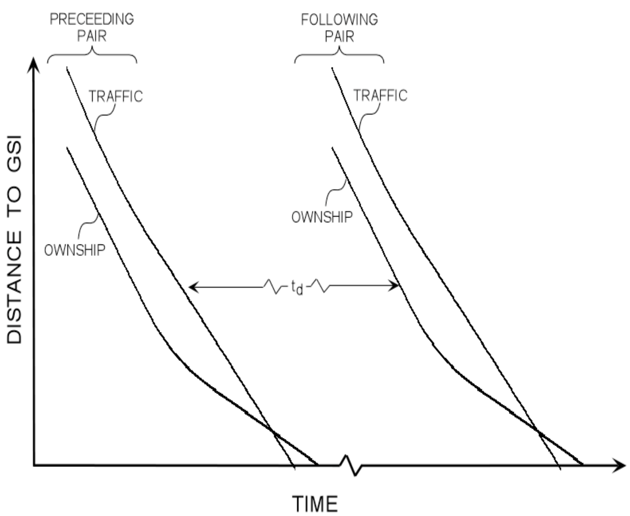


Figure 15. Backwards Integration Distance Profiles for the Nominal Right Crosswind Scenario

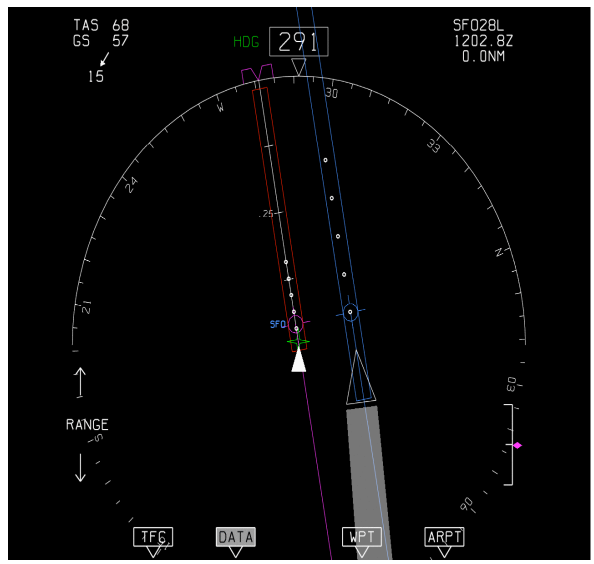


Figure 16. Light RIA/Heavy Conventional Aircraft Approaching Touchdown on Runways 28L/28R

2. Two Heavy Conventionals

Figure 2 shows the NAV display for this scenario. Both heavy conventionals are on a three degree approach. The Ownship conventional aircraft approaching runway 28L maintains a distance profile equivalent to a constant time interval (five seconds was used) on the conventional aircraft Traffic approaching runway 28R. This procedure is very similar to the present VMC procedure and therefore has no airport acceptance rate penalty.

C. Approach Scenarios with Abuses

Four Heavy RIA / Heavy Conventional abuse case scenarios were also flown: Right Crosswind with Error, Head Wind Error, Traffic Fast, and Traffic 0.5 NM Initial Position Error. These are discussed next.

1. Heavy RIA / Heavy Conventional - Right Crosswind with +5 KT Error

For the scenario shown in Fig. 12, "Heavy RIA Approaching GSI after Being Overtaken by a Heavy Conventional on Final with a 10KT Cross-Wind Component", the actual wind was the same 10KT as used in predicting the longitudinal spacing. If the actual crosswind component is significantly larger and the spacing is not adjusted, then Ownship may have a conflict with the Traffic wake approaching GSI. Figs. 17-19 show the NAV display for this case where the crosswind component was 5KT (15KT total) greater than that used in calculating the longitudinal spacing. Figure 17 shows the Traffic aircraft about to pass Ownship at about 0.8NM on final. Traffic's large wake drift angle can be seen and alerts Ownship that he may have to abandon the approach. Figure 18 shows the situation with Ownship at 0.2NM on final and Traffic on the rollout. The Traffic wake color has changed to amber as the c.g. of Ownship is less than 100 feet from the hazardous wake area and Ownship should consider a go-around. When Ownship's c.g. entered the Traffic wake, it turned red. Figure 19 shows Ownship on a go-around. Since no specific go-around guidance was provided for this phase of the study, Ownship's icon has turned red in color to indicate that he is more than 2xRNP off his desired approach path.

2. *Heavy RIA / Heavy Conventional - Head Wind Error, Traffic Fast Error, and Traffic Initial Position Error*

A -5KT headwind error, Traffic fast +10Kt, and Traffic 0.5 NM initial position error on downwind abuses were also examined. No lateral position or wake problems were encountered for any of these abuses and after correcting for the Traffic's initial position error, only minor longitudinal spacing errors were experienced.

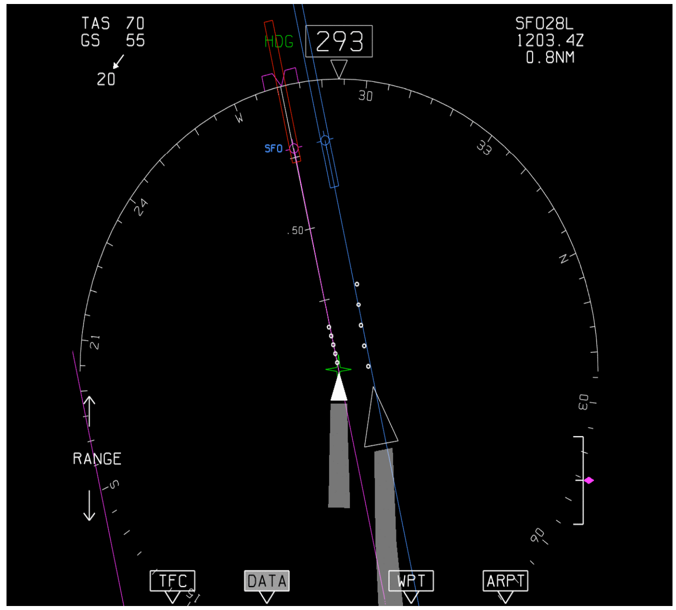


Figure 17. Heavy RIA/Conventional Approaching with a 15 KT (versus 10 KT Predicted) Right Crosswind - 0.8 NM on Final

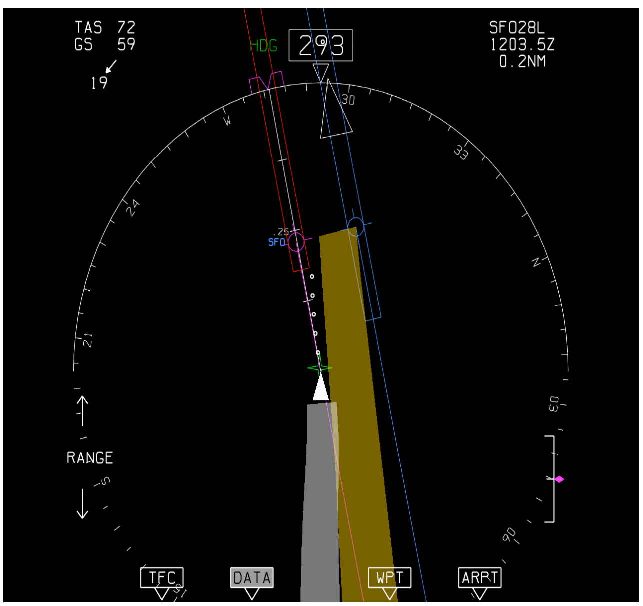


Figure 18. Heavy RIA/Conventional Approaching with a 15 KT Right Crosswind - 0.2 NM on Final

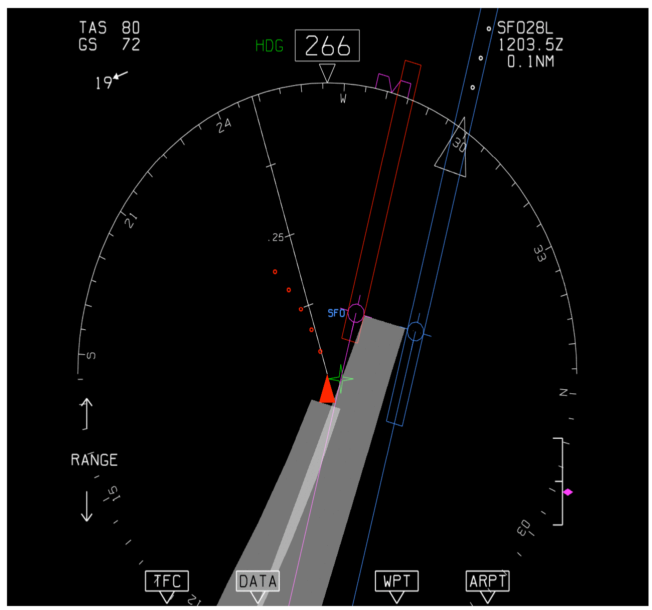


Figure 19. Heavy RIA/Conventional Approaching with a 15 KT Right Crosswind - RIA Executing a Go-Around

VII. Performance Summaries

Three NASA Research pilots with extensive experience in both heavy fixed wing and powered lift vehicles including helicopters and tilt rotors evaluated five of the Heavy RIA/Heavy Conventional approach scenarios with differing approach speeds in order to obtain a representative set of performance data. The nominal left crosswind, the nominal right crosswind, unpredicted head wind error, Heavy Conventional Traffic flies faster than cleared, and the Traffic aircraft having a 0.5NM initial position error scenarios were flown for data. The remaining scenarios were demonstrated to all three pilots for comments but were not included in the data shown below. In addition to the head winds and crosswinds in the various scenarios flown, turbulence (2.5 fps RMS) was simulated for all scenarios.

A. Lateral Errors

Figure 20 shows the lateral Flight Technical Error, FTE, for these five scenarios and the three pilots. The allowable 1xRNP TSE (one dot from Fig. 8) and the actual FTE are shown. For reference, the mean and the absolute value of the mean + two times the standard deviation are also shown. From Ref. 20, the difference between the desired flight path and the actual flight path, TSE, is the sum of the path definition error, navigation system error, and FTE (including any display error). FTE is the accuracy with which the aircraft is controlled as measured by the indicated aircraft position on the display with respect to the indicated command. The path definition and display errors were assumed to be zero for this system. Moralez, et al.[23], has shown, in flight, that with GPS navigation and a suitable Local Area Augmentation System, LAAS, the navigation system error is small compared to the FTE. His means and standard deviations of the lateral and vertical navigation system errors were less than one foot. The along track values were on the order of five feet. Navigation system errors were not simulated for the present study and it was assumed that FTE was a good approximation to TSE. It can be seen from Fig. 20 that the FTE is significantly less than that required. The only significant deviation from the desired path occurred at the base turn initiation where, because of a fairly abrupt turn entry, the pilots tended to overshoot to the outside of the turn slightly with a mean of about 40 feet. Especially on final where lateral separation for the CSPA is important, the FTE cross-track error at roll out onto final is less than 30 feet, and reducing to about 10 feet approaching minimums.

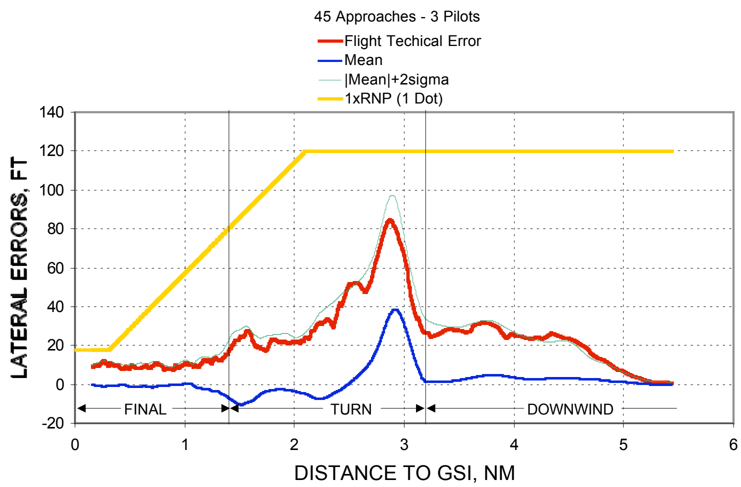


Figure 20. Lateral Errors

The calculation of FTE (performance error less than this value 95% of the time) is a little cumbersome. A sorting routine was developed and used for the data shown. Some approximations to FTE using standard statistical measures were tried, and a reasonable approximation for the data analyzed was found to be the absolute value of the mean + two times the standard deviation as shown in Fig. 20.

B. Vertical Errors

Figure 21 shows the vertical FTE for these five scenarios and the three pilots. The allowable 1xRNP TSE (one dot from Fig. 8) and the actual FTE are shown. Again it can be seen that the FTE is well below the 1 dot required value. On the downwind and base segments, FTE is about 30 feet, and on final approaching minimums it is about 10 feet

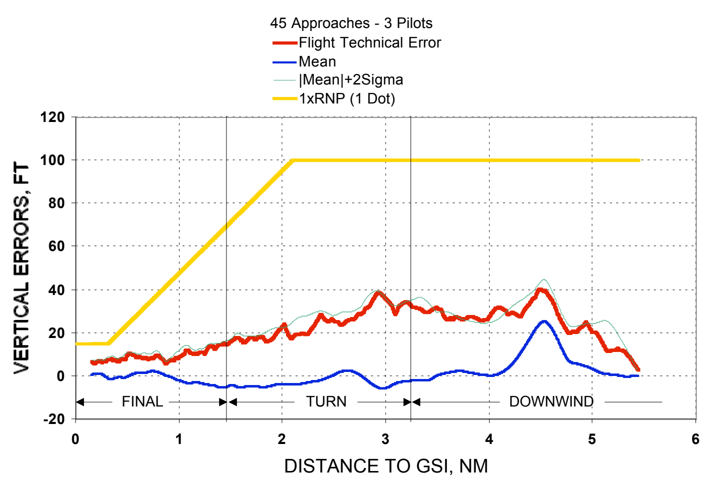


Figure 21. Vertical Errors

C. Longitudinal Errors

Figure 22 shows the longitudinal distance FTE for these five scenarios and the three pilots. No allowable 1xRNP TSE was specified. The FTE is shown. Since the initial 0.5NM position error abuse scenario for the Traffic was included in these data, the FTE is close to the 0.5NM initial position error at the start of the downwind portion of the flights. This initial position error was nulled out by the base turn and it can be seen that the FTE is about 500 feet rolling out on final and stabilized at about 250 feet on final. While this was acceptable performance, it is felt that it can be improved.

Figure 23 shows the airspeed FTE for these five scenarios and the three pilots. It can be seen that during the base turn and rolling out on final, large deviations in the actual airspeed from that commanded by Eq. (1) are evident. Since the commanded airspeed from Eq. (1) only includes distance error, it is felt that the addition of wind prediction errors and Traffic aircraft airspeed errors to Eq. (1) may improve airspeed performance and decrease the distance errors.

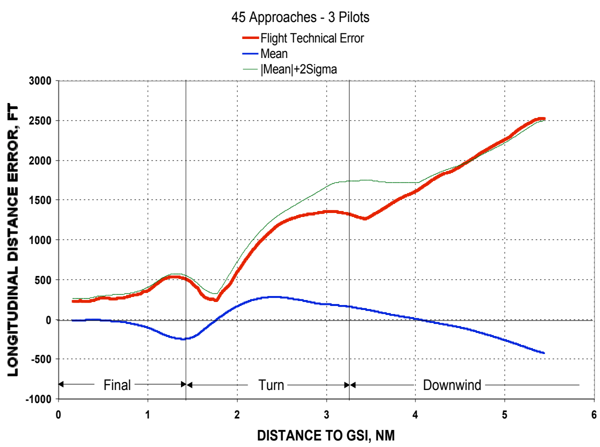


Figure 22. Longitudinal Distance Errors

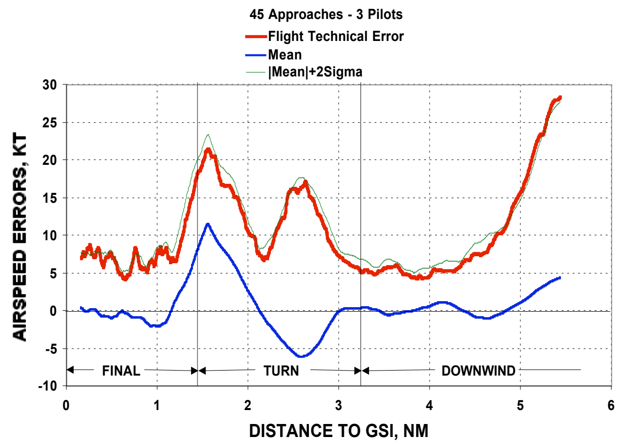


Figure 23. Airspeed Errors

VIII. Pilot Ratings

Figure 24 shows a summary of the pilot ratings for the five scenarios and the three pilots. The Cooper-Harper Pilot Rating Scale[24] for handling qualities was used. A pilot rating of 3.5 is the boundary between satisfactory and adequate. Satisfactory lateral and vertical performance was specified as less than one dot deviation (Fig. 8). No numeric value was specified for satisfactory longitudinal performance. As long as the traffic and wake situation on the NAV display were acceptable, the pilots considered their performance satisfactory. For the approach scenarios used for data, the closest approach to traffic was 644 feet and the closest approach to a wake was 21 feet. From Fig. 24, the lateral and longitudinal handling characteristics on the downwind and the longitudinal characteristics on final were generally satisfactory with the others being borderline satisfactory/adequate. The pilots generally felt the base turn entry was too abrupt and that the flight director was a little active. They also felt that while the NAV display gave good situational information, the workload in tracking the desired flight path using the PFD didn't allow them time to adequately monitor the NAV display. As mechanized for this simulation, they felt it would definitely be a two pilot task. The level of monitoring required was similar to that required for manually flown Cat IIIA approaches.

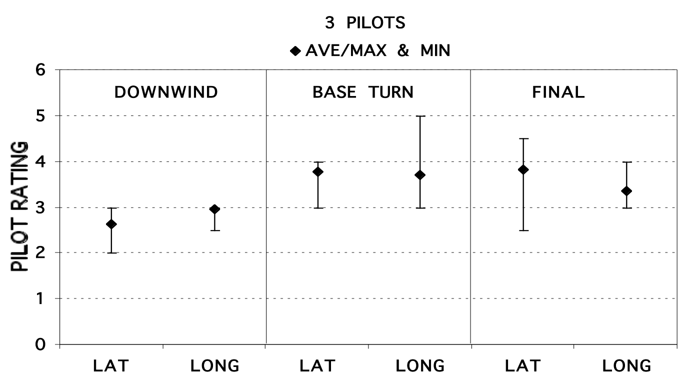


Figure 24. Pilot Ratings for Three Approach Segments

IX. Conclusions

The results of this preliminary study showed that the proposed concept for CSPA under instrument conditions is feasible. Further simulation and eventually flight verification are warranted.

1. The study showed that maintaining lateral traffic separation within the proposed RNP limits was possible and a fairly easy task for the pilot to accomplish. The actual lateral FTE value on final, where exposure to other traffic occurs, was on the order of 10 feet. It was shown that an allowable value of 90 feet provided lateral traffic protection much better than 10^{-9}. It is felt that with this level of protection, specific blunder prediction mechanisms may not be needed.
2. The longitudinal spacing concepts developed provided protection from wakes. For aircraft with different approach speeds, a small penalty in airport acceptance rates compared to present VMC operation was necessary. If larger penalties in airport acceptance rates for these aircraft are acceptable (or for initial operation), almost complete wake protection can be provided. For a mix of light STOL and heavy conventional aircraft and for aircraft with the same approach speeds, no penalty in airport acceptance rates during IMC is necessary compared to present VMC operation while still having almost complete wake protection.
3. The display of traffic and wakes on the NAV display provided good situational information. This allowed the flight crew to monitor the traffic and wake situation for unforecast changes in the wind, traffic airspeed errors, and any errors in the data linked profiles. It also allowed the lateral dispersion errors to be monitored to minimize any lateral dispersions.
4. The lateral and vertical FTE values at decision height (50 feet) were consistent with that required for CAT IIIA[19].
5. The pilots generally felt the concept and proposed system had potential for acceptance and safe implementation. With the implementation used for this simulation, it was felt to be a two pilot task to both control to the desired path and to simultaneously monitor the traffic and wake situation on the NAV display.

X. Recommendations

Several areas needing further work are suggested.

1. Continue the wake prediction work of Refs. 14-15. The algorithms in this work were developed for conventional aircraft and need to be extended to powered lift vehicles and helicopters. More flight verification is also needed.
2. Examine the trade-off in airport acceptance rates versus wake protection. For aircraft with different approach speeds, a penalty in airport acceptance rates is necessary. Larger wake protection margins can be provided at the expense of reduced airport acceptance rates.
3. Examine and specify along-track 1xRNP limits that provide a good compromise on required performance and airport acceptance rates.
4. Examine decelerating final approaches for the slower STOL aircraft. Equations (5) and (6) show that the penalty in airport acceptance rates is a function of the difference in times from the point of initial wake concern to touchdown. If the STOL aircraft can decrease his time on final by decelerating to the final STOL approach speed near minimums, the penalty in airport acceptance rates will be reduced.
5. Implement the display of traffic and wake on the Primary Flight Display to give the pilot flying additional traffic and wake awareness. Also incorporate into the PFD additional along track performance limits and situational information.
6. Integrate this CSPA spacing tool into the terminal area arrival control process and examine the impact of go-arounds and incorporate them into the terminal area control process.
7. Perform flight verification of the system.

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