

CASE STUDY OF PAIRED APPROACH PROCEDURE TO CLOSELY SPACED PARALLEL RUNWAYS

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This paper analyzes a new procedure called *paired approach* which has been proposed for use with very closely spaced parallel runways (less than 2500 ft between runway centerlines). The intent of the procedure is to make better use of runways during instrument meteorological conditions. The analysis includes consideration of wake turbulence and collision avoidance. We find that for very closely spaced parallel runways, an angled, offset approach is necessary to simultaneously avoid wake turbulence and collision risk.

INTRODUCTION

In current air-traffic operations in the United States (U.S.), closely spaced parallel runways are used during Visual Meteorological Conditions (VMC) to conduct simultaneous parallel operations under Visual Flight Rules (VFR). However, during Instrument Meteorological Conditions (IMC), Instrument Flight Rules (IFR) must be followed.

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Received April 19, 2000; accepted, July 17, 2000.

Air Traffic Control Quarterly, Vol. 8(3) 223–252 (2000)
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CCC 1064-3818/95/030163-20

Currently, they do not allow simultaneous use of parallel runways when the runways are separated by less than 3000 feet.

The loss of visual approach capability results in a substantial loss of throughput to many airports with very closely spaced parallel runways. At San Francisco International Airport (SFO), for example, runways 28L and 28R are separated by 750 feet. Use of VFR for approaches to runways 28L and 28R allows a typical arrival throughput of approximately 60 landings per hour. During IMC, only a single runway can be used, and the arrival throughput is reduced to 30 landings per hour¹. This loss of throughput can result in significant delays for aircraft intending to arrive at SFO, and can cause backups that affect other airports as well. Recovering some of this lost throughput should be beneficial to the air traffic system.

To address this loss of throughput during IMC, United Airlines has proposed a procedure for dependent approaches into SFO (Stone, 1998). Aircraft would be paired for approach in close longitudinal proximity. Longitudinal separation between paired aircraft would be established and maintained by the use of Automatic Dependent Surveillance Broadcast (ADS-B) combined with a Cockpit Display of Traffic Information (CDTI). The trail aircraft of a pair would be required to maintain specific longitudinal separations through the approach for both wake turbulence and collision avoidance purposes. Longitudinal separation between aircraft pairs would be based on standard IFR separations.

The paired approach procedure should be applicable to other airports besides San Francisco. In particular, MITRE conducted successful human-in-the-loop simulations in the spring of 1999 for the paired approach procedure with controllers from the Seattle-Tacoma International TRACON. Some of the other airports for which the procedure may have applicability include Boston (Logan), Philadelphia International, and Newark International.

The introduction of a paired approach procedure involves the reduction of separation standards. United's suggested longitudinal spacing of the aircraft in a pair (between approximately 1000 and 6000 feet) represents a departure from existing standards for IFR, which currently require these aircraft to be at least 2-1/2 miles-in-trail (MIT) (FAA, 1998). New avionics and cockpit display technologies, such as a CDTI (RTCA, 1997) are required to support the procedure. Elements of the procedure may well be applicable to other new throughput or capacity enhancing procedures, such as station keeping on final approach. As such, it appears that the procedure deserves detailed consideration.

This paper attempts to analyze the feasibility and detailed techni-

¹These figures are based on interviews with San Francisco Terminal Area Approach Control (TRACON) management.

cal requirements of the procedure by examining some basic procedural elements. We find that a range of feasible longitudinal positions exists (a window of longitudinal spacing that supports the procedure), for which a prediction of separation through the approach will be required when each pair begins the procedure. There exist, however, some uncertainties in predicting that an aircraft pair will stay within the window. These uncertainties need further examination in future work.

The paper proceeds with an examination of basic geometrical considerations for the procedure, leading to the establishment of the window of operation. This is followed by establishing the elements of uncertainty involved in successfully projecting that the aircraft pair will stay within the required window, and by an examination of the surveillance requirements for ADS-B to support the procedure. It is concluded that, while further examination is necessary, the procedure may be feasible.

BASIC GEOMETRY OF THE PAIRED APPROACH PROCEDURE

The basic horizontal geometry of the proposed procedure is illustrated in Figure 1. Almost all elements of the procedure, from air traffic control procedures to pilot procedures, are different from those

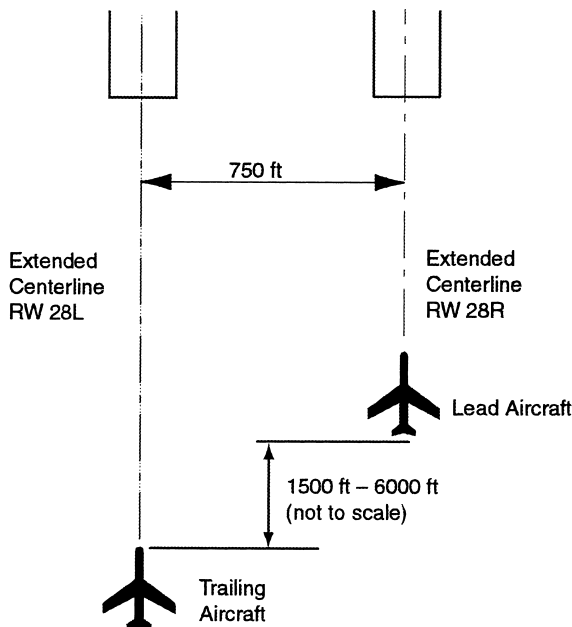


Figure 1. Horizontal Geometry of dependent approach procedure (SFO).

in use today. An aircraft pair will be placed on the approach by Air Traffic Control (ATC), initially separated by 1000 feet vertically and by approximately 1 nautical mile (nmi) horizontally. After stabilization on the localizer, the two aircraft will be cleared for a paired approach. At this point, the pilot of the trail aircraft uses automation tools and display-based cues to space the aircraft at a specified distance from the lead aircraft. The automation tools derive speed cues that are displayed to the pilot to assist in reaching the desired longitudinal spacing. The speed cues are derived by using Automatic Dependent Surveillance Broadcast (ADS-B) (RTCA, 1998a). After the final approach fix, about 5 nmi from the airport, both aircraft are expected to fly the approach without any further adjustments in longitudinal spacing. Note that the spacing between aircraft pairs will be based on standard IFR separation requirements (greater than 2.5 miles-in-trail).

The in-trail spacing of the two aircraft is to be designed such that two factors are addressed. First, the trail aircraft must be far enough behind the lead aircraft that if the lead aircraft blunders², an acceptably small collision risk is presented. Second, the trail aircraft must be close enough to the lead aircraft that there is little risk of the trail aircraft encountering the lead aircraft's wake turbulence³. Outside of the ground effect, the wake turbulence, travelling at the crosswind velocity, limits the time behind the lead aircraft that the trail aircraft can safely fly. Figure 2 attempts to illustrate these two considerations.

There are many constraints in this problem which must be understood in order to analyze the feasibility of the procedure. We will examine the following four technical and geometrical constraints in order to provide an initial evaluation of the feasibility of the procedure:

1. Total System Error (TSE)
2. The compression effect
3. Wake turbulence avoidance requirements
4. Collision avoidance requirements.

Each of these four constraints are examined independently, after which their effects are integrated and conclusions are drawn regarding their interaction.

²A blunder is an unexpected turn toward the other approach course. In past analyses, blunders have been assumed to deviate by up to 30 degrees from the nominal approach course. (RTCA, 1998b).

³The procedure is being designed such that it will safely handle ambient crosswinds to a given unfavorable crosswind limit. Therefore, the wake constraint is designed for this maximum allowable unfavorable crosswind; more benign crosswind conditions will allow for additional wake separation margin.

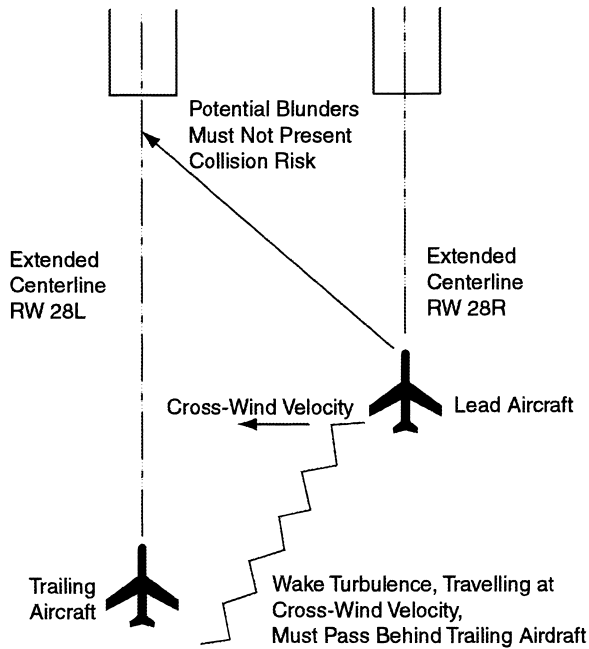


Figure 2. Wake turbulence and collision avoidance constraints.

Total System Error (TSE)

One of the initial assumptions of the proposal for the paired approach procedure was that a Local Area Augmentation System (LAAS) would be used in combination with the Global Positioning System (GPS) for navigation of the approach and landing. It was initially thought that, since the Navigation System Error (NSE) of a LAAS would be much smaller than for the Instrument Landing System (ILS), much tighter tolerances of TSE would be obtained. With runways at SFO being spaced only 750 feet apart, small TSE might be necessary.

However, investigation of the LAAS receiver and outputs has revealed that the deviation signal is designed to resemble that of ILS to maintain compatibility with existing displays and autopilots (Fain, 1994; RTCA, 1999). The resulting TSE is expected to be very similar to that of ILS.

To better understand the implications of the LAAS avionics design on the TSE, MITRE sought data collected by the FAA William J. Hughes Technical Center. The Technical Center installed the LAAS receiver and flew approaches at a variety of airports. These flights were hand flown as well as autopilot coupled approaches. The Technical Center provided MITRE with data from 31 approaches to various airports where LAAS equipment was tested.

Figure 3 shows TSE as a function of range from the runway threshold for these 31 approaches. Results were combined from the 31 approaches out to 10 nmi range from the runway threshold. The TSE is characterized in terms of one standard deviation of the lateral displacement from the runway centerline. The TSE typical of ILS approaches is shown alongside the observed TSE for the approaches flown with the LAAS. Although the LAAS NSE is extremely small (RTCA, 1999), the TSE remains similar to ILS because of the design of the deviation signal output.

It is evident that without some design changes to the LAAS interface with the pilot displays and the autopilot system, the dependent approach procedure (and any other procedures using LAAS as a navigation system for landing) will have to contend with TSE similar to that of ILS. This may prove to be an advantage from an equipment perspective (aircraft with existing navigation systems can perform the procedure), but seriously constrains the design of the procedure.

Compression

The second constraint that is important in our analysis is the compression effect. Compression is the result of deceleration during final approach. As the lead aircraft decelerates from its initial approach

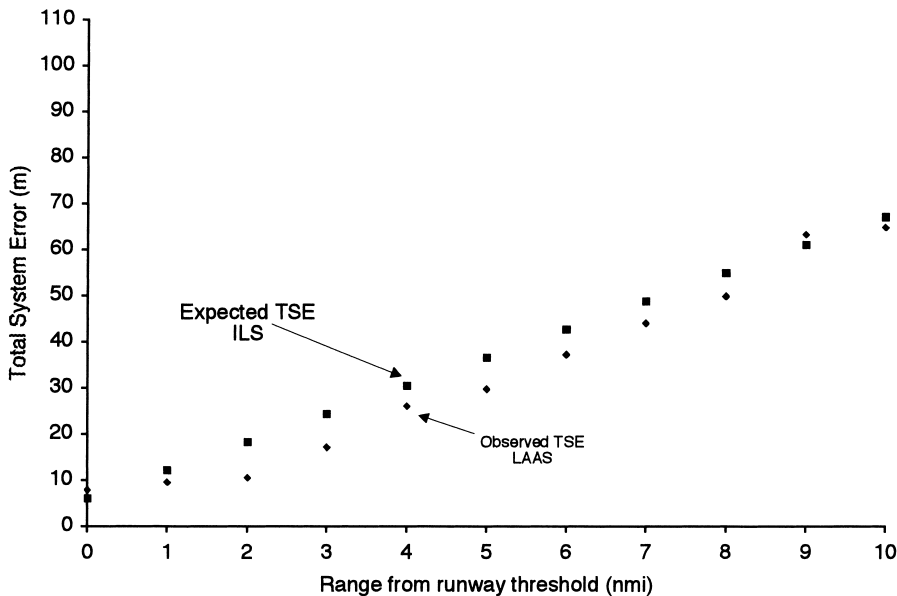


Figure 3. TSE with LAAS-based navigation vs. ILS; 31 approaches by FAA Tech Center's 727.

speed to its final approach speed, the distance between it and the in-trail aircraft shrinks. If the trail aircraft has a final approach speed that is greater than the lead aircraft's, additional compression results.

Figure 4 illustrates the basic compression result. The plot shows the longitudinal separation (ordinate) of two aircraft versus range to the runway (abscissa) as the aircraft fly to the runway threshold. In this example, the initial speed of both aircraft is 170 knots (kn) (for distances greater than about 6 nmi in the plot). During this phase of flight, the longitudinal separation between the aircraft is constant. As the lead aircraft begins to decelerate to the typical speed of 125 knots, the trail aircraft starts to close in.

The example assumes that both aircraft decelerate at 0.05 G (1.6 ft/s², or 1 kn/s), which is a typical deceleration value. Once the lead aircraft has completed deceleration, the trail aircraft continues to close due to its higher speed. As the trail aircraft begins its deceleration, the closure rate is reduced slightly. In this example, however, the trail aircraft has a final approach speed that is 10 knots faster than the lead aircraft, so the longitudinal compression continues until the runway threshold is reached.

The example illustrates that compression will play a major role in the procedure. As indicated earlier, both wake turbulence avoidance

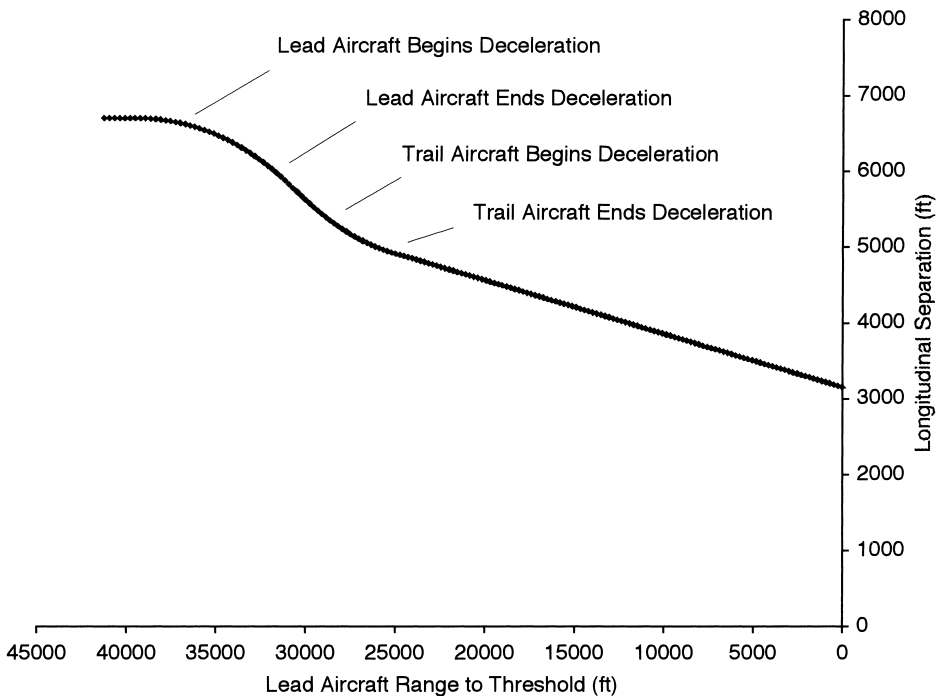


Figure 4. Basic compression geometry (trail aircraft has 10 knot higher final approach speed than lead aircraft).

and collision avoidance require limits on the longitudinal separation of the two aircraft. Compression affects the ability of an aircraft to operate within these limits.

Figure 5 illustrates the compression effect parametrically. The required separation during the initial approach is depicted (ordinate) as a function of the desired separation at the runway threshold (abscissa), and as a function of difference in touchdown speed. The required initial separation is highly dependent on the differences in touchdown speed, as indicated by the spread of the lines. Note also that for cases where the lines drop below the abscissa, a swap in position is required to achieve the desired separation at the threshold. This may be operationally unacceptable; note that under current procedures during visual approaches to parallel runways aircraft are not permitted to overtake each other.

Wake Turbulence Avoidance

Prediction of wake turbulence is a complex subject and debate continues on the details of wake turbulence transport and effects. For the purposes of this analysis, a conservative approach was adopted and some basic limits are expressed.

A very simple fact on which there seems to be broad agreement is that the wake turbulence travels across parallel runways with the speed of the crosswind. Close to the ground (less than one wing span from the ground) there is an additional velocity perpendicular to the aircraft flight path. This is called the “ground effect.” Exact values for

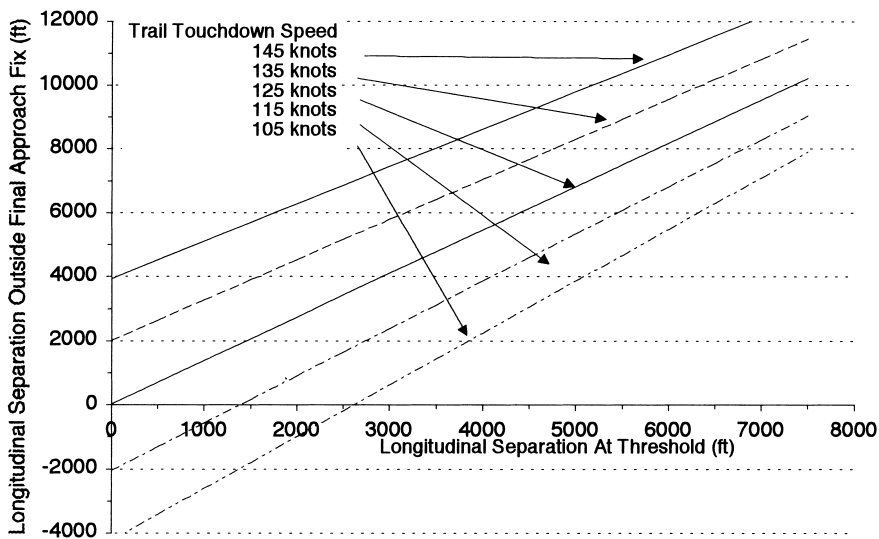


Figure 5. Initial separation as a function of differences in touchdown speed and separation at threshold (lead aircraft speed = 125 knots).

this additional velocity component are not easily predicted. Bounds on the order of 7.5 feet per second (about 5 knots), however, have been discussed as being reasonably conservative.

For the purpose of this analysis, we will examine the maximum allowable longitudinal separation as a function of wake turbulence transport velocity, regardless of the transport mechanics. The maximum spacing is the spacing beyond which the probability of a wake turbulence encounter exceeds a minimum allowable threshold. Calculation of the maximum allowable longitudinal spacing is a simple matter once the cross-runway wake turbulence velocity is known. The maximum spacing is simply the trail aircraft speed multiplied by the time for the wake turbulence to traverse the wingtip to wingtip lateral separation.

Parallel Approach Figure 6 depicts elements of the approach geometry used in the wake turbulence transport calculations. In calculating maximum longitudinal spacing for wake turbulence avoidance, aircraft wingspans of up to 200 feet were accounted for. If the fuselages of the aircraft are on centerline, the wake turbulence need only travel from wingtip to wingtip, rather than from fuselage to fuselage. This reduces an actual runway separation of 750 feet to an effective runway separation of 550 feet, since the right wing of the

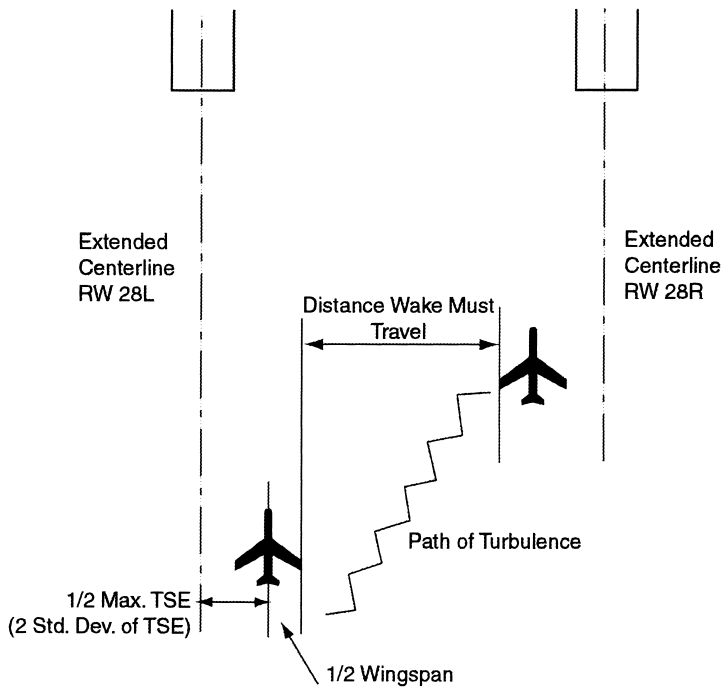


Figure 6. Wake turbulence geometry consideration.

aircraft on the left runway extends 100 feet past its centerline, and the left wing of the aircraft on the right runway extends 100 feet past its centerline. In addition to the wingspan, we must also account for total system error in calculating the required spacing. If either aircraft is displaced off the runway centerline toward the other runway, the time for the wake turbulence to travel is reduced by that displacement.

Figure 7 illustrates the maximum allowable longitudinal separation for aircraft on the parallel approaches as a function of maximum TSE for various wake turbulence transport velocities, assuming a 750-foot runway spacing, and a trail aircraft ground speed of 125 knots. We assumed the maximum TSE to be as shown in the abscissa in Figure 7.

Using the TSE measured on actual navigation systems (Figure 3), we can replace the abscissa of Figure 7 with the range from the runway threshold, given an assumption of probability of a given cross-runway error. For the example shown in Figure 8, we assumed that the maximum TSE is replaced by a 4-standard-deviation value; that is, each aircraft would be no more than 2 standard deviations off centerline at the same time. The probability of this event, given that the errors are normally distributed, is about 1 in 33,000. Note an additional assumption for this plot is that the speed of the trail aircraft is assumed to be 170 knots outside of 5 nmi from the threshold, and 125 knots inside of this point. This produces the slight relaxation of the required maximum separation at the 5 nmi point.

If we assume that a value of 1 in 33,000 is sufficient to satisfy

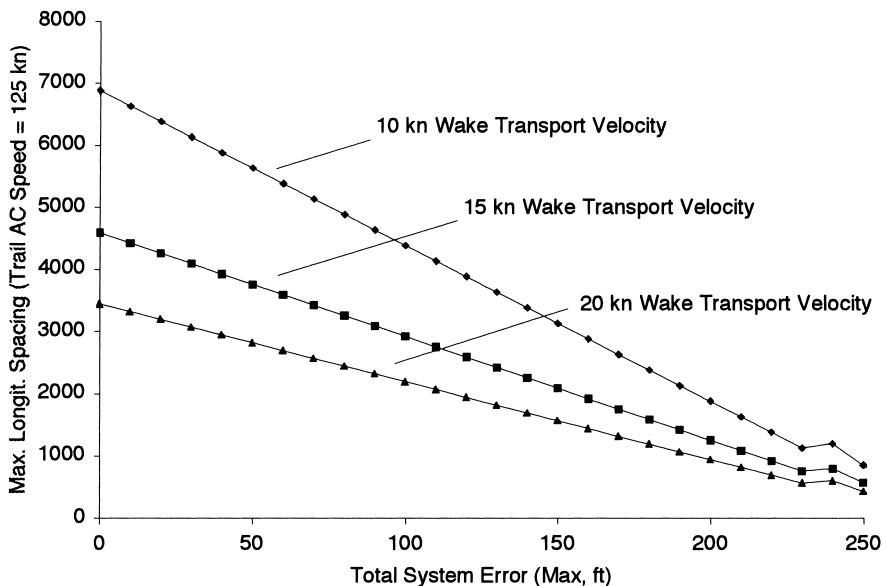


Figure 7. Longitudinal spacing requirements for 750-foot runway spacing.

safety requirements, we can see that the combination of compression and wake turbulence avoidance makes the situation with a 750-foot runway spacing very difficult. Also plotted on Figure 8 is the profile of the longitudinal separation of two aircraft as they approach the threshold with a final separation of 1500 feet. In this example the trail aircraft's final approach speed is 10 knots faster than that of the lead aircraft. We observe that the spacing is beyond the maximum allowable longitudinal spacing beyond 1-1/2 and 3 nmi from the threshold, depending on the wake turbulence transport velocity. As per Figure 5, there will be very few, if any, examples we can find that will stay within the criteria shown in Figure 8. Either much better TSE is required or another geometry is required.

Three Degree Offset Approach. As an alternative to the straight in approach, we now consider an offset approach. This should help to alleviate the constraints arising from wake turbulence, especially at longer distances from the runway threshold. Figure 9 illustrates the concept of the offset approach.

Figure 10 shows the constraints on the longitudinal spacing based on wake turbulence avoidance for a three degree offset approach. It is clear from Figure 10 that from a wake turbulence avoidance perspective, the offset approach seems much more feasible. The longitudinal separation shown, as an example, in the figure, is well below the maximum spacing for all three curves until about two nmi from the

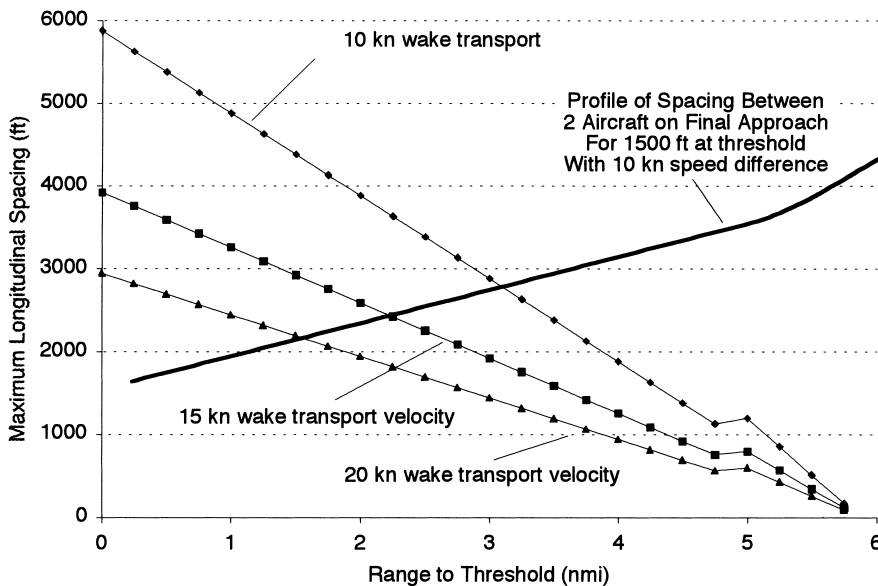


Figure 8. Longitudinal spacing requirements as a function of distance from runway threshold.

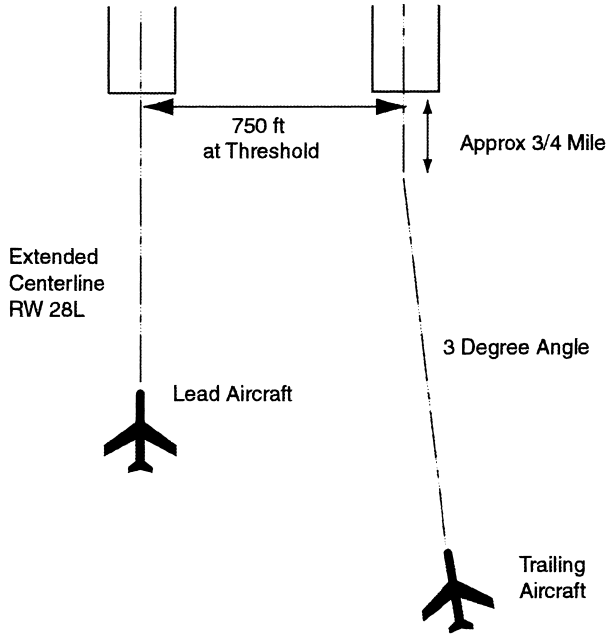


Figure 9. Three degree offset approach.

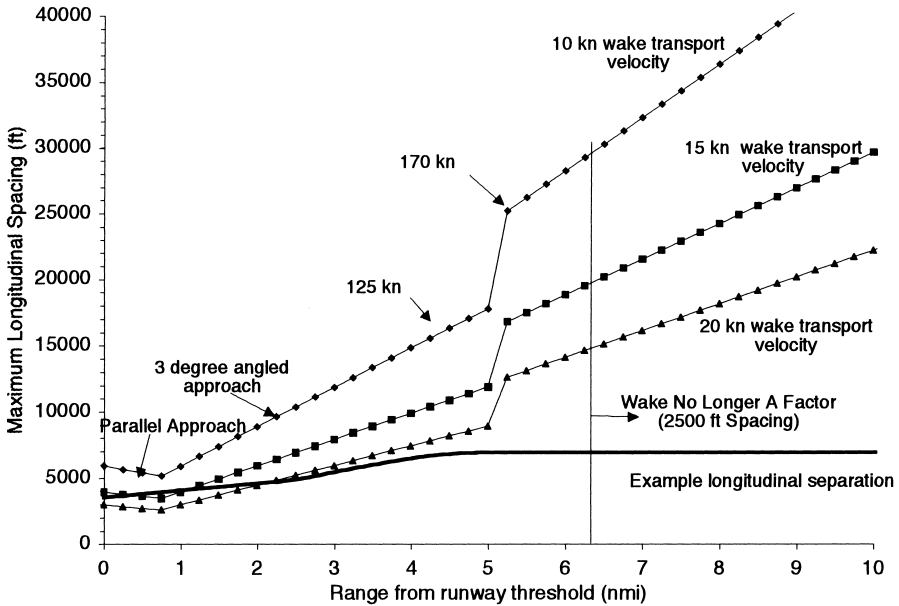


Figure 10. Wake turbulence constraint on longitudinal separation for a three degree offset approach.

threshold. The example stays below the 10 knot transport curve all the way to the threshold. As evidenced by the example, there are geometries that can meet the requirements with a three degree offset approach. Also note that the offset approach achieves a 2500-foot

lateral separation a little beyond six nmi from the threshold. Beyond this point, according to current FAA standards, wake turbulence is not a factor.

Collision Avoidance

We now consider the question of determining the minimum longitudinal spacing for collision avoidance purposes. In order to assess collision avoidance properties of the geometry, a Monte Carlo simulation was employed. The Monte Carlo model simulated sample flight paths, including a stochastic model for flight technical error. Figure 11 provides an illustration of the flight paths including FTE for two aircraft on approach with a three degree offset approach for the trail aircraft.

The simulation modeled turning blunders by the lead aircraft. Based on previous analysis performed for the Precision Runway Monitor (PRM), lead aircraft blunders were limited in extent to 30 degrees (Fain, 1994). The blunder extent was randomized, however, between 5 and 30 degrees. In addition, the bank angle of the blundering aircraft was also randomized to simulate a maneuver with centripetal accelerations between 0.1 G and 1 G. The start time of the blunder was also randomized so that it could occur anywhere along the approach path. Figure 12 shows a sample scenario with a blunder.

Our analysis was intended to determine the minimum longitudinal distance required of the trail aircraft to avoid a critical Near Mid-Air

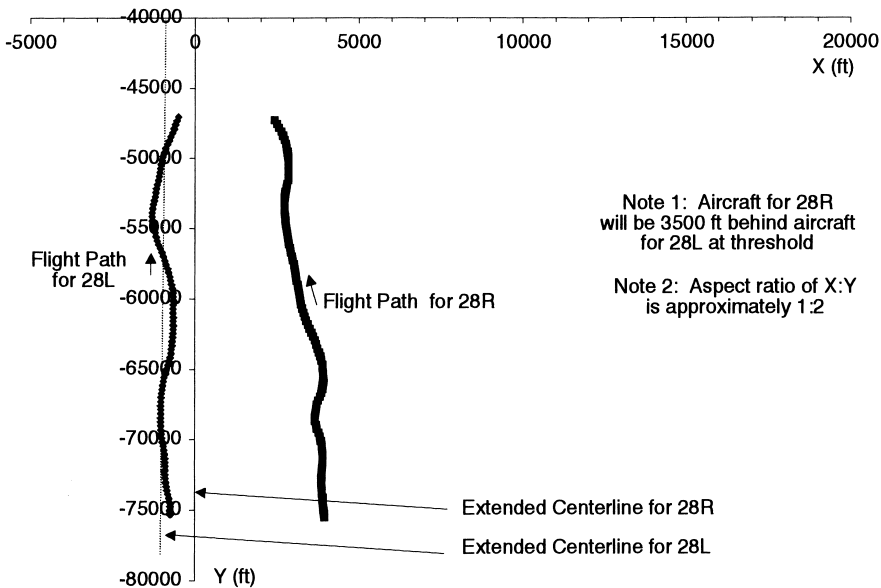


Figure 11. Noisy sample paths for three degree approach angle.

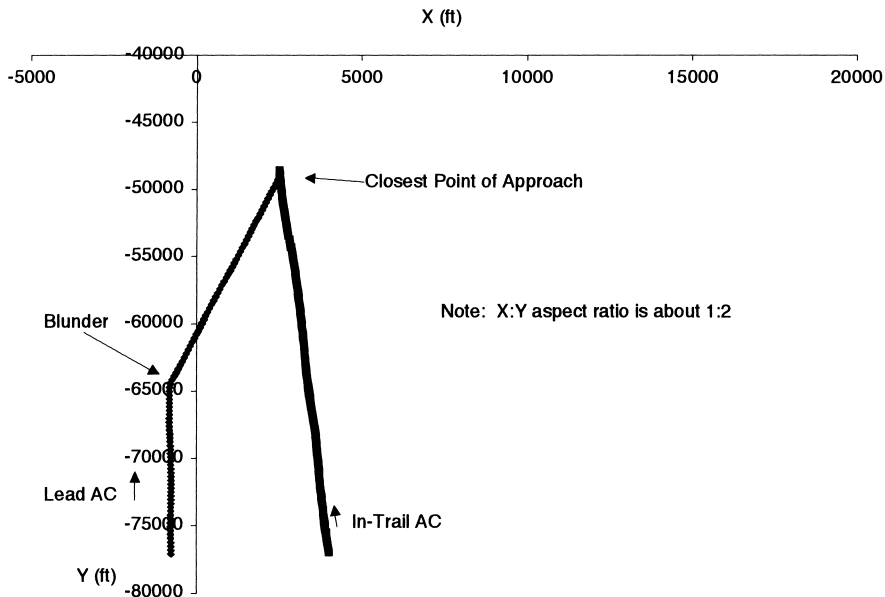


Figure 12. Example blunder (with three degree offset approach).

Collision (NMAC) during a lead aircraft blunder. A critical NMAC, for this purpose, was defined as less than 500 feet horizontal separation. No bound was placed on the corresponding vertical separation.⁴

The geometry was examined in two parts: outside the final approach fix, and inside the final approach fix. The results indicate that if the aircraft are longitudinally separated by more than 3000 feet outside the final approach fix (5 nmi from the threshold), then the probability of an NMAC is zero under the conditions simulated. Inside the final approach fix, if the aircraft maintain separations greater than 1000 feet at the runway threshold, and more than 2000 feet by the final approach fix, the probability of an NMAC is also zero. Varying the minimum separation linearly from 2000 feet at the final approach fix to 1000 feet at the threshold appears to be a satisfactory arrangement. Table 1 summarizes these results.

Table 1. Collision Avoidance Requirements Distance from Threshold Minimum Longitudinal Separation

> 5 nmi (Beyond Final Approach Fix)	3000 feet
5 nmi (at Final Approach Fix)	2000 feet
0 (at threshold)	1000 feet

⁴The Precision Runway Monitor program used a criterion of 500 feet separation in slant range (horizontal, vertical, or combination) (Fain, 1994).

GEOMETRY AND PROCEDURE SUMMARY

Based on the previous examination of the wake turbulence constraints, combined with both the collision avoidance constraints and the compression geometry, we can hypothesize a possible procedure which may be satisfactory for paired approaches. A summary of a possible procedure is enumerated below.

Before Final Approach

- 1 The pilots enter their final approach speeds into their automation systems.
 - 1.1 The controller requests a verbal read-out of the planned final approach speed from both aircraft
- 2 The controller determines an aircraft pair, lead and trail, prior to turning the aircraft on to the final approach course.
 - 2.1 The controller informs the aircraft which will be the lead and which will be the trail.
 - 2.2 The trail aircraft's automation determines if the final approach speeds are compatible for paired approach, *based, in part, on an assumption of flying a nominal speed to the final approach fix.*
 - 2.3 If the final approach speeds are incompatible, the trail aircraft's flight crew informs ATC, and standard IFR separations are employed. If the speeds are compatible, the procedure continues with step 3 below.

Final Approach

- 3 The controller turns the aircraft onto the final approach course with the lead and trail aircraft assigned. The trail is at least 3000 feet behind the lead, but is no more than 2 nmi behind the lead, and is separated vertically by standard IFR separation. *The Controller assigns the lead a speed to the final approach fix.* The controller asks the trail aircraft flight crew to report that they are "able to make required spacing."
- 4 The trail aircraft's automation calculates the Initial Required Spacing Distance (IRSD), and determines if it is possible to make up distance to the IRSD by the Missed Paired Approach Point (MPAP).
 - 4.1 If the trail aircraft's flight crew determines that it is not possible to make the IRSD, ATC is informed and the procedure is aborted.
 - 4.2 If the trail aircraft's flight crew determines that it is possible

- to make the IRSD, the trail aircraft's flight crew informs ATC that it is "able to make required spacing."
- 5 Once the trail aircraft is able to make the required spacing it is then responsible for separation from the lead through the remainder of the approach. Unless, for example, a break-out were to occur the controller would no longer be required to continue monitoring the pair's separation.
 - 5.1 The trail aircraft is cleared for paired approach.
 - 5.2 The trail aircraft may now lose vertical separation.
 - 5.3 The trail aircraft proceeds to accelerate and decelerate as commanded by on-board automation, to close with the lead aircraft to the IRSD.
 - 5.4 A safety indication is displayed three thousand feet in front of the trail aircraft. The lead aircraft must remain in front of this indication during the initial phase of the approach. This is as indicated in Table 1 above. This is the *initial collision avoidance constraint*.
 - 5.5 If, at any time the lead aircraft appears behind the collision avoidance constraint, the trail aircraft crew is alerted and the trail aircraft must execute a missed approach.
 - 6 When the lead aircraft crosses the final approach fix it immediately begins to decelerate to its final approach speed.
 - 7 Once the lead aircraft crosses the final approach fix:
 - 7.1 The trail aircraft must be in position, i.e., within allowable constraints for the IRSD.
 - 7.2 If the trail aircraft is not within constraints, the trail aircraft must execute a missed approach.
 - 7.3 If the trail aircraft is within constraints for the IRSD, the procedure continues.
 - 7.4 From here on, the collision avoidance constraint is reduced to account for additional lateral convergence of the two aircraft. The initial adjustment is to two thousand feet. This will be reduced linearly, with distance of the trail aircraft from the runway threshold, to one thousand feet at the threshold.
 - 7.5 From this point on, the trail aircraft is no longer responsible for active positioning relative to the lead aircraft.
 - 8 The wake vortex protection point (WVPP) is the point at which the aircraft are separated by 2500 feet laterally. Once the trail aircraft crosses the WVPP, an indication is presented behind trail aircraft's position; this is the wake turbulence constraint. The trail aircraft now must continue to stay in front of the wake turbulence constraint, as well as assuring that the lead is in front of the collision avoidance constraint.
 - 9 Once the trail aircraft crosses the final approach fix, it immediately begins to decelerate to final approach speed.
 - 10 The trail aircraft's automation monitors the collision avoidance

constraint and wake turbulence protection constraint. If either constraint is violated, or if either constraint is predicted to be violated, the crew is alerted and a missed approach is initiated. Note that a requirement of the initial proposal for the procedure is that the pilots are not to perform any station keeping maneuvers inside the final approach fix.

Figure 13 illustrates the basic geometry and some of the key points described above during the approach.

Figure 14 gives an example of the longitudinal separation constraints and the separation pattern for two aircraft performing the approach. The wake turbulence constraint was determined by assuming a worst case of a 15 knot unfavorable crosswind outside of 2-1/2 nmi from the threshold. Inside 2-1/2 nmi the wake turbulence transport velocity was assumed to be a worst case of 10 knots in the unfavorable direction. (This would probably be close to a calm condition inside of ground effect, since the wake turbulence transport velocity due to the ground effect is on this order). The two aircraft were assumed to fly at 170 knots to the *final approach fix*, then decelerate at 1 knot per second to their final approach speeds.

The procedure would be acceptable to fly under the stated wind

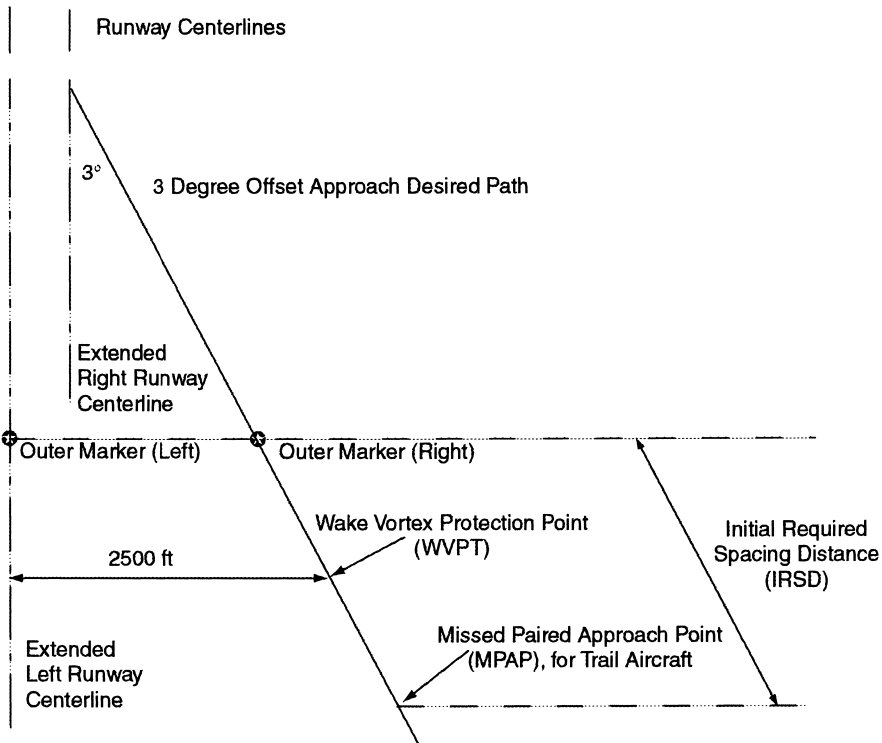


Figure 13. Paired Approach horizontal geometry.

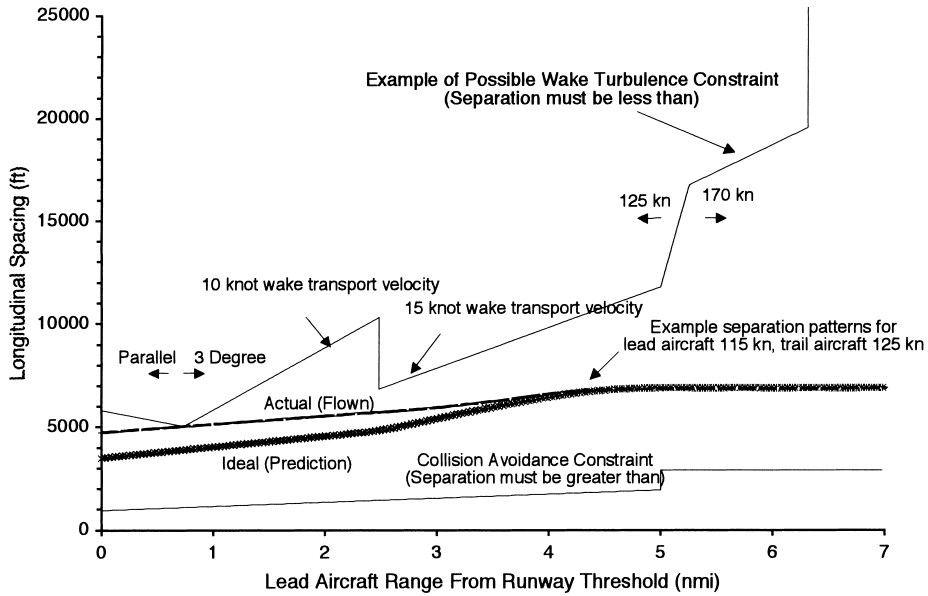


Figure 14. Example of possible wake turbulence and collision avoidance constraints.

conditions. The wake turbulence constraint curve is an illustrative example. In practice, this curve will need to be engineered to optimize the availability of the procedure for local conditions. In operation, winds would need to be monitored, and if the wind were outside the bounds of operation for the procedure, the procedure would have to be stopped. The trade-off between availability and the maximum spacing for wake turbulence avoidance needs a detailed examination in order to determine the economic viability of the procedure.

Note also in Figure 14 that the wake turbulence constraint is applied closer than 6-1/4 nmi from the runway threshold. This is where the lateral separation would become less than 2500 feet. Also note the negative slope of the wake turbulence constraint inside about 3/4 nmi from the threshold; this is where the parallel segment of the approach begins. Finally, note the change in the wake turbulence constraint outside the final approach fix, assumed in this example to be 5 nmi from the runway threshold. This is again due to the change in the trail aircraft speed from 170 knots to 125 knots, which is assumed to begin at the final approach fix.

A possible desirable separation at the threshold results from splitting the difference between 1000 feet (due to the collision avoidance constraint) and about 6000 feet at threshold (due to the wake turbulence constraint). This would indicate an aim point of 3500 feet separation at the threshold. Figure 15 illustrates, for a lead aircraft final approach speed of 125 knots, the possible trail aircraft speeds which

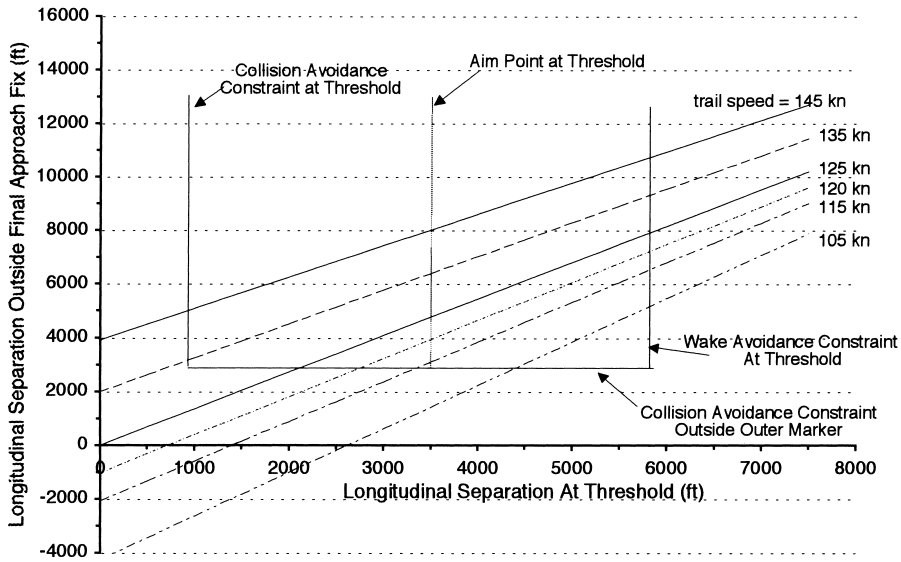


Figure 15. Geometric constraints vs. compression.

would result in a feasible geometry, again, assuming a one knot per second deceleration beginning at the final approach fix. The abscissa of the figure is the separation at the threshold, while the ordinate is the separation outside the final approach fix. The left-most vertical line, annotated on the figure, represents the collision avoidance constraint at the threshold. The right-most (annotated) vertical line represents the approximate wake turbulence avoidance constraint at the threshold (assuming a 10 knot total wake turbulence transport velocity and 125 knot trail final approach speed). The horizontal line at 3000 feet represents the collision avoidance constraint outside the final approach fix. Any line which is inside the box constructed from these three lines represents a possible geometry that will satisfy the constraints.

If the aim point is 3500 feet at the threshold, a line which is to be considered must cross the 3500 feet (dashed vertical line) which splits the box. The speed of the trail aircraft in this example must be greater than or equal to 115 knots. Note, however, that if the trail aircraft flies a 115-knot final approach speed, it will be exactly on the borderline of violating the collision avoidance constraint while outside the missed paired approach point (on the ordinate). This may be a difficult position to maintain. More latitude is obtained by having the trail aircraft no slower than 120 knots, and additional latitude is gained by having the trail aircraft faster. There is no obvious penalty in having the trail aircraft as much as 20 knots faster than the lead aircraft on final approach.

SENSITIVITY OF FINAL LONGITUDINAL SEPARATION TO ERRORS IN THE PREDICTION

Referring back to Figure 14, we observed two trajectories superimposed between the constraints. The lower trajectory, labeled “ideal prediction,” represents the nominal prediction that would occur as part of the procedure when the trail aircraft calculates the initial required spacing distance, as described in step 4 under “final approach” above. This prediction is based on:

1. The expected final approach speed of the lead aircraft
2. The expected final approach speed of the trail aircraft
3. The actual final approach speeds
4. Assumed deceleration rates for both aircraft
5. An assumed deceleration point (the final approach fix) for both aircraft
6. The head-wind profile from the final approach fix to the threshold
7. The achieved separation outside the final approach fix versus the initial required separation

Observe that in the “ideal prediction” the aircraft separation at the threshold is exactly 3500 feet, which is the desired separation. Backing up from this point using the seven parameters listed above, results in a required spacing outside the final approach fix, also called the initial required spacing distance.

In actual flight, however, one or more of the nominal expected values for the six parameters listed above may be incorrect. The actual final separation will then vary from the predicted separation. An example of this situation is depicted by the curve labeled “actual (flown)”. Our object is to determine the sensitivity of the procedure to errors in the seven parameters listed above.

As described above, the calculation of the initial required spacing distance in Step 4 of the procedure outline is based on a prediction of the final separation. This prediction is based on the seven variables listed above.

In some cases, these variables should be well known and in other cases they must be inferred from the aircraft type or other means. For example, the final approach speed for both aircraft is to be communicated by pilot input and data link. The deceleration rates for both aircraft may need to be assumed and might be highly variable. It may be necessary to have knowledge of specific aircraft types and weights, depending on the likely errors in any assumed deceleration rate. The initial approach speed can either be calculated from the lead aircraft speed after the approaches have been set up or might be another pilot entry. The deceleration point might be assumed to be the final approach fix, provided that pilots are willing to initiate their

final deceleration at this point for this procedure. Head winds must be estimated from available meteorological data.

In any case, we can examine the sensitivity of the error in final separation to the differences between the assumed values of these variables and their actual value. Equation 1, derived based on simple point mass equations of motion, characterizes the final separation at the threshold (df) in terms of all the listed variables (excepting headwinds, which will be treated separately):

$$df = ffr - sf_t \frac{ffr}{sf_l} + sf_T \frac{(si_l - sf_l)^2}{2sf_l a_l} + sf_t \frac{di}{si_t} - \frac{(sf_t - si_t)^2}{2a_t} \tag{1}$$

where:

- df is the final separation
- ffr is the final approach fix distance from the runway threshold
- sf_t is the final approach speed of the trail aircraft
- sf_l is the final approach speed of the lead aircraft
- si_l is the initial approach speed of the lead aircraft (outside the final approach fix)
- si_t is the initial approach speed of the trail aircraft
- di is the initial separation (outside the final approach fix)
- a_t is the deceleration rate for the trail aircraft
- a_l is the deceleration rate for the lead aircraft

By taking partial derivatives of df , we can determine the sensitivity of the separation at the threshold to variations in these other variables. In order to assure ourselves that the final separation will be between 1000 and 6000 feet, for example (a difference of 5000 feet), we would like assurance that the standard deviation in the final separation will be less than about 750 feet. If the aim point is 3500 feet, the error tolerance is plus or minus 2500 feet. If the standard deviation of the error is 750 feet, the probability that the actual separation at the threshold will be out of bounds will be less than 1 in 1000. As a missed approach is the result if the actual separation is out of tolerance, 1 in 1000 is probably on the order of a minimum requirement.

Variation with Respect to Initial Separation, di

The partial derivative of df with respect to di is:

$$\frac{\partial df}{\partial di} = \frac{sf_t}{si_t} \tag{2}$$

The standard deviation of df with respect to di is then:

$$\sigma_{df} = \frac{sf_t}{sf_l} \sigma_{di} \tag{3}$$

Equation 3 indicates that the standard deviation of the final separation with respect to the standard deviation of the initial separation is determined by the ratio of the final approach speed of the trail aircraft divided by the initial approach speed of the trail aircraft. For example, if the initial approach speed is 170 knots, and the final approach speed of the trail aircraft is 125 knots, the standard deviation of the final separation would be reduced by a factor of 0.74 versus the standard deviation of the initial separation.

Variation with Respect to Deceleration Rate a_t , a_l

The partial derivative of df with respect to a_t is given by equation 4:

$$\frac{\partial df}{\partial a_t} = \frac{-(s_{f_t} - s_{i_t})^2}{2a_t^2} \quad (4)$$

The partial derivative of df with respect to a_l is given by equation 5:

$$\frac{\partial df}{\partial a_l} = -s_{f_t} \frac{-(s_{i_l} - s_{f_l})^2}{2s_{f_l}a_t^2} \quad (5)$$

By combining the partial derivative for the initial spacing error with the partials for deceleration rates, we can compute the total error in the final spacing as a function of σ_a , assuming the standard deviation for the deceleration estimate is the same for both the lead and trail aircraft. The result is a sensitivity curve as depicted in Figure 16.

Figure 16 illustrates that the error in the final separation will be highly dependent on an accurate estimate of deceleration rate. In fact, this one factor alone could well exceed the error budget of approximately 750 feet if the uncertainty in the deceleration rate is above 0.4 ft/s². Hopefully an acceleration estimate based on aircraft type and possibly weight will reduce this uncertainty to a tolerable level.

It is also important to note that the uncertainty in the final distance has dependencies on the initial speeds of both aircraft, as indicated in equations 4 and 5. Thus the curve shown in Figure 16 is one example of the relationship. In this case the initial speeds of both the lead and trail aircraft was 170 knots and the final speed for both aircraft was 125 knots.

Variation with Respect to Final Approach Speed

Despite the pilot input of planned final approach speed, in practice it is likely that the pilot will fly a slightly different speed, with the

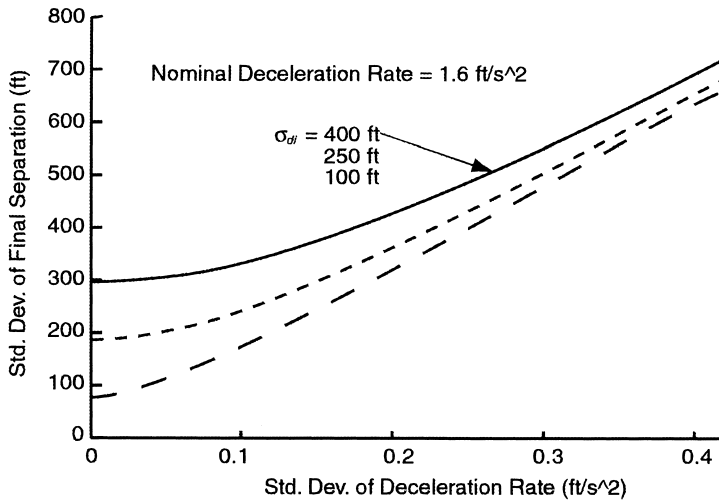


Figure 16. Sensitivity of final separation error to error in deceleration rate. (initial speeds = 170 kn; final speeds = 125 kn).

planned speed as a nominal value. The error in the final separation as a function of error in assumed final approach speed is shown in Figure 17. These results were derived using a Monte-Carlo simulation study.

United Airline’s procedures require that the pilots fly within five knots of their planned approach speed. Assuming that this is accomplished with high reliability (99%), a reasonable assumption might

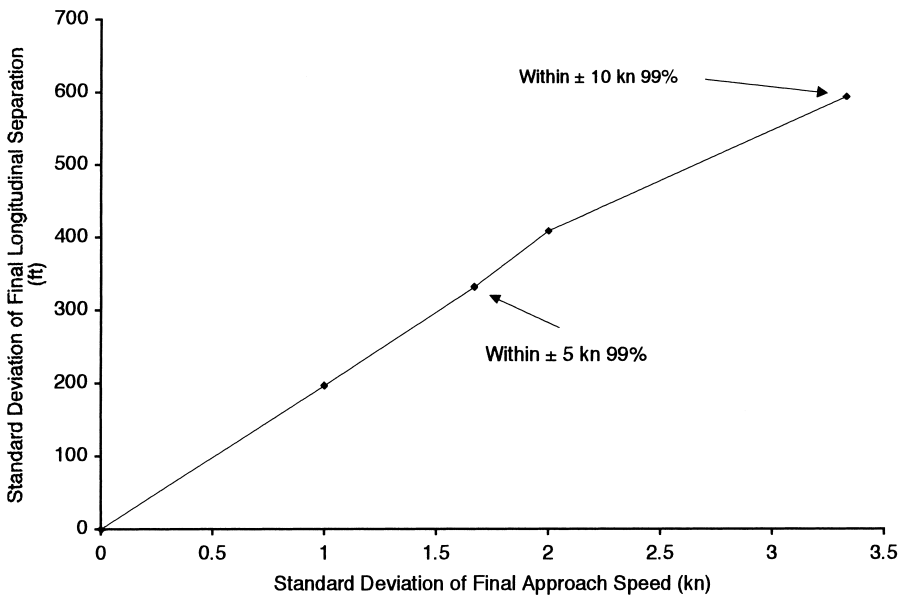


Figure 17. Error in final separation as function of error in final approach speed.

be that the standard deviation of the final approach speed is about 1.6 knots, as indicated in the figure. This assumption, however, needs verification. A larger error, within plus or minus 10 knots (99%) for example, will add substantially to the error in separation at the threshold.

Variation with Respect to the Deceleration Point

One important element of the procedure will be that the pilot (of both the lead and trail aircraft) will be assumed to begin deceleration at a fixed point (probably the final approach fix). Variations in the deceleration point will result in differences between the predicted separation at the threshold and the actual separation at the threshold. For analysis purposes, we used the time of deceleration, relative to the expected time of deceleration, as a surrogate for the deceleration point. In this way we studied the sensitivity of the separation as a timing error. Figure 18 illustrates this sensitivity, in terms of RMS error in deceleration time. These results were generated using Monte-Carlo simulations.

Variation with Respect to Head Wind Estimates

The estimate of the final separation is a result that must be calculated in ground coordinates. As such, any head winds affecting the speeds of both aircraft during the final approach will result in some difference in the actual achieved separation. Errors in the estimated

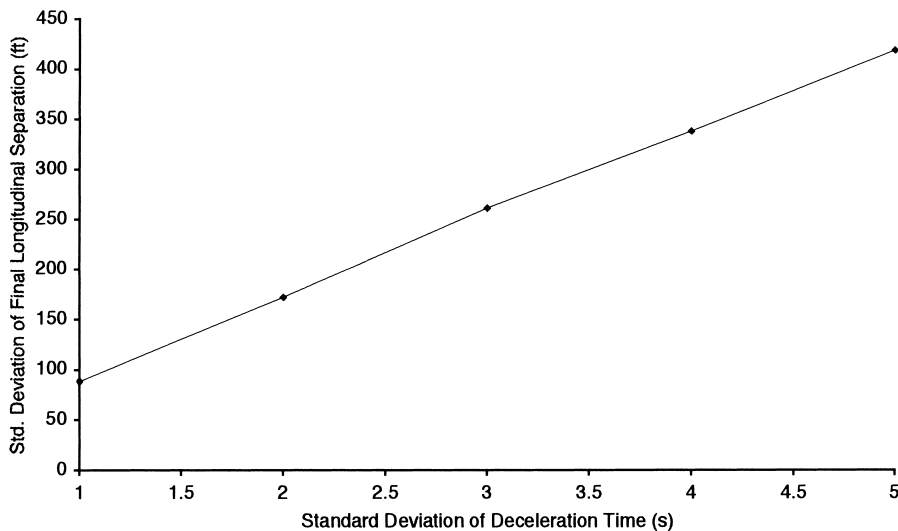


Figure 18. Error in final separation as function of error in assumed deceleration time.

head winds will cause a similar error in estimated final speed for both aircraft. This translates into error in the final separation estimate. In fact, the difference between this error and the error due to the pilot's not flying the exact intended final approach speed is similar in nature. The error is just the error shown in Figure 17 divided by the square root of two, replacing the abscissa with "standard deviation of average head wind estimate."

Combined Error

At this point it is not possible to say whether or not these errors will add up to a value that is either acceptable or unacceptable. Efforts are under way to collect data that will answer this very important question. Until we have specific data indicating the variability in deceleration rates, deceleration point, variation of actual approach speed vs. planned approach speed, and some indication of the accuracy of the wind estimates, it is not possible to draw any firm conclusions. The analysis above, however, does give us an indication of the sensitivity of the procedure to these variables.

SURVEILLANCE REQUIREMENTS AND SENSITIVITY

The paired approach will require substantial capability in terms of surveillance, interfaces to other avionics systems, alerting, and separation maintenance. The following list enumerates a set of required processing elements which surveillance data will support:

1. Receive and process final approach speed of paired aircraft
2. Monitor aircraft conformance with collision avoidance constraint
3. Calculate wake turbulence constraint based on lead aircraft speed
4. Monitor conformance with wake turbulence constraint
5. Calculate speed adjustments required for achievement of initial required spacing distance (possibly feeding these to autothrottle system)

This section begins to explore surveillance requirements from the standpoint of one key element of the processing listed as number 5 above—calculation of speed adjustments to achieve the minimum required spacing distance. At first glance, this appears to be a demanding application from the perspective of surveillance requirements. However, we will show that, in fact, the speed adjustments are rather insensitive to requirements for accuracy, update period, data latency, and report time error.

It is important to remember that the total error in the spacing at the threshold is what is of interest. One component of this total error

will be the error in the initial spacing. The error in the initial spacing will depend, in part, on surveillance data errors. It will also depend on pilot ability and/or control laws, wind gusts, etc.. We will try to isolate in this study the sensitivity to surveillance errors as a distinct set of quantities.

In order to perform this study, a Monte Carlo simulation was used that models an initial spacing error when the aircraft are turned onto final approach, then models an input to the trail aircraft in terms of a commanded speed. The simulation models a pilot response to this commanded speed and attempts to follow the commanded speed, in order to reach the required spacing by the time the lead aircraft crosses the final approach fix.

In modeling the procedure, we used a consistent model for the pilot response (a simple delay loop was used). However, it is likely that additional flight technical error will be involved during the actual procedure, as mentioned above. The results quoted in this section, therefore, should not be interpreted as an expected value for the error in longitudinal spacing at the *final approach fix*. The results can be interpreted strictly as an analysis of the sensitivity of the error in longitudinal spacing to various types of surveillance errors.

Figure 19 shows the sensitivity to error in position and velocity data observed in our simulations. A slightly higher error results with increasing position error (from 1 m RMS to 80 m RMS error). However, the increase in error is only about 40 m, which, relative to other errors in the procedure, will probably not be of great significance. We also observe slightly increasing initial position error as a function of

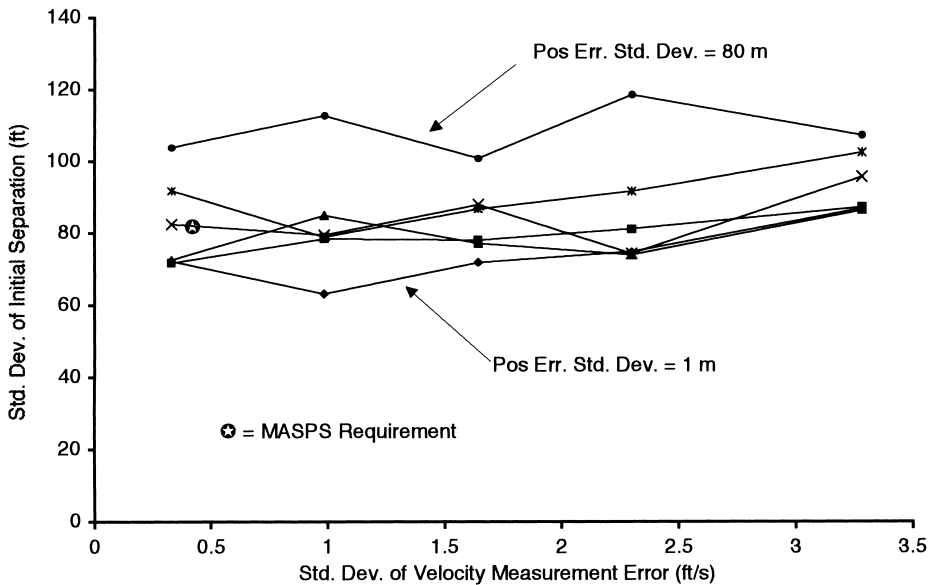


Figure 19. Sensitivity to data accuracy.

increasing velocity error. Again, however, the increases are small relative to the overall error budget for the procedures. The accuracies specified in the ADS-B MASPS (RTCA, 1998a) of 20 m position error, 0.3 m/s (1 ft/s) velocity error, appear to be adequate for the procedure.

Figure 20 studies the sensitivity of the initial position error to update period and probability of receipt. Update period (T) is defined as the time between successive state vector reports. Update probability is the probability of a successful update. The difference in error between a 1-second update period and a 4-second update period is evident, but it is still very small (about 30 feet) relative to the overall errors we are concerned with for the procedure. There is also a slight negative slope to the curves with regard to update probability. This indicates a slightly smaller error as a function of increasing update probability; however, the differences are marginal. The ADS-B MASPS requirement of a 3-second update period with 0.95 probability of receipt appears to be adequate.

Tables 2 and 3 illustrate that the error in the initial position is also insensitive to data latency and report time error. Data latencies of up to 4 seconds and report time errors of up to 0.5 seconds had no appreciable effect on the initial position error. Again, the MASPS requirements appear to be adequate.

CONCLUSIONS

A procedure for paired approach has been formulated which can meet both wake turbulence and collision avoidance constraints. It remains

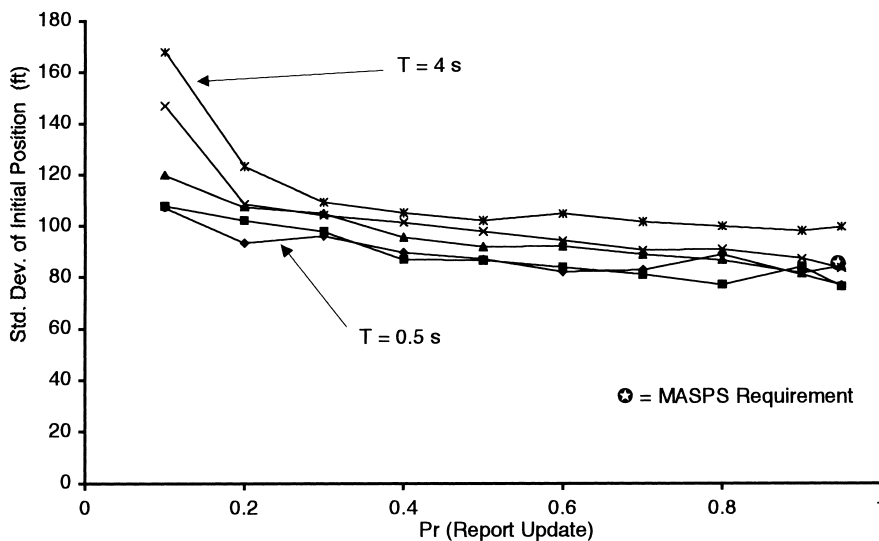


Figure 20. Sensitivity to state vector update period (T) and update probability.

Table 2. Initial Position Error as a Function of Latency in State Vector Reports

Latency (s)	Mean Error (ft)	Error Standard Deviation
1	229.1981	97.16
2	226.273	95.35
3	229.5219	98.14
4	221.2164	95.186

Table 3. Initial Position Error as a Function of Error in Report Time of State Vector

Report Time Error Standard Deviation(s)	Mean Error (ft)	Error Standard Deviation
0	208.868	87.7
0.25	204.8281	87.7
0.5	189.3612	97.6

to be determined if it is feasible to meet both constraints with high reliability during the final approach. The procedure is sensitive to variations in wind speed, final approach speed, and deceleration rates, which all need to be examined in more detail to determine reliability. In addition, human factors issues, which were not considered in this paper, need to be examined in detail.

We also examined the sensitivity of the procedure to surveillance inaccuracies and found that, from this standpoint, the procedure is robust.

Results of this analysis are being coordinated with United Airlines, FAA, and other members of industry.

ACKNOWLEDGMENTS

The author would like to thank Dr. Anand Mundra for his support of this work, including his detailed and thoughtful insights into the approach of this analysis. I would also like to thank Ed Hahn for his management support of this effort.

This work was produced for the U.S. Government under contract Number DTFA01-93-C-00001 and is subject to Federal Acquisition regulation Clause 52.227-14, Rights In Data-General, Alt. III (JUN 1987) and Alt. IV (JUN 1987).

ACRONYMS AND SYMBOLS

ADS-B	Automatic Dependent Surveillance Broadcast
ATC	air traffic control

CDTI	Cockpit Display of Traffic Information
GPS	Global Positioning System
kn	knots
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IRSD	Initial Required Spacing Distance
LAAS	Local Area Augmentation System
MIT	miles-in-trail
MPAP	Missed Paired Approach Point
nmi	nautical miles
NMAC	Near Mid-Air Collision
NSE	Navigation System Error
PRM	Precision Runway Monitor
RMS	root mean square
SFO	San Francisco International Airport
TSE	Total System Error
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WVPP	Wake Vortex Protection Point

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BIOGRAPHY

Jonathan Hammer has been involved in the analysis of air-traffic control surveillance and procedure development for approximately 18 years. Mr. Hammer developed and patented distributed multi-sensor tracking and data association algorithms for advanced automation systems on FAA sponsored programs while with the Federal Systems Division of International Business Machines Corporation from 1984 through 1993. In 1994 Mr. Hammer joined The MITRE Corporation, where he

patented a horizontal miss distance filter algorithm for the traffic alert and collision avoidance system (TCAS). The filter reduces unnecessary TCAS generated resolution advisories by approximately 25 percent in the US, and is included in TCAS version 7, under current fleet-wide implementation. More recently Mr. Hammer has been involved in developing technical requirements for new procedure development. Mr. Hammer is the secretary of RTCA special committee 186 (Automatic Dependent Surveillance Broadcast), and is the co-chairman of the special committee 186's technical requirements working group.