Increasing Airport Capacity with Modified IFR Approach Procedures for Close-Spaced Parallel Runways

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Because of wake turbulence considerations, current instrument approach procedures treat close-spaced (i.e., less than 2,500 feet apart) parallel runways as a single runway. This restriction is designed to assure safety for all aircraft types under all crosswind conditions. Restricting crosswinds and/or aircraft types can permit safe operations for runways with smaller spacings than 2,500 feet. An alternative safety paradigm can be based on the pairing procedure commonly used for visual approaches to close-spaced parallel runways. In this case, wake turbulence is not a factor if there are appropriate limits on allowed longitudinal pair spacings and/or allowed crosswinds. This paper examines how these concepts can be formulated into safe instrument approach procedures.

INTRODUCTION

Airport utilization is increasing steadily from year to year. More and more airports are reaching capacity limits. Airport capacity is a critical factor affecting the growth and efficiency of air transportation.

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There are many factors that influence capacity (climatology, runway configurations, traffic mix, etc.); however, ultimately either the number of runways must be increased or the average spacing between aircraft using existing runways must be reduced [Hallock, et al., 1998]. The economic benefits of reduced wake turbulence separations at capacity-limited airports is substantial. Research programs in the United States, Europe, Canada, and Russia have endeavored to understand wake vortex behavior and use this understanding to alleviate airport capacity limitations caused by overly restrictive wake turbulence separation standards.

This paper examines how knowledge of wake vortex behavior can increase capacity for airports with close-spaced parallel runways (runways separated by less than 2,500 feet). After more than forty years of research on vortex behavior, wake transport over short times is well understood whereas wake decay is less well understood. [See web site http://www.volpe.dot.gov/wv maintained by one of the authors for abstracts and references on aircraft wake vortices.] The concepts considered herein primarily consider wake transport over short times to formulate safe procedures for more efficient use of close-spaced parallel runways.

The paper first examines the current options or procedures for preventing a wake vortex encounter. Then, wake vortex behavior near the ground relevant for close-spaced parallel runway operations is reviewed. Criteria (crosswinds and aircraft type) for reductions in parallel runway spacing limits based on vortex behavior are introduced. Finally, modified approach procedures are suggested that could have marked airport capacity increases. These procedures are presented using the Air Traffic Control manual [Anon, 2000] parlance.

CURRENT OPTIONS

The safety of aviation operations requires that aircraft not encounter either each other, or the wake turbulence from a larger aircraft. Air traffic control separation standards [Anon, 2000] have been developed to prevent both types of encounter. Current US standards are based on the four aircraft classes listed in Table 1, which are based on maximum certificated gross takeoff weight (MCGTOW). [Note that the B-757, while nominally classified as Large, has its own separation standards and therefore acts much like a fourth class between Large and Heavy.] Table 2 shows the IFR landing separation requirements by class between aircraft pairs (Paragraph 5-5-3 in the Air Traffic Control manual [Anon, 2000]). Note that separations of 2.5 nmi are permitted at some airports for some aircraft pairs when runway occupancy times can be shown to be less than 50 seconds.

Table 1. Wake Turbulence Classes

Class	MCGTOW (lbs)
Heavy	>255,000
B-757	255,000 – 270,000
Large	>41,000; ≤255,000
Small	≤41,000

Table 2. IFR Landing Longitudinal Separation Requirements (nmi)

	Follower			
Leader	Heavy	B-757	Large	Small
Heavy	4	5	5	6
B-757	4	4	4	5
Large	3 (2.5)	3 (2.5)	3 (2.5)	4
Small	3 (2.5)	3 (2.5)	3 (2.5)	3 (2.5)

The numbers larger than 3 nmi are based on wake turbulence considerations. The wake turbulence classes (Table 1), the separation requirements (Table 2), and the IFR approach procedures for parallel runways (Table 3, below) differ slightly from ICAO standards.

The spacing between two parallel runways defines what instrument operations (Table 3) are permitted:

1. Spacings of 4300 feet or greater permit *simultaneous independent* approaches. Such operations are most desirable since the controller and pilot do not have to consider what is happening on the other runway.
2. The spacing between runways for *simultaneous independent* approaches can be reduced to a value as low as 3400 feet for straight-in approaches and 3000 feet for angled approaches (Paragraph 5-9-8 [Anon, 2000]) if a high-update radar and monitor controller are used to detect aircraft blunders.
3. Runways spaced by 2500 feet or more can employ *simultaneous dependent* approaches. Such approaches impose a diagonal separation requirement between aircraft approaching the two run-

Table 3. Current simultaneous IFR Approach Procedures for Parallel Runways

Procedure	Paragraph [Anon, 2000]	Min. Spacing (feet)	Requirements
Independent	5-4-14	4300	None
Independent	5-9-8	3400	Straight-In, PRM, Monitor Controller
Independent	5-9-8	3000	Angled, PRM, Monitor Controller
Dependent	5-9-6	2500	Diagonal Separations Controlled

ways (Paragraph 5-9-6 [Anon, 2000]). Such separations prevent blunders from causing a midair collision. Maintaining the diagonal separation for dependent operations imposes a higher workload on both controllers and pilots than is required for independent operations.

4. Finally, runways spaced by less than 2500 feet (termed "close-spaced" parallel runways) are treated as a single runway and simultaneous instrument operations are not permitted. This limit is based primarily on the need to avoid wake turbulence encounters; wake turbulence decays to an insignificant level by the time it has traveled 2500 feet laterally near the ground.

Since the real estate cost of achieving simultaneous, independent approaches is great, many airports have close-spaced parallel runways, which can be used efficiently for simultaneous visual approaches (see next section), but not for simultaneous instrument approaches. When weather conditions deteriorate to the point where instrument approaches are required, such runways suffer a factor of two drop in capacity.

Paired Visual Approaches

Visual approaches to close-spaced parallel runways avoid wake turbulence encounters by using a different paradigm than the one used to restrict simultaneous approaches to runways spaced by 2500 feet or more. Instead of requiring that wake turbulence *never* migrate to the parallel runway, the visual approach procedure takes advantage of the *time* it takes for the wake to travel from one runway to the other. If the paired aircraft have longitudinal separations shorter than the wake travel time, then neither aircraft can encounter the wake of the other. This rationale provides wake turbulence safety for paired, nearly side-by-side, visual approaches to close-spaced parallel runways. Paired visual approaches are routinely used, even for runway spacings as small as 750 feet, such as at San Francisco International Airport (SFO).

The use of paired visual approaches requires that the ceiling be above the altitude where the visual merge takes place. The normal altitude for merging follows the normal IFR 3-degree glideslope from the runways out to the merge region, which may be 10 nmi from touchdown. When the ceiling drops below the normal altitude for merging, the controllers and pilots can still avoid the drop to single-runway landing capacity by reducing the merge altitude below the normal level. This process requires that controllers vector the aircraft to a lower merging altitude and may require greater workloads for both controllers and pilots, especially when terrain limits the safe aircraft paths.

Localizer-type Directional Aid (LDA) Approaches

Using a precision approach (glideslope and localizer) to descend through the ceiling can provide lower workloads for both controllers and pilots. To provide safe lateral separations above the ceiling, the localizer for one runway is displaced laterally and angled slightly (e.g., 2.5 degrees) with respect to the runway orientation. Such an LDA approach has been used for 15 years at St. Louis (runway spacing = 1300 feet) and is proposed for use at San Francisco (runway spacing = 750 feet). The proposed San Francisco procedure is called a Simultaneous Offset Instrument Approach (SOIA) and differs from the St. Louis procedure by incorporating a precision runway monitor (PRM) to permit smaller lateral separations above the ceiling.

WAKE VORTEX BEHAVIOR NEAR THE GROUND

The expected wake vortex transport depends upon its proximity to the ground relative to the wingspan of the wake-generating aircraft:

Out of Ground Effect (i.e., wake more than one wingspan above the ground) – The wake is transported laterally by the ambient crosswind. The wake normally descends because of the mutual interaction of the two wake vortices. Exceptions to descent can occur with atmospheric stratification, thermal activity, or strong crosswind shear. The wake behavior out of ground effect has been studied and modeled, but large statistical databases (e.g., 50,000 arrivals) do not exist.

Into Ground Effect – As the wake nears the ground, the interaction of the two wake vortices with the ground causes them to separate and halt their normal descent. The wake vortex height reaches a minimum value of about half the initial vortex spacing and then may increase. The behavior of wakes descending into ground effect has been studied and modeled extensively; large statistical databases (e.g., more than 50,000 arrivals) are available, but do not include many of the newer aircraft types.

In Ground Effect (i.e., wake less than half a wingspan above the ground) – Wake vortices generated near the ground may not attain their full strength, but also may be at lower altitudes than reached by descending into ground effect. The limited data available on wakes generated in ground effect suggest that the interaction of the wake with the ground causes rapid lateral motion, but also rapid decay. Data currently being collected by the wake turbulence tracking system at SFO will provide statistically significant amounts of data on in-ground-effect wakes.

On Ground – After an aircraft has landed, much of its weight is carried by the landing gear. However, until the spoilers are deployed, the wings are still generating lift and hence generating a wake. Wakes from landing aircraft on the ground have not been studied and are not expected to be a problem, but are a part of the current SFO investigation.

Lateral Transport is Critical

Wake descent and wake decay play important roles in the wake turbulence safety of diagonal-separation procedures where the longitudinal separations can be 60 seconds or larger. The longitudinal separations for typical paired approaches are smaller, perhaps 30 seconds or less. At SFO, the longitudinal pair separations are kept short so that departures can be launched on the crossing runways between arriving pairs. For such short separations, the wake has not had much time to descend or decay. In fact, the descent may be less than the vertical variation in flight path. Thus, a robust safety algorithm for side-by-side approaches cannot consider descent or decay, but must be based on lateral transport. Note that, when parallel runway thresholds are displaced by more than a few hundred feet, vertical separations *can* affect the probability of wake encounters; the analysis herein assumes that the runway thresholds are not displaced.

Using lateral transport alone greatly simplifies the safety analysis. Out of ground effect safety can be assessed in terms of the ambient crosswind. In ground effect, where the ground interaction can accelerate the lateral transport, safety can be assessed by sensors which can track the vortex lateral position.

If the longitudinal pair separation is small enough, wake turbulence encounters are not possible. For larger longitudinal separations, wake turbulence encounters may become possible when the crosswind is strong enough to move the wake from the leading aircraft into the path of the following aircraft on the other runway. Wake turbulence safety then depends upon a tradeoff between the maximum allowed longitudinal separation and the maximum allowed crosswind.

Effective Crosswind

The development of procedures based on measured or predicted crosswinds must have a safety methodology that can accommodate the way such information can be provided. For example, NASA's Aircraft Vortex Spacing System is provided crosswind values [Hinton, 1996] in terms of a mean and standard deviation. Alternatively, the following methodology is proposed:

1. Separation standards are stated in terms of "effective crosswind" limits. The "effective crosswind" correctly predicts wake lateral

transport, and can be derived by working backwards from observed vortex transport. Although some variation in the "effective crosswind" could come from possible lateral variations in aircraft positions, such variations can be incorporated into a safety buffer in defining the safety limits on the "effective crosswind."

2. The procedure is determined by assessing the probability (based on mean and standard deviation values) that the actual crosswind violates the effective crosswind limits. The safety level is set by how small this probability must be. This analysis must also include any variations in crosswind between the measurement location and the wake location.

Burnham, et al. [2000] developed a model for wake transport using the "effective crosswind" concept and the methodology just described. The model was based on approximately 80,000 landings and was used to distinguish the wake vortex transport effects from the crosswind measurement effects. Currently [Hallock, et al., 2000], a substantial data set on vortex transport between parallel runways at Frankfurt Airport is being analyzed to further develop the model.

REDUCTION IN RUNWAY SPACING LIMITS

The 2500-foot limit on parallel-runway spacing is designed to assure wake turbulence safety for all aircraft types under all weather conditions. A worst case might be a PA-28 landing on one runway after a B-747-400 has landed on the other, with a 10-knot crosswind blowing from the B-747's runway to the PA-28's runway. Limits on crosswind and/or aircraft types could eliminate wake turbulence considerations for runways spaced by less than 2500 feet. Runway threshold displacements will also play a role, but, as noted earlier, will not be addressed herein.

If the 2500-foot limit can be reduced under certain restrictions, then the diagonal-separation instrument procedure should be applicable. Although the diagonal-separation procedure has been defined for many years, it has seldom been implemented because of the small number of runways with the necessary spacing (2500 to 3000 feet) and perhaps also the relative high controller workload of simultaneous dependent approaches.

Crosswind Criteria

Frankfurt Airport (parallel runway spacing of 1700 feet) has spent more than 15 years developing a parallel runway wake turbulence system [Tetzlaff, et al., 1991; Gurke and Lafferton, 1997] based on crosswind and aircraft type criteria. Two types of criteria were developed:

1. When the crosswind magnitude is below a certain value, then wake turbulence from neither runway can migrate to the other. For Frankfurt, crosswinds below 4.7 knots (measured at 50-ft height) were found to prevent wake transport between the runways.
2. When the larger aircraft is assigned to the downwind runway, its wake turbulence cannot reach the upwind runway. If the wake turbulence from the smaller aircraft on the upwind runway were to reach the downwind runway, it is too weak to affect the larger aircraft.

The selection of operating mode depends upon the ambient crosswind, which is measured operationally at Frankfurt using an array of anemometers between the runways. The Frankfurt development devoted considerable effort to the transitions between operating modes and the need to forecast changes in operating mode. Pilot acceptance of the German system has bogged down over questions of wake turbulence safety along the glideslope to the merging point. An LDA approach would reduce the range of such questions.

Burnham and Hallock [1999] analyzed US data on how the crosswind affects wake transport between parallel runways for wake vortices moving into the ground effect region. Wake vortices travel farther in medium crosswinds (6-9 knots) than in weak crosswinds (0-3 knots) or in strong crosswinds (>12 knots). In weak crosswinds, vortex aging is important; in strong crosswinds, the interaction with the ground and crosswind shears (particularly on the downwind vortex) lead to rapid vortex decay. For a given crosswind range, the probability of a vortex reaching a certain distance from the runway centerline decreases as that distance increases. In many cases, the log of the probability is proportional to the distance squared.

Aircraft Criteria

The 2500-foot spacing limit, needed for the worst case (e.g., Heavy aircraft on one runway and Small aircraft on the other), is likely to be reduced for smaller aircraft types (e.g., no Heavies) or smaller differences between the size of the types (e.g., only Large) landing on the two runways. An old study recently published [Burnham and Hallock, 2000] developed a methodology for estimating what runway spacing would be required for different classes of aircraft. The parallel runway criteria were based on the longitudinal spacing criteria used for single runways and a model for wake transport between runways. Because of the uncertainties in the assumptions of the model, the absolute values determined in the report cannot be used. However, the results indicate that wake-independent operation of parallel runways may be possible for restricted aircraft classes at spacings much less than the current 2500-foot standard.

The application of reduced wake-turbulence runway-spacing criteria would again make use of the diagonal-separation procedure. Suppose that Large and Small aircraft can safely simultaneously use parallel runways spaced by 1500 feet or greater. Consider Boston's Logan International Airport with a spacing of 1500 feet between runways 4L and 4R. The diagonal-separation procedure would be used for Small and Large arriving aircraft. When a Heavy arrives in the traffic mix, it would block arrivals on both runways for the single-runway separation distance of 5 or 6 nmi for a following Large or Small aircraft, respectively. Since Heavy aircraft are a small fraction of the Logan traffic, the single-runway requirement would have only a minor impact on the two-runway capacity of the diagonal-separation procedure.

PROCEDURE COMPARISONS

Two procedures have been proposed for instrument approaches to close-spaced parallel runways. The two have opposite longitudinal separation requirements. Each has advantages and disadvantages. One question for future consideration is the relative pilot and controller workload for the two procedures.

Diagonal Separation

The diagonal-separation procedure specifies a minimum diagonal separation (really a longitudinal separation requirement for close-spaced runways) to prevent aircraft encounters. Wake turbulence encounters are prevented by restrictions on aircraft types and/or crosswind. Aircraft type restrictions are fixed and hence readily incorporated into the air traffic control rules. Crosswind limits, unless they are very broad, will vary in time and will be more difficult to apply.

The diagonal-separation procedure has no visual segment and hence is applicable under all IFR conditions. However, the safety of its wake turbulence criteria may be more difficult to validate and maintain than those for paired approaches.

Paired Approach

The paired-approach procedure requires a visual segment to prevent aircraft encounters. It is therefore applicable only when ceilings are high enough to permit the visual segment. Wake turbulence considerations become important only when the smaller aircraft lags behind the larger aircraft by an amount that depends upon the crosswind. Since lateral wake transport over short times is well understood, the safety criteria are likely easier to validate than those for the diagonal-separation procedure, where safety depends upon wake decay, which is less well understood.

As discussed above, an LDA or SOIA paired approach can safely bring a pair of aircraft below the ceiling, where the landing can be made as a visual flight segment. However, since a pilot has no information about the location of his paired aircraft until he breaks into the clear air, he cannot take full responsibility for safe wake turbulence separation requirements. In this situation the controller must guide the aircraft pair into positions where wake encounters cannot occur. [Future technology may provide enough cockpit situation awareness that the pilot can take full separation responsibility even though he cannot directly see the other aircraft.]

While the prevention of midair collisions is the most obvious safety requirement of side-by-side instrument approaches, wake turbulence avoidance must also be accomplished before a new procedure can be accepted. Such avoidance can be achieved by various restrictions on the operation, including such alternatives as:

1. Lead aircraft on downwind runway, trailing aircraft on upwind runway;
2. Larger aircraft on downwind runway;
3. Larger aircraft trailing; and
4. Combined restrictions on crosswind and longitudinal separation.

PROCEDURE FORMULATION

Diagonal-Separation

The simplest standard to formulate is the aircraft class dependence of the 2500-foot rule. Paragraph 5-5-3 of the ATC manual could be revised: *because of the possible effects of wake turbulence, consider parallel runways spaced by less than the values listed in Table 4 as a single runway for the class pairs involved.* The values in Table 4 are conservative extrapolations of the results in Burnham and Hallock [2000].

The diagonal-separation rule in Paragraph 5-9-6 could be restated: *provide a minimum of 1.5 miles radar separation between successive aircraft on adjacent localizer/azimuth courses when runway centerlines are spaced by at least the value in Table 4, but no more than 4,300 feet apart.* In other words, this procedure is limited to aircraft

Table 4. Possible IFR Landing Parallel Runway Spacing Requirements (feet) by Class Pair

Lead AC	Trailing Aircraft Heavy	B-757	Large	Small
Heavy	1500	2000	2000	2500
B-757		1200	1500	2000
Large			1000	1500
Small				700

pairs with values in Table 4 equal to or less than the actual runway spacing. Note that the values in Table 4 are hypothetical until validated. When combined with runway threshold considerations, they could support the example of Logan Runways 4L and 4R (or 22L and 22R) discussed earlier.

Crosswind limits on diagonal separations are perhaps more difficult to specify since the source of the crosswind data must be considered. A possible formulation (to be added to Paragraph 5-9-6) could be that *this procedure can be used for runways spaced by less than 2500 feet provided that:*

1. *The crosswind is monitored over the airspace where the aircraft lateral spacing is equal to the runway spacing;*
2. *The larger aircraft are assigned one of the runways; and*
3. *The crosswind from the larger-aircraft runway toward the other runway is no larger than the value in Table 5.*

For example, with a parallel runway spacing of 1000-1500 feet, the crosswind must be such that the larger aircraft is downwind (a negative crosswind) or that the crosswind does not exceed +1 knot in the direction of the smaller-aircraft runway.

The crosswinds are measured in multiple locations (condition 1 above) and are 1-minute averaged values; wind variability and persistence are important operational issues, but are not addressed here. Again, the values in Table 5 are hypothetical [Burnham and Hallock, 1999] until validated. They do represent the expectation

Table 5. Crosswind Limits on Diagonal Separation Operations

Runway Spacing (ft)	Crosswind Limit (knots)
<500	-2
500-1000	0
1000-1500	+1
1500-2000	+2
2000-2500	+3

that wake transport will need some assistance from the crosswind to reach greater lateral transport distances.

The proposed formulations using Tables 4 and 5 consider separate aircraft and crosswind criteria. Since many airports have few Heavy aircraft, it may be worthwhile to formulate crosswind criteria that exclude Heavy aircraft.

Paired Approach

The paired-approach procedure will likely need a new paragraph in the ATC manual: *Simultaneous Paired Parallel Dependent ILS/MLS Approaches - Terminal:*

a. *Authorize simultaneous dependent ILS, MLS, or ILS and MLS paired approaches to parallel dual runways with centerlines spaced by less than 2500 feet, with one localizer offset by 2.5 degrees and displaced laterally by 4300 feet (3000 feet with PRM) at the missed approach point. Aircraft on the offset localizer must accept a visual final approach segment before the missed approach point or execute missed approach.*

b. *Establish pair longitudinal spacing such that wake turbulence encounters will not occur according to one of the following criteria, some of which require monitoring the crosswind over the critical distance where the aircraft lateral spacing is equal to the runway spacing:*

1. *The smaller aircraft is in the lead;*
2. *The larger aircraft is on the downwind side over the critical distance;*
3. *When the smaller aircraft may be behind the larger aircraft, its longitudinal separation will not exceed the values in Table 6, where the crosswind listed is the maximum value from the larger-aircraft runway toward the smaller-aircraft runway over the critical distance* [i.e., for a crosswind that does not exceed 10 knots from the larger-aircraft runway, the two aircraft must be separated by no more than 31 seconds for parallel runways spaced 1000-1500 feet apart or 52 seconds for parallel runways spaced 1500-2000 feet apart]; *or*
4. *When the smaller aircraft may be behind the larger aircraft, its longitudinal spacing will not exceed the values in Table 6 for 20 knots crosswind.* [The 20-knot value is assumed to cover normal operations and hence apply when crosswinds are not monitored.] The model of Burnham, et al. [2000] was used to derive the values listed in Table 6. Additional validation will be required before Table 6 can be adopted for ATC use. A safety assessment of a similar simultaneous paired parallel dependent approach has been completed [Lankford, et al., 2000].

Table 6. Maximum Longitudinal Separation (seconds) versus Runway Spacing and Crosswind

Runway	Crosswind (knots)		
Spacing (ft)	6	10	20
750-1000	28	20	12
1000-1500	43	31	18
1500-2000	73	52	30
2000-2500	102	73	43

CONCLUSIONS

The results of years of observations and analyses of wake turbulence data and the use of simple wake turbulence transport models indicate that safe instrument approach procedures can be developed for close-spaced parallel runways. Diagonal separations and paired-approach procedures incorporating appropriate limits on the longitudinal aircraft pair separations, aircraft categories, and/or crosswinds offer capacity gains in the near term. The potential limitations identified in this study (displaced thresholds, wind variability, confirmation of rapid decay of vortices generated very close to the ground, pilot/controller workload, operational acceptance) need to be addressed and are being addressed, but the results are encouraging.

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ACRONYMS

ATC	Air Traffic Control
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
LDA	Localizer-type Directional Aid
MCGTOW	Maximum Certificated Gross Takeoff Weight
MLS	Microwave Landing System
NASA	National Aeronautics and Space Administration
PRM	Precision Runway Monitor
SFO	San Francisco International Airport
SOIA	Simultaneous Offset Instrument Approach

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