A PHASED APPROACH TO INCREASE AIRPORT CAPACITY THROUGH SAFE REDUCTION OF EXISTING WAKE TURBULENCE CONSTRAINTS

Steven Lang, Federal Aviation Administration, Washington, DC

Anand D. Mundra, Wayne W. Cooper, Jr., Benjamin S. Levy, Clark R. Lunsford, Arthur P. Smith III, Jeffrey A. Tittsworth, The MITRE Corporation, McLean, VA

Abstract

This paper outlines the operational issues involved in using knowledge of wake turbulence behavior to develop candidate terminal approach procedures that would increase arrival capacity at a variety of United States airports. Later procedures build incrementally on the experience that would be gained with these initial procedures. The process by which the Federal Aviation Administration (FAA) and The MITRE Corporation's Center for Advanced Aviation System Development (MITRE/CAASD) have been analyzing these candidate procedures will be discussed. This process is part of the broader effort to implement an FAA/National Aeronautics and Space Administration (NASA) Wake Turbulence Research Management Plan (RMP).

Two candidate procedures, and their operational variations, are described in detail, along with expected capacity benefits at selected airports. The analysis methodology is described. The first procedure is a near-term proposed change to the 2500 foot separation minimum for dependent approaches to two parallel runways. The second procedure is a mid-term proposed change to reduce wake constraints for departures from parallel runways spaced closer than 2500 feet using a short-term prognosis of crosswinds at and near the area of aircraft rotation. Activities, such as additional wake data collection at a field site, that are planned during the current year to advance towards the specific design and implementation of the procedures are also briefly outlined.

Introduction

Wake vortices are a natural by-product of lift generated by aircraft. An aircraft exposed to the wake vortex circulation of another aircraft can experience an aerodynamic upset which it may or may not be able to easily correct with its control authority, especially when an aircraft is close to the ground. For this reason, numerous Air Traffic Control (ATC) separation standards include consideration of wake vortex behavior, defining the separation at which operations can be conducted without a concern for a wake vortex hazard. These separation standards have served us well in that there has never been a fatal accident in the U.S. due to wake vortex when instrument flight rules (IFR) separations are being provided.

Wake vortex behavior is strongly dependent on ambient weather conditions. In certain conditions, such as calm winds without turbulence, they linger and last longer. Separation standards and ATC procedures have been designed for the worst conditions with respect to wake behavior. For this very reason, however, it has long been believed that there may be room for enhancing ATC procedures if wake vortex behavior were known more precisely.

Over the years, there have been several efforts in the U.S. and abroad to develop technologies that provide improved knowledge of wake behavior based on environmental conditions, and to implement ATC procedures utilizing this improved knowledge. Some of these efforts are beginning to yield successful results.

The U.S. has deployed a procedure called Simultaneous Offset Instrument Approaches (SOIA) [1]. Depending upon the runway geometry, the SOIA procedure can require specific wake vortex related features. SOIA is in the implementation phase at San Francisco (SFO) and St. Louis (STL). Several other procedures have been considered or proposed over time and some are incorporated in the FAA/NASA Wake Turbulence RMP [2]. The RMP has been developed jointly by the FAA and NASA to direct current and future efforts. The research described in this paper is part of the work laid out in the RMP

Numerous wake vortex research and implementation efforts are underway in Europe. The German ATC provider Deutsche Flugsicherung (DFS) has developed the High Approach and Landing System (HALS) [3], which has been in operational trials at Frankfurt, Germany, since June 2001. DFS is also developing a Wake Vortex Warning System (WVWS), which appears to have a good outlook for implementation [4]. The current research and development efforts in the U.S. and Europe are being coordinated through the FAA/Eurocontrol Cooperative R&D Action Plan 14 [5].

The benefit to be derived in the U.S. National Airspace System (NAS) from wake vortex related procedures depends on the operational applicability of each specific procedure. Some procedures may promise a larger benefit, but may require a greater technological component, and a correspondingly greater commitment of resources for development and implementation. Other procedures may not provide the same degree of benefit but may require less technology and correspondingly less developmental risk.

MIT Lincoln Laboratories and MITRE/CAASD developed an initial list of candidate procedures, and after interviewing wake research experts and stakeholders, provided an initial qualitative assessment of risks to developing these procedures, which was briefed to the community [6]. Additional work led by MITRE/CAASD yielded a description of 25 candidate terminal procedure concepts [7] that have been used as a starting point for analysis that led to the selection of the two procedure concepts described in this paper. This initial MITRE/CAASD work, performed in FY2001, was internally funded as MITRE Sponsored Research.

Procedures belong to one of three development phases, depending on the level of new technology required:

1. Near-term (implementation within five years): procedures requiring procedural changes only, without any new decision support tools for the controller or pilot. Wake behavior is bounded with field data and procedures are certified through modeling and simulation. No real-time measurement or prediction of wind or aircraft wakes is incorporated in the operational system as part of the implemented procedure.
2. Mid-term (implementation within 10 years): procedures requiring procedural changes and simple controller tools. Active measurement and prognosis of wind behavior can be included.
3. Far-term (implementation after mid-term): procedures requiring procedural changes, more complex controller tools, and potentially also pilot tools. Active measurement and prognosis of weather and wake behavior can be included.

The ranking of potential wake avoidance solutions also resulted in the identification of mid-term and far-term goals for the FAA/NASA wake program. The far-term goal for the program is to develop and implement an active wake avoidance solution, similar to NASA's Aircraft Vortex Spacing System (AVOSS) [8, 9]. This solution may include weather and wake sensors, weather forecasting, wake prediction, and controller tools to present safe wake turbulence separation standards and assist in the decision making of how best to apply those standards.

The mid-term goal is to provide a bridge between the procedural changes in the near-term and the complex system of the far-term. The first mid-term goal of the program is to develop a wind-dependent solution for Closely Spaced Parallel Runway (CSPR) departures (i.e., for departures from parallel runways spaced from 700 to less than 2500 ft between centerlines). This solution would consist of a set of wind sensors, a wind prediction algorithm, and a simple controller tool that indicates the period of time in which independent departures can safely be performed. The mid-term goal matures some of the components needed to meet the far-term goal. It is expected that a periodic reassessment of the associated technology risks and procedure risks of potential solutions, and the potential airport capacity constraints, will lead to additional evolutionary steps between mid and far-term goals.

These goals are depicted on a timeline in Figure 1.

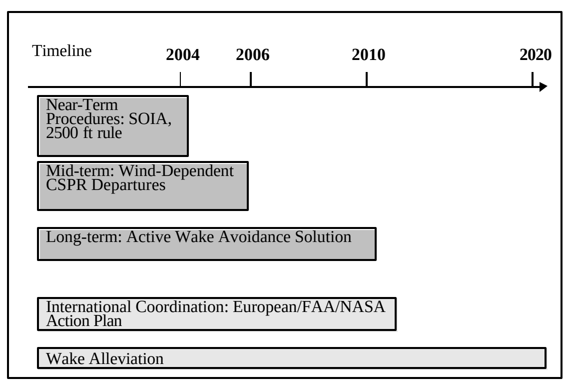

Figure 1. RMP Timeline

Procedure Down-Selection Process

Over the last 30 years, many wake turbulence avoidance solutions have been proposed as efforts to gain some capacity increase while maintaining safety. As technologies in weather and wake sensing and modeling have advanced, these proposed solutions have become more complex. In FY02, the FAA initiated a process to lay out an evolutionary approach to implementation of wake turbulence avoidance solutions. A key goal of that process was the selection of near-term solutions and applicable airports for implementation of early capacity improvements.

The process ranked more than 25 wake avoidance solutions based on their potential for increasing capacity at existing capacity-constrained airports and on the technology development and procedure change risks associated with each solution. The solutions ranged from ATC procedure changes to solutions requiring complex systems and procedures that predict and monitor wake behavior. They included applications for single and parallel runways for arrivals and departures, as well as intersecting runways. The airports considered in the down-selection process included the 35 airports in the NAS experiencing the highest average delays. The two procedures described in this paper were identified through that down-selection process. Figure 2 depicts the iterative process used.

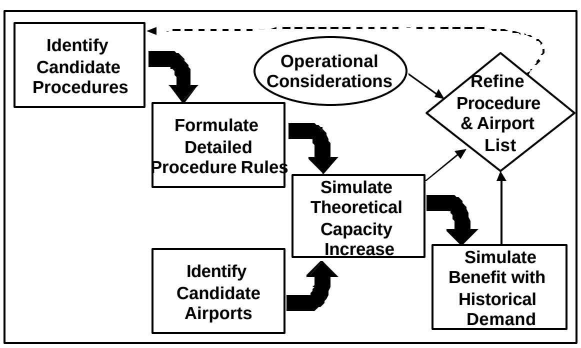

Figure 2. Procedure Down-Selection Process

First, candidate terminal procedures were developed, based on current knowledge of existing procedures and of wake behavior, using the 25 procedures described in previous MITRE/CAASD work. Second, procedural rules were developed to the level of detail required for Monte Carlo simulations for capacity computations. Third, a theoretical estimate of the capacity of each procedure was simulated by a Monte Carlo simulation methodology, for airports with specific characteristics (e.g., eligible runway configurations, excess demand, frequency of suitable weather conditions, etc.). It is the results of this step that are documented in this paper.

The down-selection process also included the application of the capacity benefits simulated for each airport for the conditions for which the candidate procedure can be used to the historical demand and weather conditions at the candidate airports for a substantial period of time, in this case, 11 months. Results of this process are not reported in this paper, but the process is described here briefly for completeness. FAA Aviation System Performance Measurements (ASPM) data was used to provide an hourly time series of weather conditions and a quarter-hourly time series of airport demand, operations and capacity for the period from October 2000 through August 2001. An "effective increase" in capacity was computed as the additional number of aircraft which could land in their desired time period as a result of the simulated capacity increase, given the historical weather, demand and capacity. The capacity increase for each quarter hour was calculated as the historical capacity (i.e., rate called by the ATC tower) multiplied by a capacity expansion factor as computed from the Monte Carlo capacity simulations. This step is outlined with interim results in previous work [10], and is not covered in this paper.

Finally this theoretical analysis was augmented by a practical consideration of the operations at the candidate airports and of the proposed procedures themselves. This process was repeated several times at different levels of detail. In these iterations, the analyses measured potential capacity benefits for all the most promising procedures, including arrival and departure procedures for single runways (e.g., reduced in-trail wake vortex spacing), as well as procedures for intersecting runways. The relative capacity benefits of the parallel runway arrival procedures far exceeded those for other procedures, while the technology requirements and risks were less than those for other procedures. For these reasons, procedures for closely spaced parallel runways were selected for the near-term and first mid-term development. This process and the associated analytical results are documented in previous work [10, 11].

In less than Visual Meteorological Conditions (VMC), the current FAA rule requires parallel runways spaced less than 2500 ft to be treated as a single runway. While in-trail wake separation standards are dependent on wake categories of the generating and encountering aircraft, this rule is not. This paper shows that, by refining this standard to reflect the differences between different generating and encountering aircraft pairs, substantial capacity benefits may be possible. As indicated above, the capacity computations were based on a Monte Carlo capacity simulation process, described next.

Monte Carlo Simulation Methodology

The "Simulate Theoretical Capacity Increase" step in Figure 2 is based on a straightforward application of the Monte Carlo simulation technique. The final simulation results are expressed as a mean and standard deviation of the modeled capacity increase in aircraft per hour (i.e., maximum throughput increase) for a specific procedure concept and airport. These simulation results were based on a set of 500 experiments per procedure, with each experiment being a simulation of a 50 aircraft arrival or departure stream, to correspond operationally to a sustained peak arrival or departure period at that airport.

Figure 3 depicts the process of simulating a proposed procedure at a candidate airport. There are six main inputs to the Monte Carlo simulation: (1) Traffic Distribution by Weight Class for Airport: The average percentage of flights in each weight class, based on historical averages from FAA Enhanced Traffic Management System (ETMS) data. A weight class is randomly assigned to each flight based on this distribution; (2) Detailed Procedure Separation Rules: The specific rules used to maintain the minimum time or distance separation required by the procedure, considering both in-trail separation, and, if required, separation from the flight on another path (e.g., a parallel path); (3) Control Parameters: The number of flights per experiment and number of experiments in simulation; (4) Distribution of Spacing Precision: A uniform distribution of excess distance by which a flight is expected to follow a separation rule, from zero to a specified upper bound, to reflect natural variation in controller and pilot use of a procedure; (5) Runway Pair and Approach Geometry: Runway center-line separation, threshold offset, runway length for departures, and approach geometry (offsets, etc.) for arrivals and departures; (6) Landing Speed Distribution by Weight Class: Expected range of aircraft speeds at threshold, modeled as a uniform distribution.

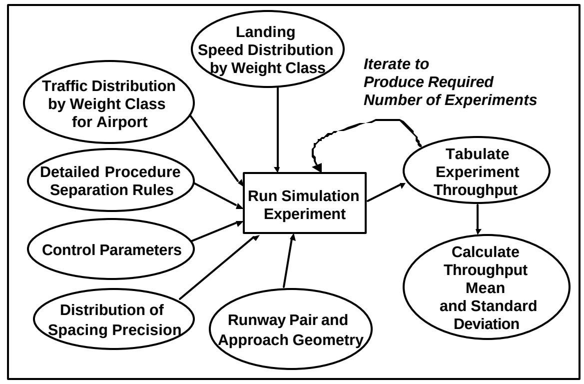

Figure 3. Monte Carlo Simulation Process

The procedure is simulated for the runway or pair of runways at the specific airport, for the specified number of randomly generated flights. Each flight is assigned a particular weight class, with spacing from the previous flight in nautical miles (nmi) reflecting the spacing standards proposed in the procedure and a spacing precision, and the landing speed in knots. After each experiment, the mean throughput per hour for the runway or runway pair for that experiment is calculated and stored. After all experiments are run, the global mean and standard deviation of throughput for all experiments is calculated. The standard deviation is useful in determining if two procedures have statistically significant differences in their average throughputs, as the average benefit of each procedure at an airport is a function of the randomly chosen values of weight class and spacing precision for each flight in each experiment. The computed capacity numbers are strongly dependent on the precision value used to reflect natural variation in controller and pilot use of a procedure. The results presented in this report use a precision value of 2.2 for uniformity of presentation. A precision value of 2.2 means that if the separation standard were 3 nmi, the actual separation used in the simulation would be randomly assigned anywhere from 3 to 5.2 nmi.

Both the current procedure and the proposed new procedure concept are simulated in this process for each candidate procedure and airport. The mean average hourly capacities have been found to be generally too conservative. However, as the mean average increase in hourly capacities is calculated as the difference in the simulated baseline and new procedure values, and the percentage increase is calculated as the ratio of these two simulated values, this conservative bias should be mitigated in the final results.

Near-Term Approach Procedure

The proposed near-term procedure is for dependent parallel approaches in Instrument Meteorological Conditions (IMC) and marginal VMC to CSPR pairs. Figure 4 depicts the current separation rules for such runways. In good VMC for an airport, for parallel runways spaced 700 ft or more, a pilot may accept a clearance to a visual approach, which allows the two approach streams to be independent of each other (i.e., only in-trail separation standards are used). In Instrument Meteorological Conditions (IMC) for an airport, for parallel runways spaced 2500 ft or more, a dependent parallel approach procedure may be used, which imposes a minimum diagonal spacing of 1.5 nmi between aircraft on adjacent paths, in addition to the in-trail separation standards. When visual approaches cannot be conducted (i.e., in IMC and marginal VMC), for parallel runways spaced less than 2500 ft, the two runways are treated as a single runway, and single runway in-trail separation standards are applied to pairs of flights in-trail as well as on adjacent paths.

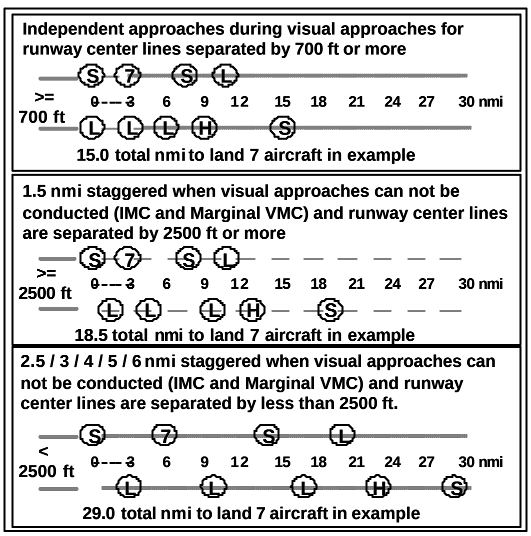

Figure 4. Current Final Approach Separation Standards for Closely Spaced Parallel Runways

The proposed procedure would provide a dependent approach for selected pairs of aircraft on adjacent parallel approaches when it can be determined empirically by wake research that the wake of the leading aircraft on one approach path will not affect the flight of a trailing aircraft on the other approach. The procedure would specify the minimum lateral separation between runway centerlines and minimum stagger between runway thresholds for which a specific pair of leading and trailing aircraft of specified weight classes can run this dependent parallel approach. If the minimum runway centerline and threshold stagger limits are not satisfied, then the procedure would revert to the current IMC procedure for CSPR. In all cases, the current in-trail separation standards would be imposed on each of the two arrival streams for wake vortex separation, and a minimum 1.5 nmi diagonal stagger would be imposed between aircraft on the two streams to eliminate the potential for collision.

The current separation standard, which limits the use of the dependent parallel approach to 2500 ft in all cases, is designed for the worst pairing of aircraft from a wake perspective, a Small aircraft following a Heavy aircraft. Wake research has shown that wakes of Heavy aircraft are stronger and transport themselves further laterally from the generator aircraft's flight path than do wakes of smaller aircraft. Burnham, Hallock and Greene analyzed the available historical data and hypothesized a new conditional separation table, based on the weight class of the leading and trailing aircraft [12]. This wake research was the necessary precursor for the analysis described in this paper. Their hypothetical lateral runway separation minima are depicted in Table 1. Note that the current separation standard would be depicted in a similar table, with all values set equal to 2500 ft.

Table 1. Hypothesized Lateral Runway Separation Minima (Feet)

Burnham et al. (2001)				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small				
Large	1500	1000		
B757	2000	1500	1200	1200
Heavy	2500	2000	2000	1500

This analysis considers the capacity benefit achievable by focusing on reducing the separation behind Small and Large leading aircraft, with the eventual option of reducing the separation behind Heavy and B757 aircraft when additional data becomes available. The near-term procedure concept includes a number of options to show the sensitivity of the expected increase in the capacity of aircraft arrivals per hour as a function of different variations in the assumptions. It should be emphasized that the proposed separation criteria are hypothetical, and must be either validated or refined based on further data collection, and all potential risks (e.g., wake encounter, collision, effect on controller and pilot workload) must be analyzed before any changes to current procedures are made.

The minimum lateral runway separations of the proposed basic procedure are contained in Table 2. It is assumed that the relatively weak wake of a Small is not a factor for a trailing aircraft[1], so a 700-ft minimum lateral runway separation is assumed to be safe behind a small aircraft. Likewise, it has been shown in the FAA safety analysis conducted for SOIA at SFO, where the runways are 750 ft apart, that the wake of a Large aircraft is not a factor for a trailing B757 or Heavy [13]. This table assumes this safe lateral separation to be 700 ft. The only value chosen from Table 1 for the basic procedure in Table 2 is the 1000 ft minimum lateral separation for a Large following a Large.

Table 2. Basic Procedure Lateral Runway Separation Minima (Feet)

Proposed Procedure (Runway Separation Only)				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	700	700	700	700
Large	2500	1000	700	700
B757	2500	2500	2500	2500
Heavy	2500	2500	2500	2500

The adjacent in-trail separation minima of the current CSPR separation standard when the leading aircraft is over the threshold is depicted in Table 3. For a Small leading any aircraft and for a Large leading a Large or larger aircraft, the adjacent in-trail separation is the minimum in-trail separation at the threshold, which is 2.5 nmi for runways meeting FAA runway occupancy time criteria, or else 3.0 nmi. For other cases, the minimum in-trail separation is specified by wake vortex minima, which varies from 4 to 6 nmi.

Table 3. Current Adjacent In-Trail Separation Minima For CSPRs (nmi)

Current Rule				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	2.5/3.0	2.5/3.0	2.5/3.0	2.5/3.0
Large	wv*	2.5/3.0	2.5/3.0	2.5/3.0
B757	wv	wv	wv	wv
Heavy	wv	wv	wv	wv

*WV=Wake Vortex

The aircraft stagger separation minima for the proposed procedure is depicted in Tables 4 and 5. Procedure Option 1A (Table 4) is for the case where the runway centerline separation is greater than or equal to 1000 ft, and 1B (Table 5) is for the case where it is less than 1000 ft. "Aircraft stagger separation" includes both the in-trail separation from the adjacent path ("wv" in this case), and the diagonal separation minima of 1.5 nmi.

Table 4. Procedure 1A Aircraft Stagger Separation Minima (nmi)

Proposed Procedure 1A: Runway Separation >= 1000 ft.				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
Large	wv*	1.5	1.5	1.5
B757	wv	wv	wv	wv
Heavy	wv	wv	wv	wv

*WV=Wake Vortex

Table 5. Procedure 1B Aircraft Stagger Separation Minima (nmi)

Proposed Procedure 1B: Runway Separation < 1000 ft.				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
Large	wv*	wv	1.5	1.5
B757	wv	wv	wv	wv
Heavy	wv	wv	wv	wv

*WV=Wake Vortex

Table 6 summarizes the capacity benefits of this procedure for seven CSPR airports in the U.S.: Boston (BOS), Cleveland (CLE), Los Angeles (LAX), Philadelphia (PHL), Seattle (SEA), STL and SFO. There are a total of 41 airports in the NAS in the U.S. with CSPRs, i.e., runways separated by less than 2500 ft. Only 27 of these airports report ASPM data. Only 11 of these use or plan to use their CSPRs for simultaneous arrivals. Of these, the seven airports listed in Table 6 rank the highest in arrival delays, based on average daily Operations Network (OPSNET) reported delays per 1000 operations, using data for the year 2000. SFO, BOS and PHL rank as the 4th, 5th and 6th most delayed airports in the FAA Capacity Benchmark Study [14]. Table 6 also shows the runway configurations used by those airports for arrivals, and the traffic mix at these airports.

Table 6. Capacity Benefit For Proposed Procedure Based On Runway Separation

Airport	LAX	SFO	SEA	CLE	STL	PHL	BOS
Runway Spacing (ft)	700	750	800	1250	1300	1400	1500
Runway Pair1	24L/R	28L/R	16L/R	6W/R	12L/R	27L/R	4L/R
Runway Pair 2	25L/R		34L/R	23L/W	30L/R	9L/R	
Minimum In-Trail Sep. (nmi)	2.5	3.0	2.5	3.0	2.5	2.5	3.0
% Small Ops.	18%	23%	10%	8%	8%	28%	18%
% Large Ops.	58%	49%	78%	91%	85%	63%	66%
% B757 Ops.	12%	16%	7%	0%	6%	6%	9%
% Heavy Ops.	12%	12%	5%	1%	1%	3%	7%
Procedure capacity increase (arrivals/hr)	2.3	3.4	1.5	13.4	9.2	6.6	8.7

[1] The fact that different separation standards currently exist for different trailing weight classes implies that aircraft encounter residual wakes all of the time. Whether a wake is a factor affecting the trailing aircraft depends on the pair of aircraft involved; e.g., a Small following a Heavy requires 6 miles in-trail separation, while a Heavy following a Heavy requires 4 miles in-trail separation. Thus, the same wake is a factor for a Small aircraft but not for a Heavy.

It can be seen that this basic procedure can provide 6.6 to 13.4 extra arrivals per hour for an airport if its CSPRs are at least 1000 ft apart. The increase in capacity depends strongly on the traffic mix at each airport. It also depends on other characteristics of the airport, such as whether it is authorized for 2.5 nmi separation on final. The capacity gain is less than 4 arrivals per hour if the runways are separated by less than 1000 ft.

Runway Threshold Enhancement

As an enhancement to the basic procedure, runway threshold stagger was considered. It is well known that when visual separation is accepted by pilots, they fly high and land long in order to mitigate or alleviate potential wake hazards. Many CSPR pairs have runway threshold staggers of greater than 1000 feet. This procedural enhancement proposes that the existing threshold stagger be used to reflect the technique used by pilots today in wake avoidance, since an aircraft on the higher approach path trailing an aircraft on the lower approach path would naturally fly high and land long.

It was assumed for this analysis that if the two runway thresholds are staggered by at least 1000 ft, then the wake of a Large aircraft landing on the "low" approach can effectively be avoided by an in-trail Large or larger aircraft on the adjacent "high" closely spaced parallel approach[2]. Given this assumption, Table 7 provides the lateral separation minima for a dependent parallel approach for each pair of weight classes, and Tables 8 and 9 provide the aircraft stagger separation minima for each pair of weight classes. Procedure 1A1 (Table 8) is for the case where the runway centerline separation is greater than 1000 ft, and Procedure 1B1 (Table 9) is for the case where the runway centerline separation is less than 1000 ft.

Table 7. Procedure 1A1 and 1B1 Lateral Runway Separation Minima (Feet)

Proposed Procedure (Runway Separation and Threshold Stagger >= 1000 ft.): Procedures 1A1 and 1B1				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	700	700	700	700
Large: low approach	700	700	700	700
Large: high approach	2500	1000	1000	1000
Heavy/757: low approach	2500	2500	2500	2500
Heavy/757: high approach	2500	2500	2500	2500

2 Aircraft wake vortices tend to drop after they are generated, but this descent can sometimes be affected by wind shear above the surface of the earth, or eliminated altogether when the vortices are generated near touchdown. Wake research will need to establish the minimum vertical separation of parallel glide paths necessary to ensure wake avoidance for the trailing aircraft.

Table 8. Procedure 1A1 Aircraft Stagger Separation Minima (nmi)

Proposed Procedure 1A1: Runway Separation >= 1000 ft. and Threshold Stagger >= 1000 ft.				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
Large: low approach	1.5	1.5	1.5	1.5
Large: high approach	wv*	1.5	1.5	1.5
Heavy/757: low approach	wv	wv	wv	wv
Heavy/757: high approach	wv	wv	wv	wv

*WV=Wake Vortex

Table 9. Procedure 1B1 Aircraft Stagger Separation Minima (nmi)

Proposed Procedure 1B1: Runway Separation < 1000 ft. and Threshold Stagger >= 1000 ft.				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
Large: low approach	1.5	1.5	1.5	1.5
Large: high approach	wv*	2.5/3.0	2.5/3.0	2.5/3.0
Heavy/757: low approach	wv	wv	wv	wv
Heavy/757: high approach	wv	wv	wv	wv

*WV=Wake Vortex

With this enhancement, a Large on the low approach is always followed on the adjacent approach by a minimum of 1.5 nmi, while a Large on the high approach is followed by a minimum of 1.5 nmi (diagonal stagger) or 2.5/3.0 nmi in-trail, depending on the runway centerline separation. If a runway threshold stagger of at least 1000 ft is not available, then the procedure reverts to that described in the previous section.

Table 10 shows the capacity benefit that can be derived for the seven CSPR modeled airports with this procedure. The table shows the runway configurations at each airport along with their runway stagger values. It shows that the capacity benefit at these airports now increases, ranging from about 9 to 15 extra arrivals per hour. The potential capacity benefit at airports with runways separated by less than 1000 ft also increases slightly, providing about 4 or 5 extra arrivals per hour when the thresholds are staggered by at least 1000 ft. For configurations with runway stagger values less than 1000 ft, capacity values in Table 6 apply.

Table 10. Capacity Benefit For Proposed Basic Procedure Based On Runway Separation And Threshold Stagger

Airport	LAX	SFO	SEA	CLE	STL	PHL	BOS
Runway Spacing (ft)	700	750	800	1250	1300	1400	1500
Rwy Pair1 Thr. Stagg. (ft)	24L/R 0	28L/R 0	16L/R 0	6W/R 1500	12L/R 3400	27L/R 4800	4L/R 2200
Rwy Pair2 Thr. Stagg. (ft)	25L/R 1000		34L/R 2500	23L/W 2300	30L/R 1500	9L/R 6100	
	When runway thresholds staggered by >= 1000 ft (arrivals/hr)						
Procedure capacity increase	4.3	NA	5.1	15.2	10.3	8.7	10.3
	When runway thresholds staggered by < 1000 ft (arrivals/hr)						
Procedure capacity increase	2.3	3.4	1.5	13.4	9.2	6.6	8.7

The analysis presented here is based on the use of runway end staggers. It is being modified to reflect runway threshold stagger values

Variations

Several variations of this basic procedure were also explored:

1. A variation based on runway threshold stagger alone, and not at all on runway centerline separation
2. Several variations involving stagger separations behind Heavies and B757s on the low approach, also including the restriction of Heavies and B757s to a specific runway

It was found that a procedure based on the minimum runway stagger alone can provide 6 to 10 extra arrivals per hour for four of the seven CSPR airports modeled, if their thresholds were staggered such that the wake of a large aircraft on a low approach would not be a factor for a large or larger aircraft on the high approach. The several variations studied with respect to restricting Heavies and B757s to a specific runway had a very modest effect on the overall benefit at these airports. Detailed results regarding these variations are included in the appendix.

A procedure named "Option 2" has been formulated by the FAA as a candidate for near term implementation and involves restricting Heavies and B757s to the high approach in order to facilitate departures for the CSPR configuration. The appendix shows that the capacity of this basic FAA proposal is essentially that reported in Table 10, and provides 9 to 15 extra arrivals per hour for airports with runways separated by at least 1000 ft.

In summary, it appears that a change in the runway separation standard regarding closely spaced parallel runways involving just Small and Large aircraft could provide significant capacity benefits. Benefits of 7 to 15 additional landings per hour in IMC at airports with arrival runways separated by 1000 ft or more (Procedure 1A and 1A1) and 2 to 5 additional landings per hour in IMC at airports with arrival runways separated by less than 1000 ft (Procedure 1B and 1B1) appear possible.

The assumptions for this standard change are:

1. No wake consideration for Large (or larger) following Large for runway separations equal to 1000 ft or more
2. No wake consideration for any aircraft following a Large on a low approach. A low approach is defined in this report by a minimum of 1000 ft threshold stagger.
3. No wake concern behind a Small aircraft or for a heavier aircraft behind a Large, for runway separations equal to 700 ft or more.

Of these, Assumption 1 provides the greatest benefit; followed by Assumption 2 and 3. Assumption 1 alone (Procedure 1A) can provide 7 to 13 extra arrivals per hour for 4 of the 7 CSPR airports modeled. In addition, no loss of benefit at these seven airports would occur if the minimum runway separation for Large to Large was 1200 ft rather than 1000 ft. Very little benefit would occur at these airports if the minimum runway separation for Large to Large was greater than 1500 ft. Assumption 2 alone (see Procedure 1B2 in the appendix) can provide 4 to 10 extra arrivals per hour at 6 of the 7 CSPR airports modeled[3]. Assumption 3 alone (Procedure 1B) can provide 2 to 4 extra arrivals per hour depending on the airport.

The other implication of this analysis, reported in the appendix, is that the inclusion of certain additional enhancements dealing with stagger separation behind Heavies and B757s on the low approach would have only a modest effect on the expected capacity benefit. This is due mostly to the small percentage of these weight classes at the airports studied where these enhancements would be applicable (i.e., CLE, STL, PHL and BOS). If runway pairs existed with adequate centerline separation and threshold stagger at airports with higher percentage of these weight classes, the

[3] Applicability using threshold stagger values reduces to 4 of the 7 airports if the stagger threshold is 2000 ft; and to one airport, if it is 3000 ft.

simulated benefits for these enhancements may be more significant.

Mid-Term Departure Procedure

Current ATC procedures require wake vortex separation to be applied between successive departures if parallel runways are separated by less than 2500 ft. These increased separations can not be waived, and are applied at all times, whether the conditions are IMC or VMC. When visual separation can be applied by the tower, the two runways are treated as one only when the leading aircraft is a Heavy or a B757. On the other hand, when visual separation can not be applied, two runways separated by less than 2500 ft are treated as one regardless of the aircraft type. Currently, this increased separation is required regardless of the wind direction or speed.

A departure procedure has been proposed that could take advantage of the fact that cross winds blow wakes generated by aircraft departing from the downwind runway away from the path of aircraft departing from the upwind runway. Thus, under appropriate crosswind conditions, a trailing aircraft departing on the upwind runway will not experience the wake of a leading aircraft on the downwind runway, enabling the waiving of these restrictions in such conditions. The procedure is depicted in Figure 5. Of course, such a procedure will require a short-term wind prognosis for the area where departing aircraft become airborne. Such a procedure would be targeted for the mid-term due to the need for a new wind forecast product and an appropriate controller tool. A visual "use/do not use" indication to the local controller giving departure clearances may be adequate as a controller tool for this procedure.

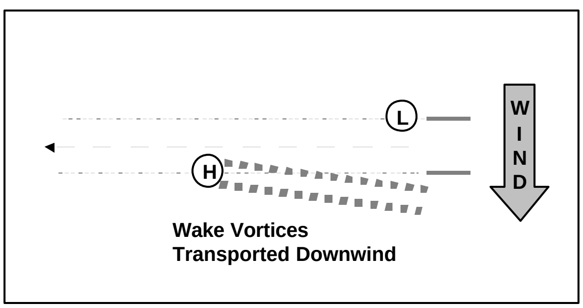

Figure 5. Mid-Term Wind-Dependent Departure Procedure

The prediction of when a wind-dependent procedure is usable (either "use" or "do not use") must consider two time windows: (1) the time window required to stage the additional operations to use the added capacity of the wind-dependent procedure, and (2) the time window required to maintain reduced separation of those operations that have accepted the clearance to use the wind-dependent procedure. The forecasting accuracy requirement for the staging time window is high, but can allow some small percentage of forecasting error to occur, so that the procedure would stop, and the additional staged demand would be delayed while airborne (arrival procedure) or hold in the departure queue (departure queue). The forecasting accuracy requirement for the separation time window is much higher, as a forecasting error in this time window would potentially increase the wake hazard for the aircraft using the procedure. The staging time window ends at the beginning of the separation time window.

A wind-dependent departure procedure for CSPR will likely be easier to implement than an arrival procedure for CSPR, as both the staging time window and separation time window are smaller for a departure procedure than an arrival procedure. For a departure procedure, the separation time window begins at the current moment and ends at the maximum time it would take the aircraft on the upwind runway receiving a departure clearance to rotate and, after a suitable time, turn-away from the path of the leading aircraft on the downwind runway (at most several minutes). For an arrival procedure, the separation time window begins at the current moment and ends at the maximum time it would take all flights currently on long final to land (at most about 10 minutes). For a departure procedure, the staging time window may include the time to taxi aircraft to the additional departure runway (at most, 5-10 minutes). For an arrival procedure, the staging time window includes the time necessary to bring in additional arrival demand from nearby departure airports and holding patterns to the terminal area (30 minutes or more).

In all of these cases, the values on the time window limits would vary from airport to airport, but the window sizes for a CSPR departure procedure are always expected to be smaller than those for a CSPR arrival procedure. Finally, the band of altitudes for which a wind prognosis would be required would be considerably smaller for departures than for arrivals, although a wider horizontal region may need to be covered for departures, especially when they are being "fanned".

The set of wind conditions that eliminates the possibility of a wake generated from a departure on the downwind runway from being a hazard to a trailing departure on the upwind runway will have to be determined from an appropriate data collection.

Then, for those wind conditions, departures from the upwind runway would be guaranteed not to encounter the wakes from downwind departures and therefore would not need the 4-mile, 5-mile or 2-minute wake separation behind Heavies and B757s. Under those wind conditions, departures from the upwind displaced threshold or intersection would not require the 3-minute delay currently required behind Heavies and B757s departing from the downwind runway. Of course, in-trail wake separation would still be applied behind traffic departing from the same runway, and applicable visual and radar separations would still be applied between all aircraft.

Capacity benefits for the wind-based departure procedure were estimated using a simple simulation of departure operations for nine runway pairs at eight U.S. airports with CSPRs that have the largest average departure delays. Several variations of environmental and operational conditions were modeled. These conditions were:

1. Conditions sufficient to remove wake hazard for upwind runway departures
2. Ceiling and visibility sufficient to run visual separation of departures
3. Ceiling and visibility not sufficient to run visual separation of departures
4. Heavy and B757 aircraft depart from downwind runway only
5. Heavy and B757 aircraft depart from either parallel runway
6. Operations where departures can be assigned diverging courses (fanned)
7. Operations where departures can not be fanned

These simulations assumed that both parallel runways are dedicated to departures[4]. If departure points on the parallel runways were displaced by more than 500 feet, the intersection departure rule was also modeled.

Table 11 shows the simulated departure capacity results for nine airports: BOS, CLE, Dallas-Fort. Worth (DFW), Detroit (DTW), Newark (EWR), PHL, SEA, SFO, STL. These results are for both the current departure separation rules and the wind-based departure procedure, in both cases assuming that visual separation can be provided. These airports are sorted by the average percentage of operations that are Heavy and B757. The wind-based procedure offers a 7 to 19% improvement in departure capacity for airports with at least 10% Heavies and B757s[5].

Table 11 also shows, as could be expected, that the benefit is increased to an 11 to 23% capacity improvement for airports with 10% or more Heavy and B757 operations where Heavy and B757 aircraft can be restricted to the downwind runway. Overall, capacity improvements ranged from 3%, at CLE, to 23%, at DTW, with most of the airports experiencing a 10 to 16% improvement in their hourly departure rate.

Table 11. Mid-Term Procedure Visual Departure Capacity Comparison

		Percentage Improvement Over Baseline Departure Capacity	
Airport/ Runway Pair	Percentage Heavies and B757s	Wind-Based Departure Procedure	Wind-Based Departure Procedure with Heavies/B757s Departing From Downwind Runway
CLE 5 W/R	1%	1%	3%
STL 12 L/R	7%	3%	14%
PHL 9 L/R	9%	5%	16%
SEA 16 L/R	12%	7%	11%
DTW 21 C/L	13%	19%	23%
DFW 35 C/L	14%	8%	12%
BOS 22 L/R	15%	8%	13%
EWR 22 L/R	18%	9%	14%
SFO 28 L/R	27%	14%	19%

Next Steps

During FY2003 several activities will begin that will further the development of the two procedure concepts outlined in this paper:

- The FAA will begin to collect wake data at STL in preparation for a future field trial of the near-term procedure. This data will be used to refine safety assessment tools used in the certification of the new procedure. FAA Flight Standards will use these assessment

4 In practice, this is usually not the case, and enhanced modeling is planned.

5 The differences in actual benefit values are a result of the specific detailed mix at each airport and other factors such as runway threshold staggers that result in the use of intersection departure rules. Benefits are reported here in percentages because these departure simulations were conducted assuming dedicated departures from both runways. This results in unrealistically high departure rates. In actual practice, most closely spaced parallel runways are shared with arrivals. It is hoped, however, that the percent increases computed would be indicative of the actual benefits that could be realized when the runways are shared for arrivals and departures.

tools to determine the minimum lateral separation and threshold stagger values required for a particular leading and trailing weight class. These refined rules will then be used to update the benefits calculated in this paper. The data collected will also be useful towards refining and certifying the mid-term procedure.

- The FAA will conduct a safety analysis, including a collision risk analysis, to determine the viability of the proposed runway separation standards.
- The FAA and MITRE/CAASD will organize a series of Human In The Loop (HITL) experiments in the CAASD ATM Lab in McLean, VA. These experiments will bring in the participation of key stakeholders, including both controllers at the facility and pilots from the major air carrier at STL. Operational issues raised by the changes from current procedures to the proposed procedures will be analyzed through the use of stakeholder discussions, designed HITL experiments and the resulting statistical analysis of the results.

Conclusion

This analysis has shown that significant arrival capacity benefits can be achieved in the near-term future with procedural changes only, at a number of major airports in the U.S. that have closely spaced parallel runways and that have significant capacity problems. Of the eight airports analyzed in this study that currently use one or more CSPR pairs for arrivals or departures, SFO, BOS and PHL ranked as the 4th, 5th and 6th most delayed airports in the U.S. in the year 2000. Thus, capacity improvements at these airports will likely result in reduced delays throughout the NAS.

The near-term benefits reported in this paper can be obtained by changing only the runway separation standards for a dependent approach when Small and Large aircraft are leading, without any changes to separations behind Heavies or B757s. The analysis also shows significant capacity benefits from a procedure that would use a short term wind prognosis to enable the release of departures on an upwind runway under conditions when the wake of a downwind Heavy or B757 is not going to be a hazard to the upwind runway.

For both procedures, the collection of the appropriate wake vortex data is being guided by issues identified by stake-holders. The statistical and operational analysis of this data will refine existing FAA safety analysis models, as necessary. Modifications to the standards will be authorized based on the appropriate FAA safety analyses.

Appendix: Procedural Variations

This appendix documents and compares several variations of the basic procedure described in the main body of the paper.

A variation of Procedure 1B1, Procedure 1B2, was analyzed to consider the case where there is no wake vortex consideration behind a Large and Small on the low approach, when both thresholds are staggered by 1000 ft or more, without including the proposed 1000 ft minimum runway separation rule for a Large following a Large. This variation considers the effect of a new separation standard for Large aircraft based on the minimum threshold stagger only, and not also the minimum runway centerline separation.

A second optional enhancement is possible with larger threshold staggers. At some level of threshold stagger, the wake of a leading Heavy or B757 on the low approach will not significantly affect the flight of a trailing aircraft. For this analysis, it was assumed that the wake of a leading Heavy or B757 will not affect a trailing aircraft if the runway thresholds were staggered by 1500 ft or more.

The three options analyzed for this enhancement are variations on Procedure 1A1:

1. Procedure 1A2: Assume that the wake of a leading Heavy or B757 on the low approach will not affect any trailing aircraft on the high approach, and restrict arriving Heavies and B757s to the high approach. This variation is referred to as "Option 2" by the FAA Wake Turbulence Program Office
2. Procedure 1A3: Assume that the wake of a leading Heavy or B757 on the low approach will not affect any trailing aircraft on the high approach, and do not restrict the approach used by Heavies or B757s
3. Procedure 1A4: Assume that the wake of a leading Heavy or B757 on the low approach will not affect any Large or larger trailing aircraft on the high approach, and do not restrict the approach used by Heavies or B757s

Tables 12 and 13 display the lateral runway separation and aircraft stagger separation minima for Procedures 1A2 and 1A3. Tables 14 and 15 display the lateral separation and aircraft stagger separation minima for the Procedure 1A4.

Table 12. Procedure 1A2 and 1A3 Lateral Runway Separation Minima (Feet)

Proposed Procedure (Runway Separation >= 1000 ft. and Threshold Stagger >= 1500 ft.): Procedure 1A2 and 1A3				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	700	700	700	700
Large: low approach	700	700	700	700
Large: high approach	2500	1000	1000	1000
Heavy/757: low approach	1000	1000	1000	1000
Heavy/757: high approach	2500	2500	2500	2500

Table 13. Procedure 1A2 and 1A3 Aircraft Stagger Separation Minima (nmi)

Proposed Procedure (Threshold Stagger >= 1500 ft. and Runway Sep >= 1000): Procedure 1A2 and 1A3				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
Large: low approach	1.5	1.5	1.5	1.5
Large: high approach	wv*	1.5	1.5	1.5
Heavy/757: low approach	1.5	1.5	1.5	1.5
Heavy/757: high approach	wv	wv	wv	wv

*WV=Wake Vortex

Table 14. Procedure 1A4 Lateral Runway Separation Minima (Feet)

Proposed Procedure (Runway Separation >= 1000 ft. and Threshold Stagger >= 1500 ft.): Procedure 1A4				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	700	700	700	700
Large: low approach	700	700	700	700
Large: high approach	2500	1000	1000	1000
Heavy/757: low approach	2500	1000	1000	1000
Heavy/757: high approach	2500	2500	2500	2500

Table 15. Procedure 1A4 Aircraft Stagger Separation Minima (nmi)

Proposed Procedure (Threshold Stagger >= 1500 ft. and Runway Sep >= 1000): Procedure 1A4				
	Trailing on Adjacent Approach			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
Large: low approach	1.5	1.5	1.5	1.5
Large: high approach	wv*	1.5	1.5	1.5
Heavy/757: low approach	wv	1.5	1.5	1.5
Heavy/757: high approach	wv	wv	wv	wv

*WV=Wake Vortex

Variation 1A2 and 1A3 benefits may be compared to measure the effect of restricting Heavies/B757s on arrival capacity. Variation 1A3 and 1A4 benefits may be compared to measure the effect of excluding Small aircraft from the enhancement.

Table 16. Traffic Distribution and Hourly Mean Capacity Increase for Variations

Airport		LAX	SFO	SEA	CLE	STL	PHL	BOS
Rwy Spacing (ft)		700	750	800	1250	1300	1400	1500
Rwy Pair1 Thr. Stagg. (ft)		24L/R 0	28L/R 0	16L/R 0	6W/R 1500	12L/R 3400	27L/R 4800	4L/R 2200
Rwy Pair2 Thr. Stagg. (ft)		25L/R 1000		34L/R 2500	23L/W 2300	30L/R 1500	9L/R 6100	
Min. In-Trail Sep. (nmi)		2.5	3.0	2.5	3.0	2.5	2.5	3.0
% Small Ops.		18%	23%	10%	8%	8%	28%	18%
% Large Ops.		58%	49%	78%	91%	85%	63%	66%
% B757 Ops.		12%	16%	7%	0%	6%	6%	9%
% Heavy Ops.		12%	12%	5%	1%	1%	3%	7%
Prc.	Rwy. Stagg. (ft)	Procedure 1A and Variations: Runway Separation >= 1000 ft						
1A	< 1000	NA	NA	NA	13.4	9.2	6.6	8.7
1A1	>=1000	NA	NA	NA	15.2	10.3	8.7	10.3
1A2[6]	>=1500	NA	NA	NA	15.1	10.3	8.6	8.7
1A3[7]	>=1500	NA	NA	NA	15.3	11.3	9.8	8.7
1A4[8]	>=1500	NA	NA	NA	15.3	11.1	9.5	8.7
Prc.	Rwy. Stagg. (ft)	Procedure 1B and Variations: Runway Separation < 1000 ft						
1B	< 1000	2.3	3.4	1.5	NA	NA	NA	NA
1B1[9]	>=1000	4.3	NA	5.1	NA	NA	NA	NA
1B2[10]	>=1000	4.3	NA	5.1	9.9	5.7	6.5	7.8

Given all of the procedural options and variations described above, the key issue is how the capacity benefit is affected by the different assumptions in each option and variation. Table 16 lists the simulated capacity benefits for all of the aforementioned procedural options, for the specific runway pairs currently used in VMC for simultaneous arrivals at seven major U.S. airports. In addition, it tabulates the key statistics for each runway pair, the centerline separation and runway

[6] Procedure 1A2: Heavies and B757s restricted to high approach only.

[7] Procedure 1A3: Heavies and B757s not restricted and no wake concern for Small or larger on high-approach following Heavy on low-approach.

[8] Procedure 1A4: Heavies and B757s not restricted and no wake concern for Large or larger on high-approach following Heavy on low approach.

[9] Procedure 1B1: No wake concern for trailing aircraft on high approach behind Large on low approach.

[10] Procedure 1B2: No wake concern for Large or larger trailing aircraft on high approach behind Large on low approach.

stagger[11], and the percentage of daily operations at each airport in each weight class[12].

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Airport Capacity, Monte Carlo Simulation, Parallel Runways, Terminal Procedures, Wake Vortex

Biographies

Steven Lang has been an Air Traffic Controller for the past 26 years. With the Federal Aviation Administration since 1984 he has been involved in Facility Management and Traffic Flow Management. He is the FAA's Wake Turbulence Program Office Manager. Mr. Lang received a B.A. in Psychology from Bellevue University in Nebraska.

Dr. Anand Mundra is a Senior Principal Engineer at The MITRE Corporation. He has 30 years of experience in developing automation and procedural enhancements to ATC systems in the U.S., Canada and Europe. He is the inventor of the Converging Runway Display Aid (CRDA), also known as "ghosting", operational at over a dozen facilities in the U.S. and Canada. Dr. Mundra received his Ph.D. from the University of Washington.

Wayne Cooper, a Lead Engineer with The MITRE Corporation, has spent 20 years in the development of decision-support tools and operational and statistical analyses for the areas of ATC, ground transportation, energy and military manpower planning. He received a M.S. in Operations Research from the Georgia Institute of Technology and a B.S. in Systems Engineering from the University of Florida.

Dr. Benjamin S. Levy is a Senior Engineer at The MITRE Corporation. He has worked at MITRE for over two years on modeling and simulation projects. His research interests include statistical pattern recognition. He holds a Ph.D. from the University of Maryland in Civil Engineering.

Clark Lunsford is a Lead Engineer with The MITRE Corporation and has been working in the area of ATC automation requirements and operations concepts for the last 18 years. He is a Commercial/Instrument Pilot and has B.S. degrees in Physics and Mathematics from Principia College.

Arthur Smith is a Principal Engineer with The MITRE Corporation. In his 30 years at MITRE he has participated in many ATC projects developing and analyzing procedures and estimating the benefits of such procedures. He holds Master's degrees in Applied Physics from Stanford and Systems Engineering from Virginia Tech.

Jeffrey Tittsworth, a Lead Engineer with The MITRE Corporation has spent the previous two years on special assignment as Research Coordinator for the FAA/NASA Wake Turbulence Program. Prior to this, he spent 18 years in modeling, simulation and analysis in the areas of defense, remote sensing and ATC. He has worked at MITRE for the last 11 years focusing on terminal and oceanic ATC. He has a B.S. in Aeronautical and Astronautical Engineering from the University of Illinois.

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