AN ANALYSIS OF POTENTIAL CAPACITY ENHANCEMENTS THROUGH WIND DEPENDENT WAKE TURBULENCE PROCEDURES

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Abstract

The Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) are jointly embarking on a multi-phased research and development program to develop and implement wake avoidance solutions that can safely reduce separations and improve capacity at airports in the National Airspace System (NAS). The mid-term phase of the research focuses on the potential application of wind-dependent procedures for improved departure operations from Closely Spaced Parallel Runways (CSPR) in the U.S. This paper describes the research performed to date by a few members of the larger research team, including the FAA, Lambert St. Louis International Airport operational staff, MIT Lincoln Laboratory and MITRE Center for Advanced Aviation System Development (CAASD). It describes the operational concept, the wind prediction algorithms being developed to support this concept and an analysis of expected algorithm performance. In addition, this paper addresses the information requirements for a decision support tool to support this procedure and the potential benefits that may be realized by this procedure at several CSPR airports in a weather and traffic demand environment.

NASA is in early stages of extending this wind-dependent solution for other operations such as single runway departures. The paper also describes the thrust of these evolutionary concepts and the directions of research.

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 may or may not be correctable with aircraft 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 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 can linger and last longer. Separation standards and ATC procedures have been designed for the worst-case conditions with respect to wake behavior. For this reason, it has long been believed that there may be room for enhancing ATC procedures, if wake vortex behavior was more precisely understood.

Over the years, there have been several efforts in the U.S. and abroad to develop technologies that provided improved knowledge of wake behavior based on environmental conditions, and to implement ATC procedures using this improved knowledge. 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 [1]. Some of these efforts are beginning to yield successful results.

The German ATC provider Deutsche Flugsicherung (DFS) has developed the High Approach and Landing System (HALS) [2], 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 [3].

The U.S. has deployed a procedure called Simultaneous Offset Instrument Approaches (SOIA) [4]. 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 Research Management Plan (RMP) [5].

The RMP has been developed jointly by the FAA and NASA to direct current and future efforts in the US. Wake avoidance solutions that are addressed in this plan belong to one of three development phases, depending on the level of new technology required:

1. Near-term (implementation within five years): operations requiring procedural changes only, without any new decision support tools for the controller or pilot. The effort underway at STL [6, 7] to enable dependent staggered approaches after Large and Small aircraft to parallel runways spaced less than 2500 ft is an example.
2. Mid-term (implementation within 10 years): procedures requiring procedural changes and simple controller tools. Active measurement and prediction of wind behavior can be included.
3. Far-term (implementation 10+ years): procedures requiring procedural changes, more complex controller tools, and potentially also pilot tools. Active measurement and prediction of weather and monitoring of wake behavior can be included.

These goals are depicted on a timeline in Figure 1. In addition to these three phases, two other separate activities are presented in Figure 1. The US and Europe are coordinating wake research to share findings from their individual research programs. Also, NASA and industry are performing research in the area of wake alleviation. Both are presented in separate shading and are provided for context.

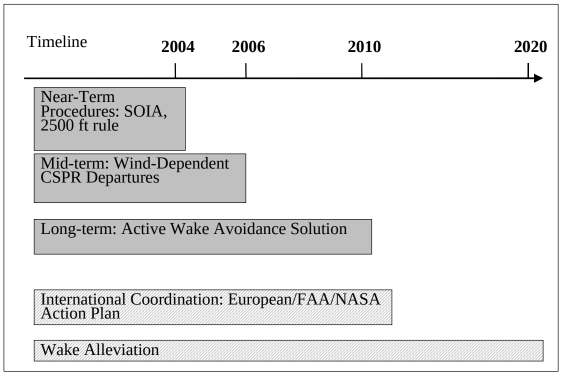


Figure 1: RMP Timeline

The mid-term goal is to provide a bridge between the procedural changes in the near-term and the more complex system of the far-term. The first mid-term solution of the program, and the focus of this paper, 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 the following components:

- a set of wind sensors
- a wind prediction algorithm
- a simple controller tool that indicates the period of time in which wake-independent departures can safely be performed

The exact design of any one of the components of this solution will depend on the performance of the other components. The research conducted to date on this solution and described in this paper provides some insight into these interdependencies.

Some members of the larger Wake Turbulence research team have begun to focus on the CSPR wind-dependent solution. The work being conducted by the FAA, Lambert St Louis International operational staff, MIT Lincoln Laboratory and MITRE/CAASD is described in this paper. This work is presented in the context of the overall research plans for this solution. The operational concept is presented along with a description of wind forecast algorithms and an analysis of the forecast performance. Early benefits estimates for the solution, based on a wind forecast algorithm, are presented along with early results in the investigation of information requirements for a controller decision support tool. This paper also discusses the NASA effort to extend this research into applications for wind-dependent single runway operations and CSPR arrivals.

CSPR Wind-Dependent Concept

Situational Opportunity

Current ATC procedures require wake turbulence separation to be applied between successive departures from parallel runways that are separated by less than 2500 ft. These increased separations are applied at all times behind Heavy Jet and B757 aircraft, whether the conditions are Instrument Meteorological Conditions (IMC) or Visual Meteorological Conditions (VMC). In the case of a trailing aircraft departing from a parallel runway with a threshold offset by 500 ft or more, the aircraft must be held 3 minutes after a departing Heavy or B757. These wake turbulence separations restrict departure capacity at CSPR airports in proportion to the percentage of Heavy and B757 aircraft in the departure demand fleet mix and affect delays throughout the NAS.

At CSPR airports such as STL, stable wind conditions are observed such as those depicted in Figure 2 below, bringing into question the need to apply wake separation during those conditions. The proposed wind dependent concept seeks to gain back some of the lost departure capacity, due to the use of wake turbulence separations, by identifying those wind conditions when an aircraft departing off runway 30L does not need wake turbulence separation to safely depart after a Heavy or B757 from runway 30R.

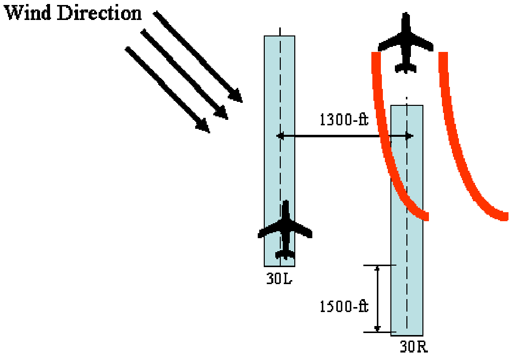


Figure 2: Depiction of Stable Wind Conditions Relative to Operations at St. Louis Lambert Airport

Concept Description

A wind-dependent CSPR departure procedure has been proposed that could take advantage of the fact that cross winds transport 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. Of course, such a procedure will require a short-term wind forecast for the area where departing aircraft become airborne and until a point where other means of safe separation is applied. A visual "wake independent/wake dependent" indication to the local controller giving departure clearances may be adequate as a controller tool for this procedure. The adequacy of this simple controller tool will depend not only on how well it supports the ATC operations, but also on the performance of the wind forecast subsystem and the ability of the overall procedure to provide a safety net function. The stable wind conditions depicted in Figure 2 range from quartering headwinds to true crosswinds and allow pilots and controllers to easily recognize the upwind and downwind runway. It is anticipated that by focusing on these wind conditions for the initial operational concept, the path to operational acceptability will be more straightforward.

The initial operational concept envisioned at STL by the team is designed to minimize the impact on ATC operations, minimize the requirements for new technology, and provide a measurable benefit to the user. The ceiling and visibility conditions targeted for this procedure are a primary contributor to meeting those design goals. Table 1 shows the ceiling/visibility conditions at STL as a percentage of time during normal airport operational hours (0600-1800 hrs local). The Good VMC and Low VMC conditions are periods of time at STL when visual separation can be applied between departing aircraft until aircraft divergence is observed. If the procedure can alleviate the use of wake separation after Heavy and B757 departures from the downwind runway during these meteorological conditions, there will be fewer exception cases to the use of visual separation, thus simplifying operations when the procedure is in use. These visual conditions also simplify the requirements for sensors supporting data collection and analysis. The combined percent of STL operations for Good and Low VMC is 88.3%, a good indicator that the procedure may provide measurable user benefit once winds are also considered.

Airport Operational Hours Under Various Ceiling Conditions in Percent of Hours (Based on 2000 ASPM data)

Good VMC (3500ft and above)	Low VMC with Dual Arrivals (1200-3500 ft)	Low VMC with Single Arrivals (1000 - 1200 ft)	IMC (below 1000 ft)	Total
66.88%	21.42%	2.50%	9.20%	100.00%

Table 1: Operational Ceilings at STL

To further minimize the impact on ATC operations, the initial operational concept focuses on the local controller tactical decisions that are made in planning and clearing aircraft for departure. The runway assignments made by the ground controller will not be affected, nor is it envisioned that the ground controller will modify departure sequences based on the wind-dependent departure solution. Runway assignments and departure sequences will be managed to optimize departure flows under today's constraints. The local controller will take advantage of the periods of time when wind conditions allow departures from one runway to be wake independent from the other.

Both runways at STL are used for arrival and departure operations during the VMC to low VMC conditions that will apply to the initial operational concept. To optimize arrival and departure throughput, arrivals are sequenced in pairs with gaps between sequential pairs to accommodate departures. These paired arrival operations are conducted in today's operations in VMC using visual approaches and in low visual conditions using offset Localizer Directional Aid (LDA) approaches to either the 12's or 30's end of the runways. Departures are launched in the gaps between the sequential pairs of arrivals. Once released, the local controller provides visual separation between the pair of departures until such time as other means of separation can be applied. When aircraft are cleared to depart off of each of the parallel runways, a divergent heading is given to at least one of the aircraft. Visual separation is maintained until at least 15 degrees of divergence is observed by the controller. This divergence is observed to occur while the departing aircraft are below 1000 ft AGL. This coincides with the lower ceiling minimums of offset LDA operations (1200 ft) at STL and sets the geographical boundary height requirement for the wind forecast subsystem. The lateral geographic boundaries are defined by the departing aircraft positions (distances from the runway ends and the runway extended centerlines) when 15 degree divergence is observed. These geographic boundaries can be determined from data collected during Human in the Loop experiments, described in Next Steps, and validated with aircraft performance data to be collected at STL.

The local controller planning horizon defines the operational requirements for the look-ahead time for the wind forecast algorithm. During busy periods at STL, when both runways are used for arrivals and departures, two local controller positions are often staffed with each controlling one runway. Figure 3 depicts a 30L / 30R operation with typical arrival and departure demand. Prior to releasing the first aircraft in line for departure from 30L, the controller will consider the aircraft that just departed on the parallel runway and the time to land for the first aircraft on final approach to 30L and perhaps the time between the first and second aircraft on final to 30L. To develop a plan for the first three aircraft waiting for departure, the 30L controller will repeat this process, considering gaps on final approach much further out, and the departure queue for the 30R controller. Sequential arrivals are typically spaced 4 to 6 nmi in trail, or 2 to 3 minutes in trail at speeds of 120 kts. A plan developed for a 2nd or 3rd aircraft in the departure queue would look 3 or 4 arrival gaps upstream on final, resulting in an approximate 10 minute planning horizon that must be supported by the wind forecast algorithm.

The solution must also provide for a safety net in the event that a wake-independent forecast changes immediately after the local controller issues a departure clearance to an aircraft on the upwind runway. The safety net must function as a replacement for the separation minimum that is waived by the procedure; 2 minutes for a 30L departure and 3 minutes for a 30R departure following a Heavy or B757 on the parallel runway. For the 2 or 3 minute period, the safety net must assure that the size of the short term changes in winds do not put the trailing aircraft at risk from the wake of the leading aircraft.

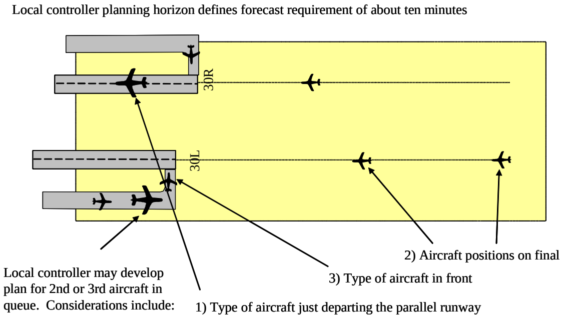


Figure 3: Local Controller Planning Horizon

The research team identified a series of evolutionary steps for the wind-dependent concept that increase the complexity of the solution while enhancing the operational benefit. The initial operational concept is the least complex, with the intent of imposing the smallest change in operations and technology to obtain a benefit. As operational experience is gained with the procedure, the concept will expand to include strategic decision making on runway assignments. The initial concept will address the stable wind conditions depicted in Figure 2 that range from quartering headwinds to true crosswinds and allow pilots and controllers to easily recognize the upwind and downwind runway. As experience is gained with the performance of the wind forecast subsystem, the concept may expand to include less intuitive wind conditions that include sufficient strength and stability to safely reduce separation. The first step in expanding the scope of the operational concept will be to affect the runway assignment for Heavy and B757 departures to take advantage of the wake independent runway in making runway assignment decisions. Clearly there are other factors in runway assignment that may be more important than wake-independence, such as runway assignment based on departure gate which keeps traffic flows separated after departure. There are occasions today when Heavy or B757 aircraft are assigned to the staggered runway, rather than the other runway more suitable for the departure gate, to avoid the 3 minute wait required for the trailing aircraft. But this procedure comes at the cost of holding departures from the other runway until the Heavy or B757 is turned toward their departure gate. More effective strategic decisions, made through coordination of ground, local and departure controller, can be supported by a wind forecast that is sufficiently stable to provide a somewhat longer planning horizon. For the purpose of initial investigation of the wind forecast algorithm a 20 minute forecast horizon is used. This forecast horizon easily addresses the 10 minute local controller planning horizon and gives an indication of the applicability for the longer planning horizon needed for concept extensions.

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. Also, 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.

Wind Prediction Algorithms and Analysis of Performance

The key to reducing the use of wake vortex avoidance separation for closely spaced parallel runways is predicting when the crosswind conditions will remain stable enough to ensure that the wake from the downwind aircraft will not impact the upwind aircraft. The relevant time scale for wind averaging is the expected one to two minute life time of a wake. In this work a two-minute time scale is used.

A prototype wind dependent wake separation system is operating in Frankfurt, Germany for arrivals into closely spaced parallel runways, using wind prediction at the surface to determine when separation for wake vortex avoidance must be used and when the extra separation is not needed [8, 9]. This led the FAA to ask the question: does the wind prediction algorithm used in Frankfurt, or perhaps another algorithm, have sufficient performance to consider it for possible use in the US for a closely spaced parallel runway departure system?

The Frankfurt algorithm uses data from a line of 10 anemometers sited along a line between the parallel runways. The airports of interest in the US do not have such a line of anemometers. However, averaging the winds from such a localized network is very similar to time averaging winds from a single anemometer; a two-minute average wind from a single anemometer corresponds to roughly an average over a 2000 ft region when the wind speeds are approximately 10 kts. It was felt that using the ASOS winds for each airport is sufficient for the purposes of the initial assessment of prediction capability.

The initial assessment showed that statistical prediction algorithms held sufficient promise that a more detailed assessment was warranted. The study continued using data from the Low Level Windshear Alert System (LLWAS). The LLWAS at St. Louis uses a 10 station anemometer network, providing 10 second updates of wind measurements over the airport region. When extended to a prediction of the crosswinds in a region, as opposed to a single point, the statistical approach continued to work well.

Crosswind prediction

Figure 4 shows a minute-by-minute plot of two-minute ASOS crosswinds at St Louis. If the requirement is crosswinds of 0 kts or greater, the goal is to predict whether or not the range of crosswinds throughout the next 5 to 20 minutes (the exact requirements will be defined by the safety net requirements and controller planning horizons) will remain above the horizontal line at 0 kts. If the entire predicted range of crosswinds is above the required crosswind threshold, the extra aircraft separation for wake avoidance is not required. If any part of the predicted crosswind range lies below the threshold, the extra separation would be required. The crosswinds must stay above threshold for 5 minutes to easily satisfy safety requirements and a 10 or 20 minute look ahead is desired for planning.

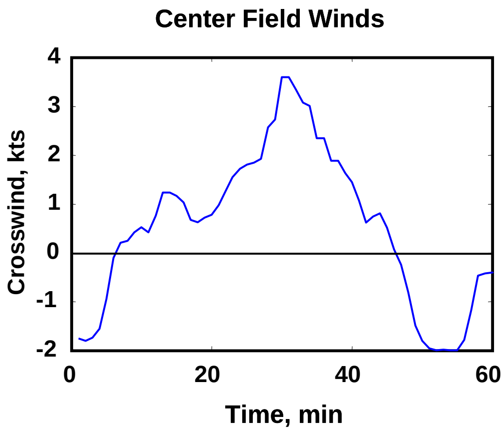


Figure 4: Trace of centerfield ASOS winds

Three prediction algorithms are examined in this paper: One based on the Frankfurt algorithm running on ASOS data, an enhanced algorithm based on ASOS data, and an algorithm based on LLWAS data. The Frankfurt based algorithm uses a simple technique based on historical ASOS data. The enhanced ASOS algorithm uses the same input data, and is based on linear regression. The LLWAS based algorithm is much like the enhanced ASOS algorithm, but uses a network of 10 anemometers. These algorithms are described in more detail in Apendix A.

Performance

The FAA is considering four airports with closely spaced parallel runways as possible future test sites: St Louis, Boston, Philadelphia, and Detroit. St Louis is currently being used as a heavily instrumented data collection site. The ASOS based wind prediction results for each airport are similar, and LLWAS data are only available for St Louis. To simplify the discussion of the results, only the results from St Louis (STL) are given here.

The initial issue is: Do these algorithms provide sufficient performance to justify a larger research effort to bring them to a state where they might be used in an operational system? In particular, are there few enough prediction errors to suggest that a refined algorithm would likely meet safety requirements while still providing significant benefit? Safety requirements, such as how frequently the operation should rely on a safety net, will need to be completed through data analysis and operational input from the stakeholders, air traffic controllers, pilots, and airlines. The method for determining the required crosswind and the tolerable level of prediction errors is an iterative one with dependencies on sensor performance and the specific procedures that are developed for using the wind-dependent solution. However, the community is in good agreement that at the four airports under consideration the likely crosswind thresholds will be in the range of 0 kts to -10 kts.

A prediction can be wrong in two ways. A type 1 error occurs when the predicted range of crosswinds lies entirely above threshold, but some of the actual future crosswinds dip below threshold within 5 minutes of the prediction. This is a conservative definition, since the algorithm updates every minute and current standards are based on a wake life time of two minutes or less. Keeping type 1 errors to a very small number is critical.

A type 2 error occurs when the predicted range of crosswinds does not lie entirely above threshold, but all of the actual future crosswinds stay above threshold for 20 minutes. Type 2 errors are cases where aircraft separations could have been reduced but were not identified by the algorithm, thus missing potential benefits.

In general, tuning an algorithm to reduce one type of error tends to increase the number of the other type. It is expected that an operational system that is used to reduce wake avoidance separation must have a method of safely dealing with type 1 errors, a safety net such as the one described in the CSPR Wind-Dependent Concept section of this paper. Nonetheless, type 1 errors must be extremely rare if a system is to be usable. In contrast, type 2 errors represent lost benefit. While it is desired to keep type 2 errors to a minimum, the requirement is only that type 2 errors be kept to a level that makes a system cost effective.

The fraction of the year with benefits is a function of both the probability of a type 2 error and how often the winds are favorable at a given airport. Fewer type 2 errors and more frequent favorable winds will lead to greater benefits for a fixed level of departure demand.

Frankfurt vs Enhanced ASOS

The Frankfurt and Enhanced ASOS algorithm each used two-minute average winds, updated every minute, from the airport ASOS system. Each model was built using approximately one year of data (1/1/2000-12/31/2000, with some missing data), and evaluated using data from a different year (1/1/2001-12/31/2001, with some missing data giving 4.7 x 10^5 evaluation points).

The comparison of algorithm performance is difficult if one algorithm produces fewer type 1 errors (better reliability), while the other produces fewer type 2 errors (greater benefits). In this comparison, this difficulty is eliminated by running the Frankfurt algorithm as designed, and the value of *n* in the enhanced algorithm (see appendix A) is set so that each algorithm has the same probability of a type 2 error. Thus the algorithms are tuned to provide the same benefit and a fair basis exists for comparison of type 1 errors.

Both provided the same benefits (as tuned for this part of the study), recovering 60% to 90% of the potential benefit, depending on the crosswind threshold and airport selected. The rate of type 1 errors is much smaller for the Enhanced algorithm, roughly 0.1% vs 1% for the Frankfurt algorithm.

LLWAS

The value of *n* in equation 3 (see Appendix A) can be chosen to be small to make the predictions more aggressive in providing benefit or larger to make the predictions less aggressive in providing benefits (by making the value of *n* in equation 3 smaller or larger, respectively). The trade off is that being more aggressive in providing benefits comes at a cost of increasing type 1 errors, where *n* allows one to trade type 1 and type 2 errors.

Figure 5 shows the number of runway-hours in a year when wake spacing would be reduced for three different tuning choices of *n*. Different values for the crosswind threshold are shown across the bottom, spanning the possible thresholds one might use. Note that each runway has a theoretical maximum of 8760 hours of operation per year. There are two important points. First, there are a large number of hours when spacing might be reduced, even when the algorithm is tuned for fewer hours of benefit to get fewer hours of false predictions. For negative thresholds, there are times when both sides of the airport can operate independently (say when the crosswinds are near zero and the threshold is –6 kts, since 0 is greater than the threshold when viewed from either side). Secondly, the benefits do not drop dramatically as the algorithm is tuned for fewer type 1 errors.

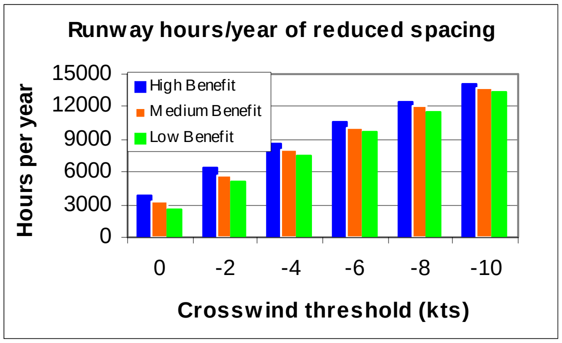


Figure 5: Number of runway-hours per year when spacing would be reduced for different tunings of the LLWAS based prediction algorithm and for different candidate crosswind thresholds.

Figure 6 shows the number of runway-minutes per year of type 1 errors, again for different tunings of the prediction algorithm, and for different thresholds. A dramatic reduction in errors can be seen as the algorithm tuning changes. Two points are worth keeping in mind. These errors are expected to be reduced greatly when better information on the local weather is incorporated, as seen below. And the number of these errors is roughly too large by a factor of two because the algorithm was in use for both departure directions, when in reality departures use only one direction at a time.

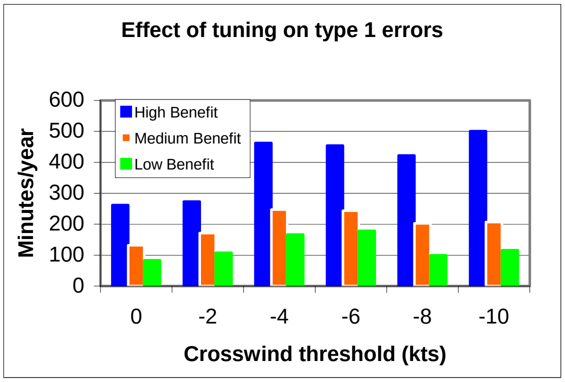


Figure 6: Number of minutes of type 1 errors per year for different tunings of the LLWAS based prediction algorithm and for different candidate crosswind thresholds.

It is important to look more closely at the type 1 errors, to better enable risk assessments to accurately evaluate risk and to help refine the predictions to remove these errors. Figure 7 shows the distribution of type 1 errors by how long after the prediction they occur for a crosswind threshold of –4 kts, and the low-benefit tuning. Recall that any given wake is likely to only last one minute or so, and the current separation minima are only 2 or 3 minutes depending on runway. Most errors occur beyond 3 minutes.

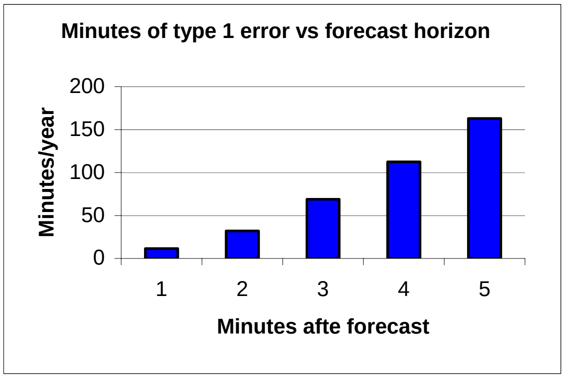


Figure 7: Number of minutes of type 1 errors per year for different forecast horizon, crosswind threshold of –4 kts, low-benefit tuning.

Figure 8 shows in which month the type 1 errors occur for a crosswind threshold of –4 kts and the low-benefit tuning. By far the worst month is June (also seen in the ASOS-based study). A closer look at the underlying data shows that the problem is very sharp changes in the wind, as associated with thunderstorm outflows. June is the most active month for convection in St Louis, and the speculation is that the problem is convective weather. If this is confirmed, the local ITWS can be used to determine when convective activity is in the airport region and the use of reduced separation should be suspended.

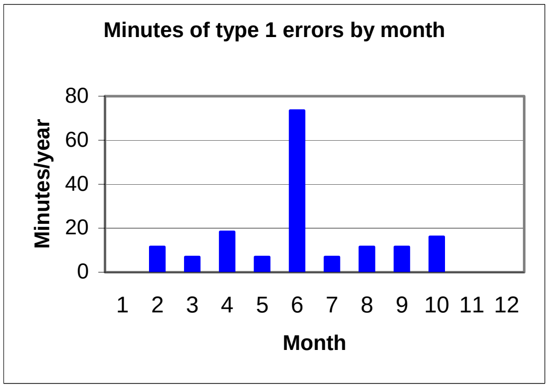


Figure 8: Number of minutes of type 1 errors per month for a crosswind threshold of –4 kts and the low-benefit tuning.

Summary of Benefits Estimates Using Wind Predictor Algorithm

Estimating the delay reduction benefits combines the operational concepts with the results of wind forecast algorithms to form a realistic basis for expectations. The process requires inputs from various sources to determine the benefits, shown in Figure 9. The runway capacities result from simulating operational concepts to determine both the baseline and additional capacity created from operating at reduced separation standards. The Aviation System Performance Metrics (ASPM) database provides a sample realistic demand profile, which when coupled with the wind forecasting determines the periods when all of the necessary conditions exist to gain benefits from additional capacity. An iterative process best describes the method of obtaining these associated benefit estimates. Additionally, since forecast winds are used in computing the delay benefits, replacing the predicted winds with actual winds provides a bound on the potential benefit that can be achieved by future improvements in the wind prediction algorithm.

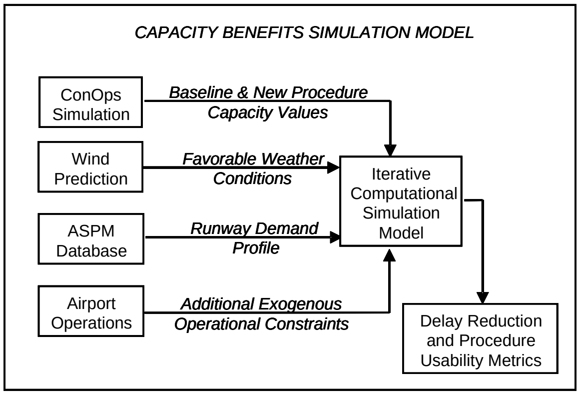


Figure 9: Capacity Benefits Analysis Inputs Diagram

The block diagram, shown in Figure 10, details the basic system of the delay computations. At each time period, the quantity of New Demand is queued with the Excess Demand from the preceding time period. It is compared to the available capacity determining the current amount of Excess Demand and tallying time delay statistics. The available capacity is defined as the simulated baseline capacity, derived from historical airport called rates, with an additional expanded capacity available only if favorable weather conditions exist. Statistics, computed for both the baseline and new procedure capacity conditions, provide a comparison for understanding the associated benefits.

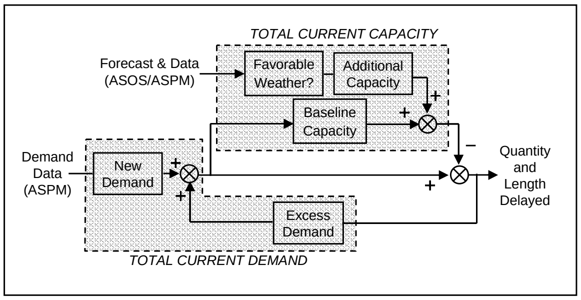


Figure 10: Capacity Benefits Analysis Block Diagram

Initially [10], delay reduction benefits were computed for eleven airports using a wind persistence computation against hourly observed surface wind data. Following the conclusion of this work, the FAA identified the four airports for additional study with the greatest delay improvement promise: BOS, DTW, PHL, and STL. Much of the refinement in this follow-on study concerned characterizing the effects of varying wind threshold criteria and narrowing the focus of data increments. As expected, increasingly stricter thresholds reduce the percentage of time that favorable conditions exist to run the procedure. Also, the ASOS based wind forecasting refined wind estimates to the 1-minute level and delay computations were estimated at the 5-minute level instead of 15-minute increment. Unfortunately, lacking sufficient ASOS data at PHL over the time period being analyzed reduced the set of airports to only BOS, DTW, and STL.

While favorable weather conditions are a necessary condition to allow the procedure to be implemented, great enough demand to make use of this increased capacity suffices to derive delay benefits. Shown in Figure 11, the upper grouping of curves marked with triangles, shows the percent time the necessary weather conditions exist for the respective wind threshold criteria across all three airports. The lower set of curves, marked with circles, graphs the coupling of the necessary weather conditions with sufficient excess demand for obtaining benefits. Sufficient demand conditions tend to have a scaling effect on the overall percentage of usable time periods. Using 2002 ASOS from the wind prediction and 2002 ASPM demand data, the average scaling factor for BOS is 5.4%, and is slightly higher at 10.2% for DTW and 16.6% for STL. It is important to note that the values shown in Figure 11 represent the upper bound of necessary and sufficient conditions to obtain delay reduction benefits by assuming no persistence of wind direction is required.

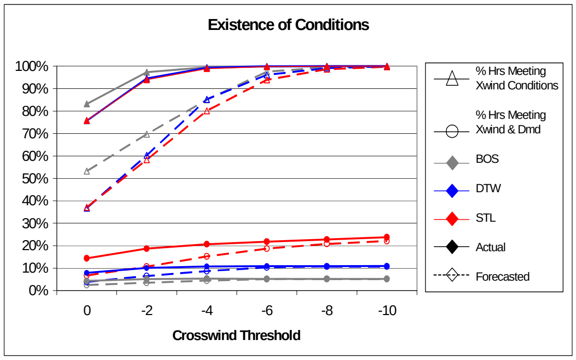


Figure 11: Percent of Favorable Conditions for Benefits Computation

As illustrated in the Total Current Capacity Block in Figure 10, if the favorable conditions exist then applying the wind dependent departure procedure enables the additional capacity. Since the concept of operations remained constant across both the initial and the detailed follow-on study, the capacity improvement values remained unchanged. Table 2 shows the capacity improvement at the nine airports and highlights the four focus airports. Airport operations and runway capacities were modeled for the period from October 2000 through August 2001 [10].

Table 2. 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%**

Using CY2002 1-minute ASOS wind data and smoothed ASPM demand data, the results were computed through the iterative process described above. The smoothing process of the demand data consisted of removing days of excessively low demand and replacing them with a "near by" approximation. Figure 12 illustrates the average delay benefits per aircraft using both the forecasting algorithm to predict time periods of sufficient weather conditions as well as the actual weather conditions, representing a prediction algorithm with perfect knowledge of the wind conditions.

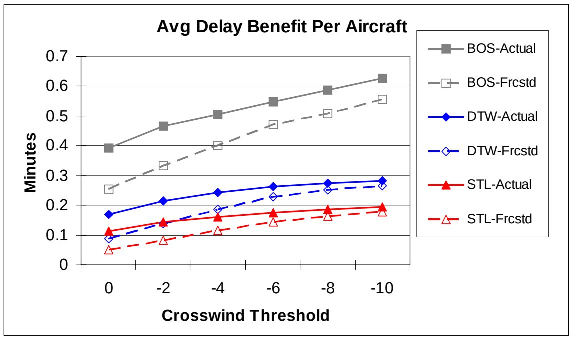


Figure 12: Average Delay Benefit Per Aircraft

Both Figure 11 and Figure 12 detail the conservatism in the performance of wind prediction algorithm, an important design factor for safety concerns. Of course, as the wind threshold criterion is relaxed, the modeled benefits from the predicted winds will converge with the modeled benefits from the actual winds.. These quantitative results are tied to the input assumptions and any changes in the solution components (assumptions, algorithm change, procedure change, weather prediction safety net, etc.) may require another complete iteration of integrated research activities.

Overall Research Addressed by the Wake Team

The research supporting the investigation of the CSPR wind-dependent concept has been organized into 5 categories that relate to major components of the proposed solution. These research areas will support the definition of an airport-specific (runway centerline spacing) wind criteria for the procedure. In addition, the research will help frame the safety net function that is necessary for the wind-dependent procedure. The wind criteria will be defined by a combination of factors associated with the procedure, including the performance of the wind forecast algorithm, the variability in performance of the aircraft along an expected departure path, the planning horizon for the local controller, and the safety net function. The safety net function will be governed by the rare occasions when the wind forecast does not hold for the entire planning horizon, and the variability of winds over a two and three minute period from the last point in time in which the wind forecast held.

ATC Operations

The first category of research is related to ATC operations. This research will define how the concept would work within the current ATC procedures and identify the minimal set of procedural changes necessary to take advantage of wind-dependent CSPR departures. This research will also provide a detailed description of the requirements for controller information and a decision support tool, and on wind forecast horizons that meet operational needs. The operational concept, described in the Concept Description section of this research paper, provides some early findings from the ATC Operations research.

Aircraft Performance

The research investigates aircraft performance on departure and will provide requirements for planning wake and wind data collection and analysis, for bounding the operational airspace for which the wind prediction capabilities will apply, and for the operational safety net for the wake avoidance solution.

Wind and Wind Forecast

The research is related to Winds and Wind Forecast and will provide design requirements on the wind measurement and wind forecast subsystems of the wake avoidance solution as well as performance expectations of those subsystems.

Departure Wakes

This research relates wake behavior from departing aircraft to the observed and forecasted winds. Within the safety net time horizon, limits of wake transport will be determined as a function of observed and forecasted winds.

Wind Criteria for Wake Avoidance

This research develops Wind Criteria for the wake avoidance procedure. The work pulls together all the variables on ATC operations, aircraft performance, wind measurements and forecasts and wake transport to define wind criteria for safe operations of a wind-dependent wake avoidance solution for CSPR departures.

Information Requirements for a Decision Support Tool

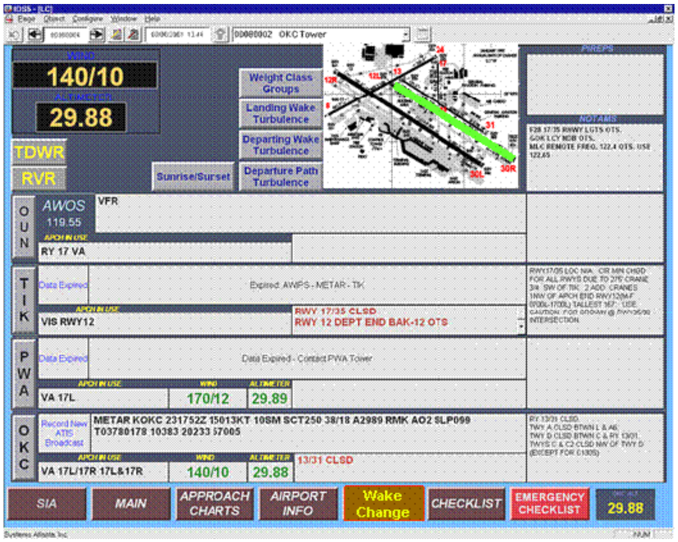
The goal of this investigation is to identify the information required by the controller to use the wind-dependent departure procedure and to determine when that information must be available to the controller. The wake team began the investigation with a review of STL operations with operations experts from that facility. The investigation included overall airport operations with the understanding that the wind-dependent departure solution must enhance departure operations while maintaining the efficiency of arrival and ground operations. Departure tasks for the local, ground, tower supervisor and traffic manager positions were reviewed. All positions were included to ensure that information requirements associated with departure coordination were considered. Based on the operational concept presented earlier in this paper, new tasks were identified that would be necessary in the proposed procedure. The information required for each of the existing and new tasks were identified as well as the sources of that information (i.e., displays, communications, direct observation, etc). A summary of those finding is provided below.

Shift briefings conducted by the tower supervisor would include information about the potential use of the wind dependent departure solution during the shift's operations. This information would include the weather pattern that is expected to enable the procedure and the approximate time in which the weather pattern would shift and the operations might expect a transition from the wind-dependent departure solution. This type of information is consistent with the use of other arrival operations at STL such as visual or LDA operations. The strategic nature of this planning information does not impose additional requirements on the wind forecast algorithm. Instead it imposes a requirement on the operations staff to become familiar with the local weather patterns that permit longer term stability of the wind forecast than the algorithm itself is designed to provide.

Ground operations would not be affected by the proposed procedure in its initial tactical implementation and therefore no new information requirements were identified for the ground position. No changes to taxi routes would be required. Coordination for runway crossings to move departures from the terminal to the outboard runway would not be affected. Similarly coordination for runway crossings to move arrivals on the outboard runway and across the inboard runway to the terminal would not be affected. It was recognized that these conclusions would have to be revisited for any expansion of the procedure that might affect runway assignment based on wind-dependent departure operation.

The local controller planning window horizon extends physically out 10 or 15 nmi of the final approach looking for departure gaps. Verbal coordination between the two local controllers will be reduced by the proposed procedure for cases when a Heavy Jet or B757 will depart from the downwind runway. A common picture of the runway status "wake independent/wake dependent" is required. The information is required during the planning horizon of 10 minutes, and must be re-verified just prior to the local controller issuance of the departure clearance to the aircraft on the wake independent runway.

The validation of information requirements can be accomplished through the use of mockups of potential display device changes during Human In The Loop (HITL) experiments. To that end, the wake team reviewed the information displays at each position in the STL tower. At the local position, several displays were identified as potentially useful in presenting the "wake independent/wake dependent" status indication. Those displays included the Remote ARTS Color Display (RACD), Airport Surface Detection Equipment X (ASDE-X), the ACE IDS, and the Runway Incursion Device (RID). The ACE-IDS display was a potentially suitable mockup platform because it is used today to provide related types of information such as active runway configuration and is located at every tower position at STL. The simple information requirement of "wake independent/wake dependent" status for each runway was color coded on the mockup. The ACE-IDS mockup is presented in Figure 13.



VFR

RY 17 VA

Expired AWPS - METAR - TIK

VIS RWY12

RWY 17/35 CLSD
RWY 12 DEPT END BAK-12 OTS

Data Expired - Contact PWA Tower

VA 17L 170/12 29.89

METAR KOKC 231752Z 15013KT 10SM SCT250 38/18 A2989 RMK AO2 SLP099 T03780178 10383 20233 57005

VA 17L/17R 17L&17R 140/10 29.88

13/31 CLSD

Figure 13: ACE-IDS Mockup

These information requirements will be further refined and validated though the use of these mockups as a part of the HITL experiments conducted in 2005.

Next Steps

During FY2005 activities will begin that will further the development of the operational concept outlined in this paper. The FAA, NASA and MITRE/CAASD will continue a series of HITL experiments in the CAASD Air Traffic Management (ATM) Lab in McLean, VA. These experiments will bring in the participation of key stakeholders, including both controllers from STL and potentially 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. The general operational utility of the wake avoidance solution will be verified and greater detail in data requirements and safety net and planning horizon times will be acquired. Initial laboratory simulations have begun and are planned to continue through FY05. Initial results have shown general controller support for the procedure and the ability of the laboratory and experimental design to support the goals of the research.

The analysis of wind forecast algorithms will be extended in FY05 to include winds aloft and the potential for integrating wind gust front detection products. Aircraft departure performance data will also be collected and analyzed at STL. This information will help determine the locations of wake sensors to collect and analyze wakes from departing aircraft and to couple the wake behavior with surface winds, winds aloft, and wind forecast algorithms.

Conclusion

A set of integrated research activities has been conducted on a wind-dependent CSPR departure concept. A simple operational concept has been investigated and provided the operational requirement for a wind forecast algorithm. Multiple wind forecast algorithms have been developed for surface winds based on those operational requirements and their performance has been assessed. Opportunities for wake independent operations have been identified based on the performance of a forecast algorithm, and operational benefits have been assessed. Information requirements are being investigated for a simple controller tool to assist with the decision of when to apply wake independent procedures. The results of the research suggest that a significant operational benefit may be achievable with small operational changes and relatively low risk technology development. Sufficient promise has been shown to continue the research to include the effects of winds aloft (i.e., to the altitude above ground at which the departure paths would safely diverge)and possibly extend the findings to other more complex wind-dependent solutions.

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Keywords

Airport Capacity, Closely Spaced Parallel Runways, Safety Net, Wake Vortex, Wind-dependent Procedure, Wind Forecast Algorithms

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Appendix A

Wind Prediction Algorithm

Frankfurt algorithm

The Frankfurt surface wind prediction algorithm uses a historical database from a series of anemometers sited along a line between the runways to predict the range of crosswinds expected to exist over the next 20 minutes. The 1-second wind values are averaged to give minute by minute values of the two-minute average wind. From the two-minute winds, 20-minute average winds are computed, and decomposed into speed and direction. These data are divided into four direction classes, grouping the data into commonly occurring directions. Each direction class is further divided into speed classes such that each direction/speed class has roughly equal numbers of data values. The direction/speed classes are further divided in half with those values from times of greater than median variance (High variability) put in one half and values from times with less than median variance (Low variability) put in the other half.

Once the data have been divided up, the historical variability in speed and in direction are computed for each data bin. For a 20-minute forecast, for each data value, the differences between the current and 20 future one-minute speed and direction values are computed. Then for each direction/speed/variability bin, the 95th percentile difference value is computed and stored. The result is a pair of tables for expected range of direction and speed, indexed by direction class, speed class, and variability class.

To make a forecast, the current 20-minute mean direction, speed, and current variability are computed, then used to select the expected 20-minute variability of the future wind direction and speed from the tables. The forecast range of possible wind direction and speed is then the current mean wind plus or minus the 95th percentile values from the tables. The predicted ranges of wind speed and direction are then used to compute a predicted range of crosswind.

Enhanced ASOS algorithm

We wanted to examine the performance of an algorithm that included more information than just 20-minute mean wind and variability reported only as High or Low. Toward that end we developed the following algorithm based on linear regression.

While the following algorithm could be used to predict the complete wind vector, we are only interested in crosswind. The complete wind vector is used, but only a predicted crosswind is produced. The algorithm predicts both the future mean crosswind, and the future variability in the crosswind (specifically the standard deviation of the crosswind, or σ). The predicted range of possible future winds is then:

Equation (1)

$$(xw_{\min}, xw_{\max}) = (xw_{mean} - n\sigma, xw_{mean} + n\sigma)$$

Where *xw* is either the predicted minimum, maximum or mean crosswind, σ, is the predicted standard deviation in the crosswind, and *n* is a constant.

In general, we are only concerned with whether the crosswinds stay above threshold, so the test for elimination of the extra wake avoidance separation is:

Equation (2) $xw_{threshold} < xw_{mean} - n\sigma$

Where $xw_{threshold}$ is the crosswind threshold.

The constant *n* can be used to tune the algorithm. The term $\pm n\sigma$ is in essence an error bar around the predicted future crosswinds. Compared to a large value of *n,* a small value of *n* leads to more frequent times when the actual future crosswinds fall outside the predicted range, possibly leading to over-reliance on the safety net. But, by producing a narrow predicted range of crosswinds it produces more predictions of times when the crosswinds will be above threshold, increasing the amount of time when reduced spacing is applied. Thus changing the value of n provides a way to tune the algorithm for maximum benefit while controlling prediction reliability.

A number of predictors are used to include both current conditions and trends. A number of averaging intervals are used in forming predictors. Long averages provide some stability, and shorter averaging intervals capture changing conditions. The predictors are defined as follows:

- Headwind, crosswind, wind speed, and wind direction, with averaging intervals of 2 minutes, 5 minutes, 20 minutes, and 35 minutes

- Standard deviation of headwind, crosswind, wind speed, and wind direction, with averaging intervals of 5 minutes, 20 minutes, and 35 minutes
- Difference in 5-minute average values 10 minutes apart

Other predictor sets have been examined briefly, and while the results might improve slightly with other predictor choices, the results are not sensitive to the choice of predictors as long as a broad range of predictors and averaging intervals is used.

The algorithm development starts much like with the Frankfurt algorithm. First, a historical data set is acquired, and at each point in time the required set of predictors is computed. These data are divided up into overlapping bins by 20-minute average headwind and crosswind. The bins used were ($-\infty$, -14 kts), (-16 kts, -9 kts), (-11 kts, -4 kts), …,(14 kts, ∞). The use of overlapping bins means some data values are used more than once. This was done to reduce the potential for discontinuities in the predictions as the winds change and move across bin boundaries. Along with the predictors which are based on the preceding 35 minutes, the future 20-minute mean crosswind, and 20-minute standard deviation of the crosswind are computed and stored. Finally, for each bin, provided there are sufficiently many data values in the bin, linear regression is used to fit the predictors to the observations. The fit to the observed future 20-minute mean crosswind produces a prediction model for the mean crosswind, and the fit to the observed future 20-minute standard deviation in the crosswind produces a prediction model for the 20-minute standard deviation in the crosswinds. The model coefficients for each data bin are then stored for future use.

To make a prediction, the required predictors are computed, and the 20-minute average headwind and crosswind are used to retrieve the model coefficients, this time using non-overlapping bins: ($-\infty$, -15 kts), [-15 kts, -10 kts), [-10 kts, -5 kts), …,[15 kts, ∞). Predictions of both mean crosswind and standard deviation of the crosswinds are produced, with the final prediction of whether the crosswind conditions require the use of wake avoidance separations given using equation 2.

LLWAS prediction algorithm

Based on the performance of the ASOS based predictions the work was extended to provide a regional prediction based on the St Louis LLWAS network. There are 10 sensors, located on poles approximately 90 ft tall, and spaced approximately one nautical mile apart along the approach corridors. The exact height takes into account nearby obstructions, and the heights are carefully set so that each anemometer measures the wind at the same effective height above ground. Each anemometer provides a measurement every 10 seconds, and these measurements are averaged to provide two-minute mean winds with a one-minute update rate.

The approach used by the Frankfurt and the Enhanced ASOS prediction algorithms was to predict the range of the future crosswinds, and to issue a prediction that spacing could be reduced when the entire predicted range of crosswinds lies above the crosswind threshold. This approach worked fairly well with the LLWAS prediction algorithm, but directly predicting the minimum crosswind gave better results. Otherwise the approach is very similar, giving rise to the following test for when spacing can be reduced:

Equation (3) $xw_{threshold} < xw_{\min} - n\sigma$

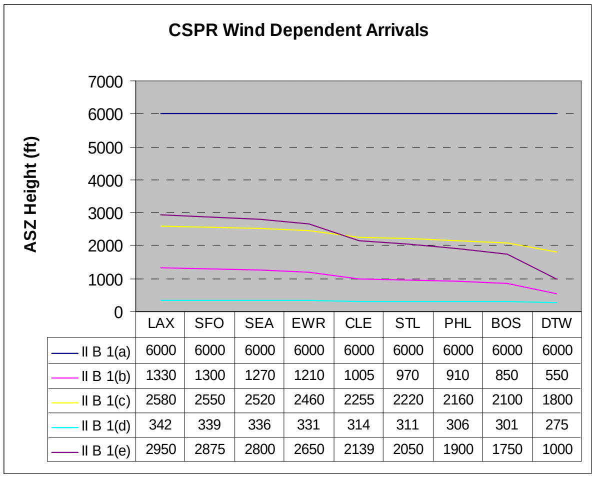
This is very similar to equation 2, except that the prediction on the right is now the predicted minimum crosswind and σ is now the standard deviation of the error in the crosswind prediction, rather than the standard deviation of the crosswind.

The LLWAS data are from the one-year period starting in April 2003. Because fewer data were available, few predictors are used than with the ASOS data. The predictors were:

- 2-min network headwind, crosswind, and wind speed
- 20-min network headwind, crosswind, standard deviations and min crosswind
- Trends in 5-min headwind, crosswind, standard deviations, speed and min crosswind

Extensions to Single Runway Operations and CSPR Arrivals

NASA has conducted an investigation of candidate wind-dependent operational enhancements through a Conops Evaluation Team (CET). This team included participation by stakeholders from many research, system engineering, system development, pilot, and controller organizations. The operational enhancements that were evaluated included wind-dependent concepts for arrivals to CSPR, departures from CSPRs operated as a single runway, arrivals to single runways, and departures from single runways. Within each of these concepts a variety of approach or departure trajectories were designed to minimize the area within which wake separations were reduced. These areas were termed Alternate Separation Zones or ASZ. These zones require accurate wind sensing and forecast and the varying geometries allow adaptation of the concept to candidate airports with differing airspace constraints. An example of the use of these geometries to limit the height to which winds would need to be monitored and forecast is shown in below.



	LAX	SFO	SEA	EWR	CLE	STL	PHL	BOS	DTW
II B 1(a)	6000	6000	6000	6000	6000	6000	6000	6000	6000
II B 1(b)	1330	1300	1270	1210	1005	970	910	850	550
II B 1(c)	2580	2550	2520	2460	2255	2220	2160	2100	1800
II B 1(d)	342	339	336	331	314	311	306	301	275
II B 1(e)	2950	2875	2800	2650	2139	2050	1900	1750	1000

Parallel Runway Arrivals

The geometries listed (II B I a through e) show the difference in ASZ height requirements when going from a concept that uses long parallel finals (a) to one with an approach geometry that incorporates LDA type converging paths (d). Similar geometries were also considered by the CET for single runway operations.

Detailed analysis of the wind requirements and the airport capacity improvement that could be expected for each concept is currently being conducted by a part of the wake team under NASA sponsorship. This analysis may help determine the next evolutionary step in wake concepts that will be pursued following the midterm CSPR Departure solution described in this paper.

Single Runway Operations

Extension of wake turbulence procedural enhancements to single runway departures requires several important additional criteria:

1. The lateral navigational deviation of the leading and trailing aircraft from the extended runway centerline must be known from rotation to the point of course divergence, so that the potential lateral path envelope is defined. It is assumed for this discussion that consideration of a departure's vertical path is not included in the procedure, since this is very dependent on aircraft loading and other variable factors impossible to predict, and would require consideration of extreme cases such as engine failure on takeoff
2. Minimum crosswind criteria must be developed so that the likelihood of a wake encounter within that lateral path envelope at the earliest time a trailing aircraft will cross the same point is minimized. In short, the leader's wake must be guaranteed to be blown out of the path of the trailing aircraft.
3. A wind forecast system must be developed to accurately provide short term forecast of when winds will exceed the desired minimum for path envelopes of the departing aircraft until the point of course divergence
4. For implementation departure runways may be chosen based on exceeding a crosswind minimum, while in current practice runways are typically chosen to minimize crosswinds, all other factors being equal

The first item is an open research question. The future possibility of GPS guidance at or just after the point of rotation may allow fairly tight departure paths to be followed, where aircraft may only deviate a small distance from the extended runway centerline before course divergence (e.g., "fanning"). The practical limits of the accuracy of such course guidance in the presence of crosswinds is yet to be determined.

The second item is directly dependent on the first (i.e., a larger envelope of likely paths will require larger minimum crosswinds to blow the wake out of it by the minimum time in which the following aircraft will cross the same point. The following paragraphs discuss the approximate bounds on the percentage of time such minimum required crosswinds occur. Such wind criteria are more difficult to achieve than the crosswind criteria for CSPR departures, as calm or near calm winds may be adequate to insure that a wake will not blow across to the path of the parallel runway, but will not be allowed when the wake of the leader must blow away from the wake of the trailer. Such relatively low crosswinds (e.g., less than 5 knots) are quite common at most airports.

The third item is likely covered by the wind forecast system that would be developed for a parallel runway departure procedure, although there may be some differences in application. The fourth item would have to be addressed procedurally as part of implementation at each airport.

The benefit of a single runway departure procedure would be limited to cases where the leader is a B757 or Heavy, as no wake turbulence separation is required now behind Large and Small aircraft. While the wind criteria for a single runway departure procedure is yet to be determined, two candidate values (5 kts and 10 kts) can be used for comparison and trend analysis. Table A-1 shows the percentage of time surface crosswinds are in the range of 5-20 knots and 10-20 knots (both to the right and to the left) for six representative airports. These airports were chosen based on the presence of current departure delays and a relatively high proportion of Heavy and B757 flight operations, as well as a desire to show representative differences in different geographical regions. A 20 knot upper bound on crosswind is included to avoid periods where the crosswind is too high for safe landings. The winds are in this range for three consecutive hourly observations, either 3-5 AM or PM local time. This analysis is based on hourly METAR wind observations as reported in ASPM for October 2003 through September 2004. The airports are ranked based on the percent of time the wind conditions are satisfied, from BOS (highest percentage) to LAX (lowest percentage).

Clearly, winds are lower on average during night-time vs. afternoon periods, and these two periods give an approximate lower (3-5 AM) and upper bound (3-5 PM) on the percent availability of the procedure for all possible 3 hour periods during a 24 hour day. A three hour period was chosen to require some minimum crosswind persistence for use of the procedure. Actual conditions, using rapid wind updates (e.g., 1 minute ASOS winds) and above surface winds as needed, would provide somewhat different percentages, but the relative percentages of time the procedure could be used from airport to airport and from afternoon to late night would be similar.

It is clear from this simplified analysis that some airports (e.g., LAX) with relatively calm winds most of the time would have minimal use of such a procedure. It is also clear that the precise value of the minimum absolute crosswind has a very large impact on the percent of the time such a procedure could be used. The potential benefit would drop by at least a factor of 3 if the minimum crosswind was increased from 5 to 10 knots for these airports. Night-time operations where a large number of Heavies are departing, such as at SDF in the 3-5 AM period, would have more limited potential to use the procedure, given the calmer winds during late night hours.

Table A-1: Percent of Time Absolute Surface Crosswind In Desired Range For Three Hour Period

Apt	5-20 kt: 3-5 PM	10-20 kt: 3-5 PM	5-20 kt: 3-5 AM	10-20 kt: 3-5 AM
BOS	58%	16%	36%	8%
JFK	49%	17%	30%	6%
DFW	39%	10%	29%	4%
SDF	32%	6%	13%	< 1%
ATL	24%	3%	10%	< 1%
LAX	13%	1%	1%	< 1%

Single runway arrival procedures have all of the requirements for departure procedures, with the additional element that the last part of the final approach must be on a stabilized course prior to touchdown, and that a precision approach for both lead and trailing would be required. The shared path of a lead and trail aircraft will also likely be longer than that of a departure, requiring that minimum crosswind constraints be satisfied for a larger airspace, but on the other hand, existing ILS precision approach technology will allow tight paths to be followed by the lead and trail aircraft. And because of such precision approaches (both laterally and vertically), other wake mitigation factors besides crosswinds could be considered. One such added mitigation factor would be to put the leading Heavy or B757 on a low approach, using the full runway, while putting a trailing Large or Small aircraft on a higher approach, landing on a second added threshold offset down the same runway from the first threshold. A displaced threshold procedure would require additional ATC procedures to be developed, but are not out of the range of possible future consideration.

Vertical wind profile data for analysis and solution extensions

Wind speed and direction can change dramatically with altitude. This is particularly true within the Planetary Boundary Layer (PBL). The PBL is the lowest layer of the atmosphere, where winds are significantly impacted by surface friction. To account for potential changes in wind direction and speed with altitude, wind data sources for wake procedure analysis and solutions need to include vertical wind profile data within the first several thousand feet above the airport. Potential candidates of this data include: lidar measurements along airport glide slopes/departure paths, aircraft in situ measurements from Aircraft Communications Addressing and Reporting System (ACARS), Integrated Terminal Weather System (ITWS) wind analysis/forecast, and the Rapid Update Cycle (RUC) analysis/forecasts.

Initial wind prediction algorithm research has focused surface wind measurements and predictions. Under some conditions, surface wind measurements alone may be adequate. Figures A-1a and A-1.b depict a case where downwind wake independence for arrival/departure procedures is supported by winds at all levels. The figures represent 24 hourly vertical wind profiles over the course of a day, as determined by RUC analysis data. This scenario provides consistent crosswind direction (Figure A-1a) at the surface and all applicable altitudes aloft, with wind speed generally increasing with altitude (Figure A-1.b). An operational solution, based on surface winds alone, would have captured this condition because of the consistency in wind direction with height and the general knowledge that winds generally increase in speed with height. Figures A-2a and A-2.b represent another case where winds increase more moderately with height and the surface crosswind remains consistent in direction with heights up to ~2,500 feet. This scenario would be supportive of downwind wake independence for departure procedures. However, above 2,500 feet the crosswind changes sign causing problems for downwind independent arrival procedures. Unlike the first scenario, a surface-based operational solution would not be able to address this 180 degree change in wind direction at 2500 ft. In both these scenarios, there is some measure of consistency in the vertical wind profiles over the course of the day that may be well forecasted by RUC, ITWS or some other source.

There are plans to explore wind vertical profile data for analysis and solution extensions. Lidar measurements along the arrival glide slope are incorporated into the Volpe data collection plan for STL. MIT/LL is looking at Integrated Terminal Weather System (ITWS) winds for potential use in solution algorithms. And, MITRE/CAASD is utilizing the RUC analysis in support of benefit and procedure applicability analysis. CAASD selected RUC’s native (isentropic) grid for this purpose, as opposed to the more common isobaric grid, because the native grid can provide three times as many levels (~17 levels) in the first 6,000 feet. Collectively, these efforts hold great promise for wake procedural development.

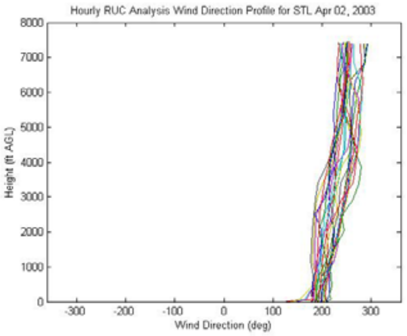


Figure A-1a: Scenario 1 – Wind Direction Vertical Profile

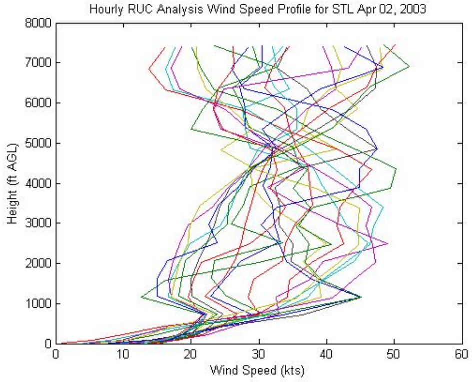


Figure A-1b: Scenario 1 – Wind Speed Vertical Profile

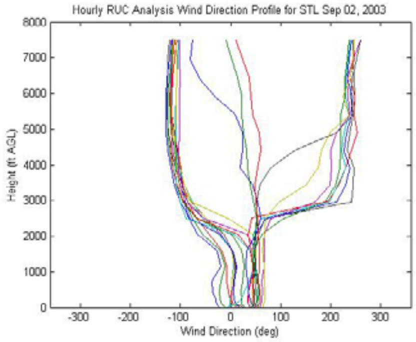


Figure A-2a: Scenario 2 – Wind Direction Vertical Profile

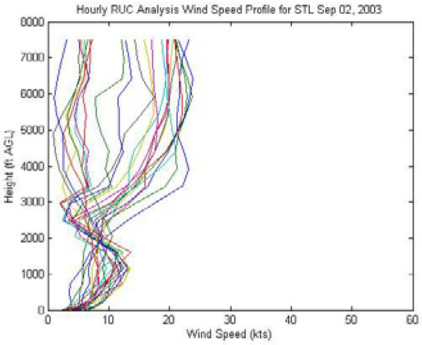


Figure A-2b: Scenario 2 – Wind Speed Vertical Profile