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P2.1 WIND PREDICTION TO SUPPORT REDUCED WAKE SEPARATION STANDARDS FOR CLOSELY SPACED PARALLEL RUNWAY DEPARTURES†

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1. INTRODUCTION

Wake vortices are a by-product of lift generated by aircraft. The vortices from the wings and other lift surfaces such as flaps spin off and trail behind an aircraft (see Figure 1). These vortices can be a hazard to other aircraft, especially lighter aircraft that are following at low altitude. For this reason, numerous air traffic control standards require increased aircraft separation when wake vortex avoidance is a concern. These separation standards provide the required safety: there has never been a fatal accident in the U.S. due to wake vortices when wake vortex separations were provided by air traffic controllers.

Wake vortex behavior is strongly dependent on atmospheric conditions, giving rise to the possibility that wake behavior can be predicted with enough precision to allow reduced use of wake vortex avoidance separations. Because vortices can not be seen, and their location and strength are not currently known or predicted, separation standards and air traffic procedures are designed to account for the worst case wake behavior. Because of this, the imposed aircraft separations are larger than required much of the time, reducing terminal capacity and causing increased traffic delay. If procedures or technologies can be developed to reduce the use of wake avoidance separations, terminal area delay reduction may be achieved.

A prototype wind dependent wake separation system is operating in Frankfurt, Germany for arrivals into closely spaced parallel runways. The system uses wind prediction at the surface to determine when separation for wake vortex avoidance must be used and when the extra separation does not need to be used [Konopka, 2001][Frech, et al., 2002]. 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? This paper reports on a research effort to answer that question. This is part of a larger FAA and NASA research effort [Lang et al., 2003].

Figure 1: In this photograph, a Cessna Citation VI is flying immediately above a fog bank at approximately 313 km/h or 170 knots (B. Budzowski, Director of Flight Operations, Cessna Aircraft Company, private communication, 1993). Aircraft weight was approximately 8400 kg. As the trailing vortices descended over the fog layer due to the downwash, the flow field in the wake was made visible by the distortion of the fog layer. The aircraft is seen initiating a gentle climb after a level flight, leaving a portion of the fog layer yet unaffected. Photo courtesy of Cessna Aircraft Company. (Higuchi, 1993).

2. OVERVIEW OF WAKE BEHAVIOR AND SEPARATION STANDARDS

Wake vortices are generated from lift surfaces, and they roll up into two counter rotating vortices behind the aircraft as seen in Figure 1. Wake strength is proportional to aircraft weight and inversely proportional to aircraft speed and wing span. The primary wake hazard is to a trailing aircraft which is much lighter than the leader, especially in the terminal area where aircraft

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speeds are low creating stronger vortices, and where aircraft have reduced control authority.

Generally wakes sink, transport with the wind, and last less than two minutes, however, in some conditions they may behave differently [Robins et al., 1998]. Atmospheric turbulence speeds wake decay. At very low wake altitudes the interaction with the ground causes the vortices to spread apart at a speed of approximately two knots. The wake transport is then the sum of the wind and ground effect motions. To date there is no accepted definition of maximum safe wake strength, so the primary issue under consideration is wake transport by the wind: if the wind blows the wakes out of the way of following aircraft, increased aircraft separation is not needed.

For the purposes of wake separation standards aircraft are divided into four groups, primarily based on take-off weight: Heavy (greater than 255,000 lbs), Large (between 41,000 lbs and 255,000 lbs), Small (less than 41,000 lbs), and Boeing 757 which while not a Heavy is treated much like a Heavy aircraft. The majority of commercial aircraft fall into the large category, including the smaller regional jets. Because wakes tend to descend, in clear conditions wake separation is generally the pilot's responsibility and aircraft that are lighter than the aircraft ahead of them take a higher landing approach, staying above the glide slope of heavier leading aircraft. In poor visibility the follower can not see the lead aircraft and aircraft are generally constrained to fly fixed approach paths.. In this case wake vortex avoidance is the responsibility of air traffic control; typically aircraft separation is increased from the 2.5 or 3.0 nmi used in clear conditions to 4-6 nmi, depending on leader and follower weight classes. On departure, the aircraft are typically not on as constrained trajectories, followers cannot reliably stay clear of trailing vortices, and increased separation is always mandated. For the same reason, increased separation is always mandated for crossing flight paths into or out of an airport. When parallel runways are closer together than 2500 ft, they are treated as a single runway as far as wake separation is concerned. These standards are summarized in Figure 2.

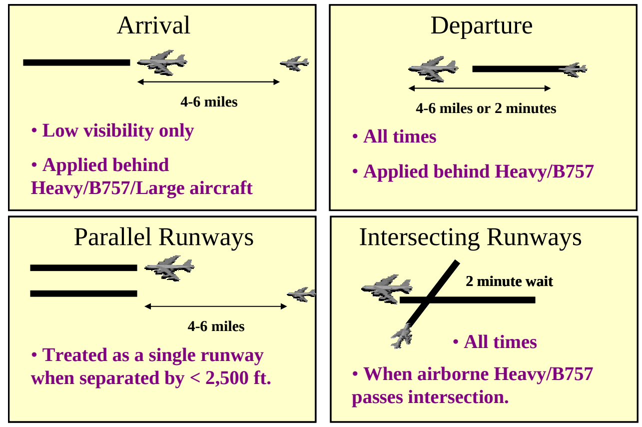

Figure 2: Summary of wake separation standards applied by air traffic control. Depending on aircraft weight for leader and follower aircraft, aircraft separations are increased from 2.5 nmi or 3.0 nmi when wake avoidance is not provided by air traffic control, to 4 nmi – 6 nmi when wake avoidance separation is provided by air traffic control.

3. OVERVIEW OF CLOSELY SPACED PARALLEL RUNWAY DEPARTURES

The FAA has chosen to look at closely spaced parallel runway departures as the first weather dependent solution for reducing wake separation. Currently, when launching aircraft from parallel runways spaced less than 2500 ft apart, if the lead aircraft is a Heavy or a Boeing 757, the following aircraft has an additional wait imposed before it may launch even if it is on the parallel runway. However, if there is a strong enough crosswind such that the Heavy is down wind, it is known that the wake will not travel upwind, and the imposed wait on the adjacent runway could be eliminated. This is shown in figure 3a. Currently when the situation is as in figure 3a, if the aircraft on the left is a Heavy or B757, the aircraft on the right must hold, even though there is no danger from the wake from the left aircraft due to the crosswind. For most runway spacings it turns out that the wake from the left aircraft is not a danger to the aircraft on the right even if the wind direction is reversed, as long as the wind speed is modest, Figure 3b.

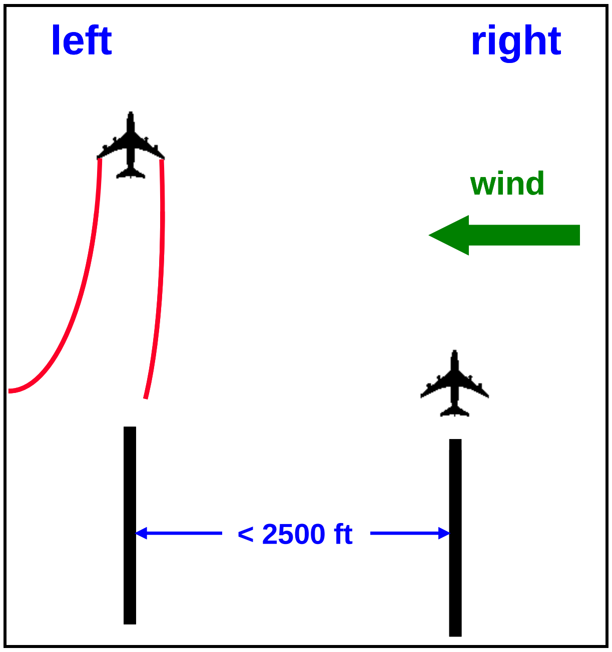

Figure 3a: Runways separated by less than 2500 ft are treated as a single runway for the purposes of wake separation. When a Heavy (aircraft weight greater than 255,000 lbs) or a Boeing 757 departs on one runway, aircraft on the parallel runway must wait to depart. However if the crosswind is as shown, a wake from a Heavy left departure will not travel upwind, and the aircraft on the right can safely depart without delay.

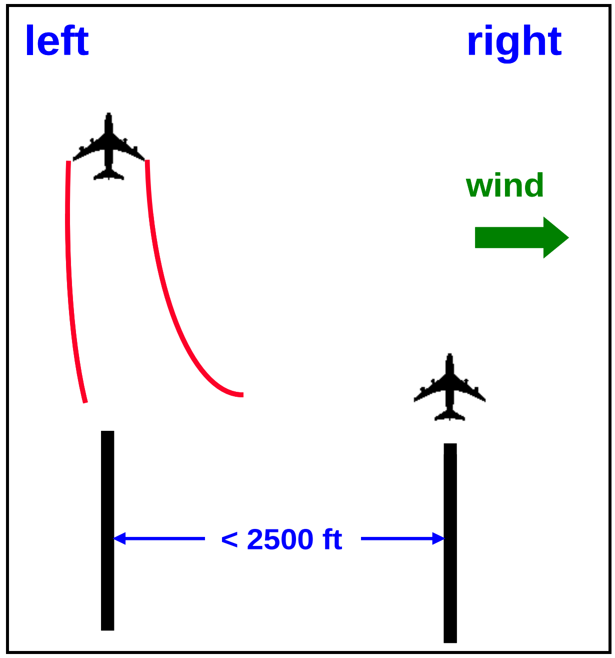

Figure 3b: For most runway separations, even if less than 2500 ft, a wake will not travel from one side to the other without actively being blown across.

In this paper the sign convention is tied to the notion of "upwind" and so is tied to a particular runway. In the example given in Figure 3, the question is "Can the right aircraft be launched without wake separation from the left aircraft?" This question boils down to "Is the right aircraft nominally upwind?" We take the positive crosswind direction to be the direction that makes the right aircraft upwind: the crosswind in Figure 3a is positive, and the crosswind in Figure 3b is negative. Generally a small negative crosswind or any positive crosswind means no wait is required before launching the aircraft on the right. When considering if wake separation is required following the launch of the right aircraft, the sign convention is then reversed and again a small negative crosswind or any positive crosswind means no wait is required on the parallel runway. The amount of crosswind required depends on the runway spacing, and factors such as the precision at which aircraft can fly a set path. The air traffic control and pilot communities have not yet come to a consensus on how to set the crosswind requirement, so crosswind thresholds from 0 kts to -10 kts are used in this study.

There are several reasons for looking into closely spaced parallel runway departures first. With departures, increased separation due to wake vortices is applied in all weather conditions, not just in low visibility as in the arrival case, possibly allowing for greater benefit. The departure forecast problem is also easier than the arrival forecast problem as the forecast horizon is very short. With a system that updates once a minute, for example, and with wake life times of two minutes (an assumption behind current standards), the requirement is for a 3-minute forecast. In contrast, aircraft on arrival need to be lined up either with or without the additional separation starting at least 20 minutes out from touch down, leading to a requirement for at least a 20-minute forecast, and possibly much longer. Departures also present less operational risk. In the event of an incorrect forecast for favorable crosswinds, the departures could be immediately halted, whereas a 20 minute queue of arrivals could be affected by an incorrect forecast.

The wind requirement for closely spaced parallel runway departures is also much simpler than for the single runway situation. With a single runway, departures may fan left or right shortly after take-off, making it difficult to even know which way the wind must blow to keep the vortices away from the following aircraft. In the parallel runway case, the center line between the runways divides the airspace into two regions: aircraft launching on the right can be kept on the right, aircraft launching on the left can be kept on the left.

The envisioned solution relies on wind transport, rather than wake decay because the transport mechanism is much better understood than the decay mechanism, and wind prediction is more reliable than turbulence prediction. The problems associated with decay prediction are being examined by NASA as a longer-term solution.

4. CROSSWIND PREDICTION

The key to reducing the use of wake vortex avoidance separation for closely spaced parallel runways is being able to predict when the crosswind conditions will remain stable enough to ensure that the wake from the down wind 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 we use a two-minute average unless otherwise specified, as that is the averaging provided by the ASOS data, as well as the averaging used in the Frankfurt system. In all cases the two-minute average is updated every minute.

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 are not yet specified) 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 satisfy safety requirements and a 10 or 20 minute look ahead is desired for planning.

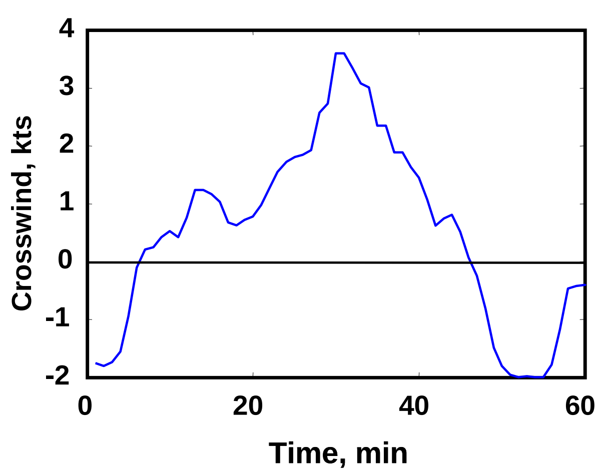

Figure 4: Trace of the two-minute ASOS winds, updated every minute, at St Louis airport. If the requirement were for a crosswind of 0 kts or greater, the goal of the prediction algorithm is to predict the time where the trace is above the solid horizontal line.

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. An example of this process for similar data from St Louis is shown in Figure 5.

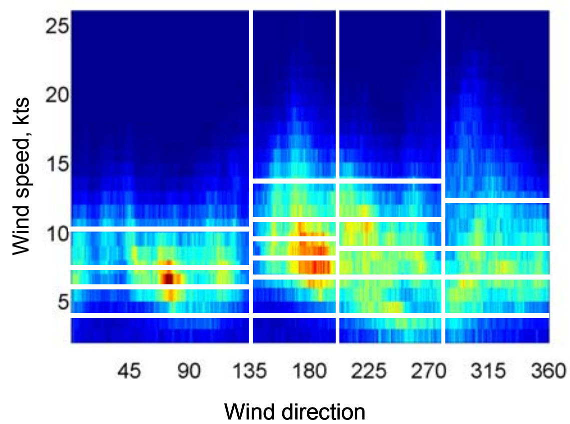

Figure 5: St Louis wind frequency plot for 2000-2001. The most commonly occurring combinations of wind speed and direction appear as hot colors and the rare combinations show as cool colors. The white lines show the wind is divided up into direction and speed classes.

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 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 could also be used as is to predict headwind if needed for a future application. The algorithm predicts both the future mean crosswind, and the future variability in the crosswind (specifically the standard deviation, 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 incorrectly removing wake separation. 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 risk.

The algorithm fundamentally considers the wind as mathematical vectors rather than as speed and direction. When considering advection this is the representation that is directly applicable. In particular, for this application the best representation for the wind is a vector with components of headwind and crosswind.

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.

5. PERFORMANCE

The following is an initial performance assessment for these two algorithms. 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 wind prediction results for each airport are similar. To simplify the discussion of the results, only the results from St Louis (STL) are given here.

The primary 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? That is, are there few enough prediction errors to suggest that with refinement safety requirements can be met, while providing significant benefit? One challenge in answering this question is that the stake holders, air traffic controllers, pilots, airlines and others have not fully defined the requirements. A method for determining the required crosswind and the tolerable level of prediction errors have not been specified. 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. The question of how much benefit might be achieved is being answered in separate studies headed by the MITRE Corporation, using the results of this study and looking at various possible specific air traffic control procedures and airport specific traffic demand.

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. While it is desired that the forecast hold for 10 or 20 minutes, the safety issues are satisfied if the prediction holds for three to five minutes. In cases of type 1 errors, an aircraft might be allowed to depart too closely behind another aircraft, thus possibly creating a hazardous situation.

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. In cases of type 2 errors, aircraft separations are not reduced, but they could have been reduced: potential benefits were not realized. This assumes that even with a reliable forecast, if the forecast is for favorable winds to last less than 20 minutes, ATC would not reduce spacings.

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 of some sort. 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.

In each of the following sections the algorithms used two-minute average winds, updated every minute, from the airport ASOS system. Each model was built using approximately a year's worth of data (1/1/2000-12/31/2000, with some missing data), and evaluated on approximately a year's worth of data (1/1/2001-12/31/2001, with some missing data giving 4.7×10^5 evaluation points).

Frankfurt vs Enhanced

The comparison of algorithm performance is difficult if one algorithm produces fewer type 1 errors (better safety), 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 is set so that each algorithm has the same probability of a type 2 error. That is, each provides the same benefit. What remains is a comparison of the rates of type 1 errors.

Figure 6 shows results for St Louis, which has a single set of closely spaced parallel runways giving two crosswind directions of interest. Departures on either 12L (left runway when departing with a compass heading of 120 degrees) or 30R need the same crosswind direction to remain safe from wakes from their parallel runways, as do departures on either 12R or 30L. Thresholds from 0 kts to -10 kts are used as this is the likely range where the crosswind threshold will be set. In general the prediction problem gets easier as the threshold is reduced simply due to climatological considerations; it is rare to have crosswinds with magnitudes greater than 10 kts. The type 1 errors are much smaller for the Enhanced algorithm. Only the Enhanced algorithm is considered further.

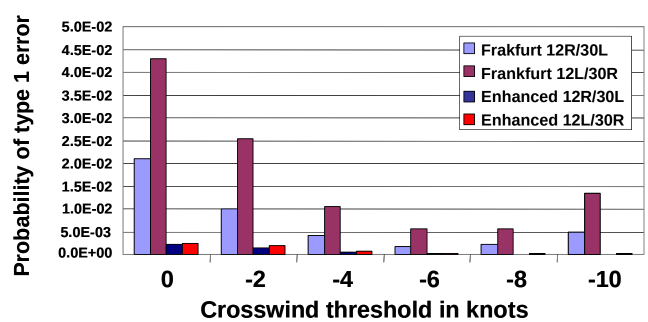

Figure 6: The probability of type 1 errors leading to the use of a safety net function is given for different possible choices of crosswind threshold for the two runway directions in St Louis. In each case the two left most bars represent the number for the Frankfurt algorithm, and the two right most bars represent the number for the Enhanced algorithm. In each case the probability of type 1 errors is much less for the Enhanced algorithm.

Enhanced algorithm

Perhaps the most critical consideration is the number of minutes of type 1 errors per year. While a safety net will be built into any eventual system to account for type 1 errors, user acceptance will only occur if that safety net is not called on very often. However, if in driving down the occurrence of type 1 errors too much benefit is eliminated there is no reason to build the system. The trade off between type 1 errors and benefit is shown in Figure 7. Here the crosswind threshold is chosen to be 0 kts which maximizes the number of type 1 errors. The number of minutes of type 1 errors per year for different values of *n* is given in Figure 7a. There is a dramatic drop in type 1 errors as *n* increases, to 31 minutes per year for *n*=4. The drop in benefits is fairly large if somewhat less dramatic. However, even for a value of *n*=4, wake avoidance separation can be eliminated about 1/3 of the time.

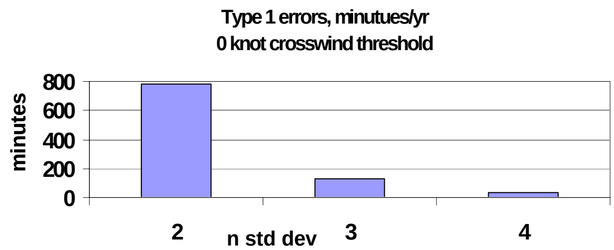

Figure 7a: Number of minutes of type 1 errors from the Enhanced algorithm at St Louis for different values of n, (see equations 1 and 2). As n increases the occurrence of type 1 errors decreases sharply.

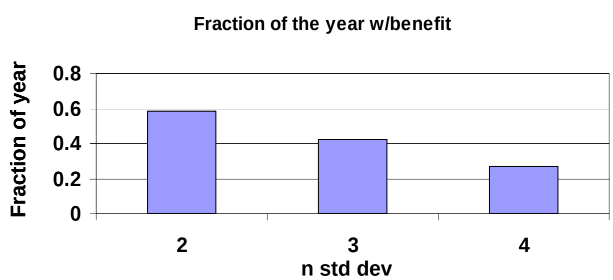

Figure 7b: The fraction of the year where wake avoidance is predicted to be unneeded also decreases as the value of n increases.

Simply counting the number of type 1 errors does not tell the entire safety story. Errors that occur out at 5 minutes likely pose no threat, or at least pose much less threat than errors that occur earlier. Similarly, failures where the crosswind is less than the desired threshold by a small amount pose less threat than failures with crosswind far below threshold. Figure 8 shows the number of type 1 errors for *n*=2, and a threshold of 0 kts, both values chosen to cause a large number of type 1 errors. While the raw number of type 1 errors is large, more than half of them occur at four and five minutes after the forecast time, and of the type 1 errors that occur within 3 minutes of the forecast time only a few are errors of greater than 2 kts.

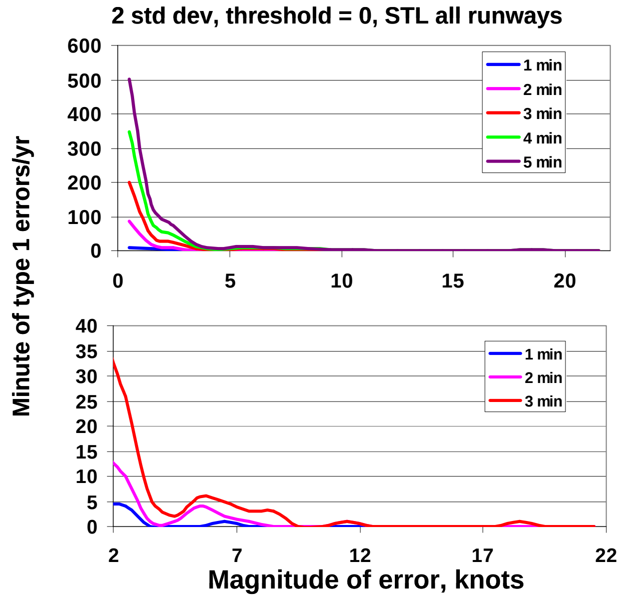

Figure 8: The number of type 1 errors per year by time of error after the forecast time and by magnitude of the error is given in the top graph. The same information for the subset of type 1 errors that occur in the first three minutes after the forecast and with magnitudes of two knots or greater is shown in the bottom graph. The majority of the errors are seen to come 4 and 5 minutes after the forecast, and the majority of the errors that occur in the first three minutes are less than 2 knots.

Refining the algorithm requires understanding what causes these type 1 errors. Clearly any algorithm that relies solely on local observations will have difficulty with wind shifts that travel to the airport; an anemometer does not see winds at a distance. However, since the Enhanced algorithm is conservative, generally providing crosswind predictions below current levels (mean crosswind minus some amount) and because the algorithm uses trend predictors, it does not produce type 1 errors in gentle to moderate wind shifts. However sharp wind shift can lead to type 1 errors. Given that we only have the airport ASOS it is hard to determine with certainty what leads to these sharp wind shifts. The only data that are well correlated with type 1 errors is time of year and time of day. Figure 9 shows the number of type 1 errors for St Louis by month and time of day (local time) with *n*=2 and the crosswind threshold set to 0 kts. The majority of type 1 errors occur in the early afternoon in June. Given that the errors are associated with sharp wind shifts, and that convective weather is common on June afternoons in St Louis, the hypothesis is that the primary cause of type 1 errors is convective outflows.

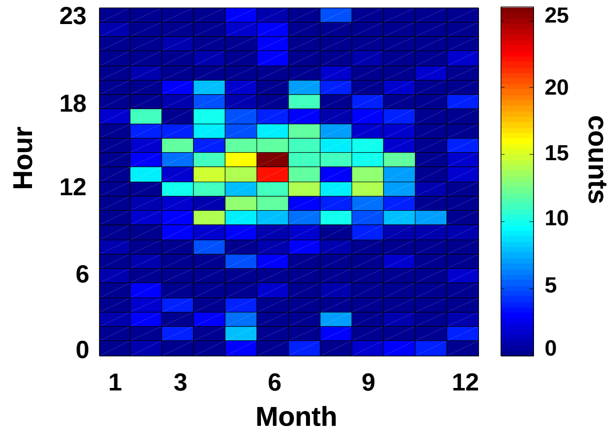

Figure 9: Plot of type 1 errors by month and hour (local time) of the day in St Louis. The problematic time is the early afternoon in June, leading to the conclusion that the most likely cause is convective weather in the area.

6. NEXT STEPS

The work to date has concentrated on the use of the airport ASOS to predict the surface winds. Given the encouraging level of success in that work, the surface prediction work will be extended to include data from the Low Level Windshear Alert System (LLWAS) at St Louis. The LLWAS provides data from a network of anemometers with a spacing of roughly one nmi, and extending nominally 3 nmi from the ends of the runways. This will give a larger region of data for both the prediction algorithm, and for verification. This is important both to help reduce the type 1 errors, and because the crosswinds must be above threshold not just at the airport, but out a few miles.

The Integrated Terminal Weather System at St Louis provides a method of determining when convective activity is in the airport region, and will be incorporated to reduce type 1 errors, while hopefully allowing a less conservative prediction algorithm leading to increased benefits.

Preliminary investigations show that there is the possibility of modest accuracy gains from using more sophisticated model building techniques. Further refinement of the underlying statistical techniques will take place.

Special sensors, in particular a lidar (laser radar) which can be used to provide vertical profiles of the winds, are deployed at St Louis as part of the larger FAA/NASA wake vortex effort. The question of what can be done to predict the winds aloft using ASOS, LLWAS, ITWS display products, and lidar data will be examined.

7. SUMMARY

The FAA is considering the issue of how to reduce the use of wake avoidance separation for closely spaced parallel runway departures (runways separated by less than 2500 ft). The ability to safely remove the wake avoidance separation requires the ability to predict when the crosswind will stay above some, as yet unspecified, threshold level. There is a candidate surface wind prediction algorithm in a prototype system operating at Frankfurt. This led the FAA to pose the question:

Is there enough to surface wind prediction based on anemometer measurements to warrant further investigation?

To answer this question the Frankfurt algorithm was examined, as well as a new algorithm developed at MIT Lincoln Laboratory. The results show that the number of prediction failures (type 1 errors) is low enough, possibly as low as a few tens of minutes per year, and the possible benefits high enough, 30%-60% of the time wake avoidance separation can be removed, that further development is warranted.

These results are based on data from a single point at the airport. Before this technology can be used in an operational system the results must be extended to cover the entire airspace where the departing aircraft remain separated laterally by less than 2500 ft.

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