10.2 A WIND FORECAST ALGORITHM TO SUPPORT WAKE TURBULENCE MITIGATION FOR DEPARTURES (WTMD)[†]

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1. INTRODUCTION

Turbulence associated with wake vortices generated by arriving and departing aircraft poses a potential safety risk to other nearby aircraft, and as such this potential risk may apply to aircraft operating on Closely Spaced Parallel Runways (CSPRs). Aircraft separation standards are imposed to mitigate this potential risk. The FAA and NASA are investigating application of wind-dependent procedures for improved departure operations that would safely reduce spacing restrictions to allow increased airport operating capacity. These procedures are referred to collectively as Wake Turbulence Mitigation for Departures (WTMD).

An important component of WTMD is a Wind Forecast Algorithm (WFA) developed by MIT Lincoln Laboratory. The algorithm is designed to predict when runway crosswind conditions will remain persistently favorable to preclude transport of aircraft departure wakes into the path of aircraft on parallel runways (Figure 1). The algorithm has two distinct components for predicting the winds at the surface (33 ft) and aloft up to 1000 ft (the altitude by which an alternate form of separation would be applied by Air Traffic Control to aircraft departing the parallel runways, typically 15 degree or greater divergence in aircraft paths). The surface component forecast applies a statistical approach using recent observations of winds from 1-minute ASOS observations. The winds-aloft component relies on the 2 to 4 hour wind forecasts from NCEP's Rapid Update Cycle (RUC) model. The baseline version of the algorithm was developed and tested using data from St. Louis Lambert International Airport (STL). Algorithm performance was evaluated using 1-minute ASOS observations and crosswind component measurements taken from a dedicated Light Detection and Ranging (LIDAR) system. The algorithm was also demonstrated and evaluated at Houston George Bush International Airport (IAH). Use of the WFA is planned for 8 other airports deemed likely to derive significant benefit from WTMD procedures.

The operational concept of WTMD for use by Air Traffic Control (ATC) includes additional decision levels beyond the WFA forecast. These include a check for VFR ceiling and visibility conditions, and final enablement by a human controller. More details concerning WTMD can be found in Lang et al. (2005) and Lang et al. (2007). A more complete description of the WFA is given in Robasky and Clark (2008). The early history of WFA development is detailed in Cole and Winkler (2004).

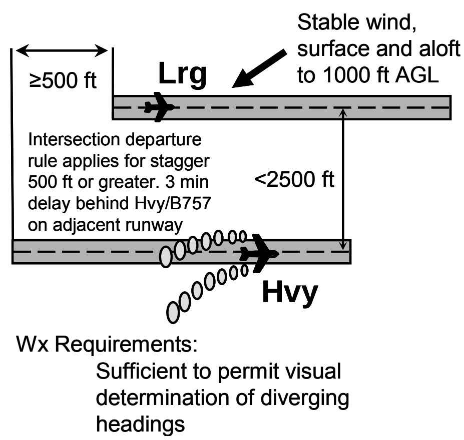

Figure 1. Requirements for WTMD. The top runway is WTMD-enabled.

2. WFA DESCRIPTION

The WFA predicts the status of runway crosswind to a height of 1000 ft, nominally for the upcoming 20-minute period, relative to a 0-crosswind threshold. For an individual runway within a closely-spaced pair, a positive crosswind is defined to be one which would transport wakes away from departures on the other closely-spaced runway (Figure 1). If crosswinds are expected to remain positive for the next 20-minutes then a WTMD-favorable, or “green”, status is indicated for

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this runway. Otherwise the status is unfavorable, or “red”. The WFA is designed to update each minute.

Functionally, the WFA consists of one component for the surface winds, a second for the winds aloft, and a third which integrates their results. This logic is illustrated in Figure 2.

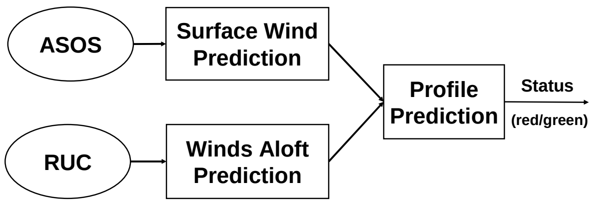

Figure 2. Block diagram of WFA functional logic.

Surface Component

The surface component of the WFA is a statistical forecast based on 1-minute update wind observations from the airport ASOS (each of which is a 2-minute average of 5-s observations). Two statistical models are involved: one for the mean crosswind over the upcoming 20 minutes, and the other for the standard deviation of the crosswind over the same period. Each is trained with one year of archived 1-minute ASOS observations. The statistical predictors are the same for each, and consist of various characterizations of wind behavior over the past 35 minutes. Specifically, the predictor set is

- The current wind (crosswind, headwind, speed, direction)
- The means and standard deviations of the above measures over the past 5, 20, and 35 minute periods
- The 10-minute trends of the aforementioned 5-minute means and standard deviations.

This amounts to 32 predictors. Models are obtained via linear regression between these predictors and the mean and standard deviation of crosswind over the subsequent 20 minutes.

A further refinement of the model is made based on the strength of the current wind. In development, the predictor space is divided into bins based on headwind and crosswind according to the following divisions: -10, -5, 0, 5, and 10 knots. This gives rise to 6 bins each for headwind and crosswind, or 36 total bins. Statistical models for crosswind mean and standard deviation are fit for each of these 36 bins. In forecast mode, the model is chosen appropriate to the current values of headwind and crosswind.

The forecast of crosswind mean and standard deviation are combined to yield an estimate of the lowest bound of expected crosswind. This is found by subtracting a certain number of forecast standard deviations (σ) from the forecast mean:

$$Xwind_{\min} = Xwind_{mean} - n\sigma$$

This forecast of minimum crosswind is compared with the 0-knot threshold to determine WTMD suitability. Situations will inevitably arise where this minimum estimate will vary back and forth across this threshold, potentially resulting in short-period “flicker” between green and red WTMD status. Such a situation is undesirable from an operational point of view. This potential is minimized by employing two values of the σ multiplier. For transitions from red to green status, a more conservative (higher n) value is chosen. Once a period of green status begins, a less conservative (lower n) value is employed until the transition back to red status occurs. These multipliers function as parameters to regulate the amount of green status, with higher (lower) values leading to higher (lower) estimates of crosswind lower bound and more (less) likely time above the WTMD threshold. They thus allow an airport-specific tuning to trade off system benefit with acceptably low risk of false green predictions.. WFA development based on STL data has led to settings of 5 and 3 for these parameters.

A further operationally-motivated constraint is imposed to prevent green status during those situations when a positive surface crosswind results from what is primarily a strong head or tail wind, or for situations where the wind is light and variable. The ATC user community does not deem such marginal conditions as constituting a reliable favorable crosswind. Therefore a test is made to ensure that the wind direction is no more than 60º offset from normal to the runway, and that the wind speed is at least 3 knots in strength. This test provides an additional safety buffer to the overall performance of the WTMD system.

Aloft Component

The suitability of winds aloft for WTMD (covering the lowest 1000 ft of the atmosphere) is determined by examining the forecast fields of gridded winds from the National Center for Environmental Prediction’s (NCEP) Rapid Update Cycle (RUC) mesoscale numerical prediction model. RUC is initialized every hour, and provides hourly forecasts out to a horizon of 6 hours (and beyond, though these are not used by the WFA).

Over the development lifespan of WFA, RUC at horizontal resolutions of 40, 20, and 13 km have been used. The “hybrid” vertical resolution product has been used throughout, which features higher vertical resolution at lower altitudes than the standard pressure-level RUC product. The typical elevations of the six levels relevant to WTMD are shown in Table 1. The adequacy of RUC in accurately representing these crosswinds is addressed by Huang et al (2007).

Table 1. Typical heights of the RUC levels that are of used in the WFA.

Level	Height (ft)	Height (m)
1	**16**	**5**
2	**66**	**20**
3	**197 - 213**	**60 – 65**
4	**394 - 443**	**120 – 135**
5	**640 - 722**	**195 – 220**
6	**1033 - 1181**	**315 – 360**

Four RUC grid points that surround the airport are chosen for wind profile extraction (Figure 3). The four points are chosen to be roughly equidistant from the airport. In an analogous fashion, profiles are chosen that bracket in time the current WFA initialization time. In most cases, this simply involves using the previous and next hourly forecast grids from the most recent initialization cycle. (Due to latencies in the generation and transmission of RUC forecast products, these are usually 2- and 3- hour forecasts.) If the future grid is for a verification time less than 20 minutes away, profiles from the next future grid are extracted as well, to ensure an adequate look ahead.

Crosswinds for the runway under consideration are computed from these 8-12 profiles for the 6 levels of interest. The most unfavorable, or minimum, crosswind is then found. As a further conservative measure (and a possible parameter for tuning), an additional buffer is subtracted from this minimum wind to yield the lower bound of expected aloft crosswinds. The current system setting of this parameter is 1 knot.

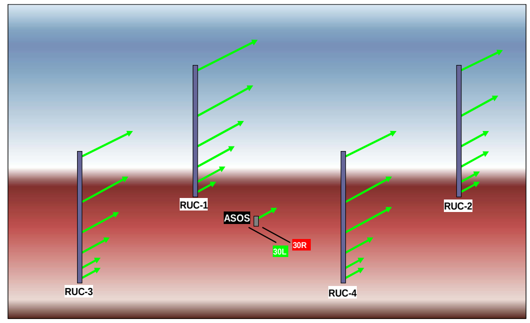

Figure 3. Schematic diagram of RUC wind selection (grid points and levels) with respect to STL CSPRs and ASOS.

Profile Integration

This component of the WFA integrates the results from the surface and aloft components and provides the final indication of WTMD-favorable wind status (green/red). The estimated lower bounds of future surface and aloft crosswind are compared to the WTMD crosswind threshold (currently 0 knots). If both future wind estimates are above this threshold, and the current surface wind is greater than 3 knots and within 60º of runway normal, then a favorable, or green, WFA status is issued. Otherwise, the status is unfavorable, or red. It should be noted that the threshold choice of 0 knots reflects an additional buffer above the negative crosswind necessary to transport a wake from one runway to the parallel runway in 2-3 minutes.

3. WFA PERFORMANCE

STL

The WTMD program has long used St. Louis Lambert International Airport (STL) as a specially-instrumented site to study various aspects of wake vortex behavior. This was the site for which the WFA was first developed and tested. The STL CSPRs are oriented in a NW-SE fashion, with the runway ends having magnetic headings of 120º and 300º (Figure 4).

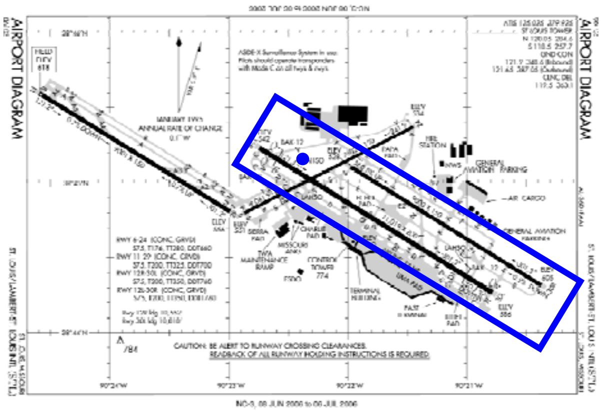

Figure 4. Airport diagram for STL. The CSPRs (box) and ASOS (dot) locations are highlighted in blue.

The surface component was trained with a full year (2001) of 1-min ASOS winds. It has been tested on various independent time periods, according to the availability of RUC wind grids for the aloft component. (An archive of 1-min ASOS surface winds is available from 2000 to the present from NCDC.) Hourly RUC initialization grids at 20 km resolution were available for 2003-04. RUC forecast grids at the 13-, 20-, and 40-km resolutions became available starting in September 2006 via the real-time demonstration of WFA, as will be discussed.

Typical behavior of the WFA during gradual wind shifts is illustrated by the time series in Figure 5, which covers a 3-hour window centered on a transition from positive to negative surface crosswinds for STL runway 12R/30L. The observed 1-minute crosswind observations are shown in light blue. The output of the surface component of the WFA (shown in dark blue), which corresponds to an estimate of the lower bound of the expected surface crosswind over the following 20-minutes, is seen to track this change well, and anticipates the transition to negative crosswinds with a lead of roughly 20 minutes. Note also the dramatic increase in the offset between the surface forecast and ASOS truth at this time, as this also marks the transition from 3σ to 5σ being subtracted from the forecast of mean crosswind to yield the lower bound estimate. The aloft component (shown in purple) has a 1-hour update rate due to its dependence on RUC, and anticipates a transition to negative crosswinds nearly an hour before the surface shift. This in turn causes the final WFA alert to transition from green to red at this time as well.

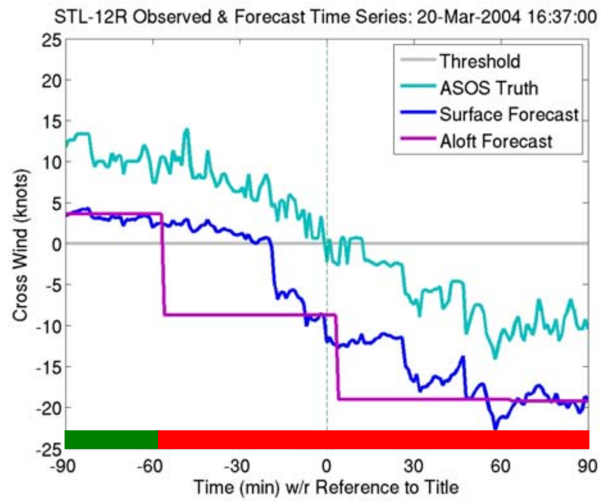

Figure 5. Time series of STL-12R WFA performance and ASOS observation for 3-hr period centered on 1637 UTC 20 March 2004. The final red/green WFA alerts are shown in the bottom solid bar.

Future surface 1-min ASOS values can be used to verify the performance of the surface component of the WFA, but for a complete evaluation aloft wind observations in the lowest 1000 ft were also required. This need was met in STL by a dedicated Light Detection and Ranging (LIDAR) sensor, with operation and processing performed by the Volpe National Transportation Systems Center. Crosswinds were extracted from high frequency scans made normal to the CSPRs. These were processed to yield crosswind at the same 1-minute update rate as the ASOS (and representing a similar 2-minute average of 5-s observations), available every 5 m in height from 15 m to 300 m. These LIDAR winds were available starting in February 2004.

Due to the availability of RUC and LIDAR, two main periods were available for bulk verification. The first was from February through December 2004 (using RUC initialization crosswinds). The second was from October through December 2006 (using RUC forecast crosswind). The WFA performance will be summarized by the following measures:

- *Green Minute Rate:* this is the fraction of all minutes for which a green WFA status is present, for either runway of the CSPR. This represents the overall potential of the site for WTMD operations.
- *False Green Rate:* this is the fraction of all green status minutes for which a negative verifying crosswind is present during the

subsequent 3-minute period. This is an indirect measure of risk exposure (not direct, as a number of mitigating factors must be overcome for a false green forecast to directly lead to an aircraft-wake encounter). The 3-minute limit was chosen as an upper bound for which the resultant departure separation would be less than that used today.

- *Missed Green Rate:* this is the fraction of all minutes for which the following 10 minutes exhibit observed crosswind entirely above threshold, for which a red WFA alert was issued. This represents missed benefit opportunity, or the rate at which stable periods of favorable winds were not properly anticipated by the WFA.
- *Green Periods < 20 Minutes:* this is the fraction of all periods of continuous green WFA alerts that are shorter than 20 minutes in length. This is an ATC usability measure, as such periods are too short to be of practical use for ATC operations.

The values of these bulk measures for the two STL verification periods are shown in Table 2. These measures are characterized by a low rate of green status minutes (and a corresponding high rate of missed green) in combination with a very low false green status rate. This is by design. WTMD is to be implemented as a FAA-certified system, and as such must meet very high and reliable safety standards.

Table 2. Bulk evaluation measures of WFA performance for STL during Feb-Dec 2004 and Oct-Dec 2006.

	STL-2004	STL-2006
Green Minute Rate	0.23	0.15
False Green Rate	3.57E-04	0
Missed Green Rate	0.73	0.81
Green < 20 Rate	0.14	0.16

The false green error rate shown in Table 2 is found to result from only 4 minutes of false green status, grouped into 2 events. The verification data for one of these minutes is shown in Figure 6. For this minute, the LIDAR verification profiles are below the 0-knot threshold at both 2 and 3 minutes into the future, and the ASOS verification is below threshold at a horizon of 3 minutes. An examination of this and the remaining event showed that both involved the passage of synoptic-scale cold fronts through the STL area. A possible mitigation of such sources of WFA false green error will be discussed in a subsequent section.

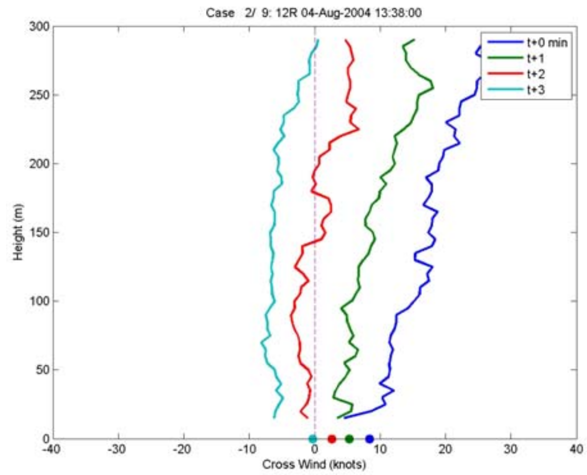

Figure 6. Crosswind profiles from ASOS (dots) and LIDAR (lines) for STL-12R on 1338 UTC 04 Aug 2004 (with WFA green status at this forecast initialization time) and the subsequent 3 minutes.

IAH

The second site for WFA development and testing was Houston George Bush International Airport (IAH). This airport's CSPRs are oriented in a NNW-SSE fashion, and have magnetic headings of 150º and 330º (Figure 7). LIDAR crosswind measurements for this site became available in April 2007.

The bulk evaluation measures for the period April – August 2007 are shown in Table 3. These numbers are characterized by a much smaller rate of green status minutes, and a correspondingly higher rate of missed green periods, than was seen for STL. At its lower latitude, IAH is further displaced from the mid-latitude westerlies, and thus has climatologically weaker winds. Also, this evaluation period consists of late spring and summer months (with their climatologically weaker winds) which probably contributes to this contrast. Note, however, that no instances of false green status were identified during the validation period, suggesting the opportunity to relax the σ parameters used to establish the expected surface crosswind lower bound.

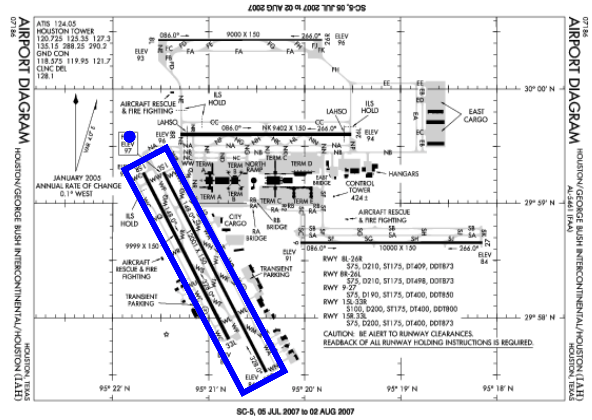

Figure 7. Airport diagram for IAH. The CSPRs (box) and ASOS (dot) locations are highlighted in blue.

Table 3. Bulk evaluation measures of WFA performance for IAH during Apr – Aug 2007.

	IAH
Green Minute Rate	0.04
False Green Rate	0
Missed Green Rate	0.96
Green < 20 Rate	0.22

4. WFA REAL-TIME TESTING

A real-time prototype version of the WFA began running for STL in September 2006, and for IAH in February 2007. This was done for in-house evaluation of algorithm performance and the use and reliability of the input data streams. The 1-minute ASOS data stream originates at the FAA William J. Hughes Technical Center in Atlantic City. RUC forecasts (13-km resolution) are obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) in Silver Spring, MD, with a backup source being the NOAA Earth System Research Laboratory (ESRL) in Boulder Colorado. During the period of October 2006 through April 2007 ASOS was seen to be missing roughly 10% of the time. This manifested itself in long (hours to days) continuous stretches of missing data, which in turn was traced to various software and communication issues at the data source. RUC was found to be unavailable 1.5% of this period. The WFA algorithm forces a red status for any minute with missing input.

The display used in-house (and made available externally to project team members via the internet) to monitor WFA performance in shown in Figure 8. Only half of the display is shown, that for one runway of the CSPR pair for IAH. The two top panels indicate overall WFA status, with the top color-coded for the current alert (red/green) and the second showing its time series over the past 35 minutes. The bottom two panels are dedicated to the surface and aloft WFA components, respectively. The first of these shows a 35-minute time series of surface crosswind observations and WFA predictions, terminating at the current time. The second of these shows RUC crosswind profiles for each of the relevant grid points and RUC forecast hours, along with a vertical line indicating the final aloft lower crosswind bound. For this example, both the surface and aloft components for the current time indicate winds above threshold. Therefore, the topmost panels indicate green for a favorable WTMD status.

WTMD team members from the NASA-Langley Research Center also demonstrated successful real-time operation of the WFA in the ATC environment at both STL and IAH. WTMD status was displayed on an ASOS Controller Equipment Integrated Display System (ACE-IDS) platform (Figure 9) at STL, and an ACE-4 at IAH. Although the demonstrations did not involve actual WTMD implementation, human-in-the-loop simulations of the proposed WTMD ATC procedures were carried out by the MITRE Corporation. Details of these aspects of WTMD are described in Lang et al. (2007).

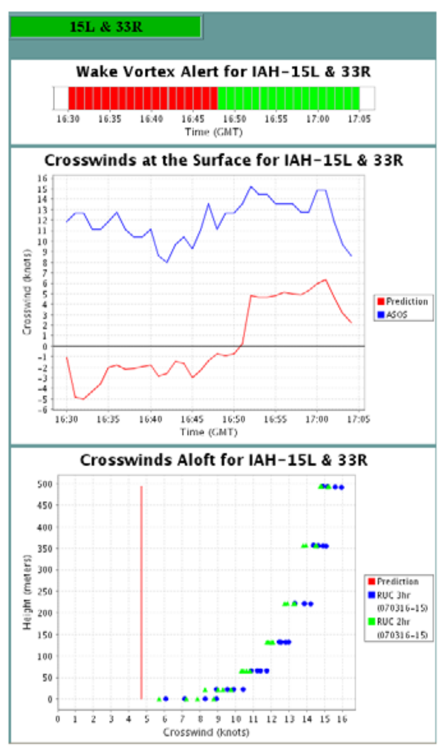

Figure 8. Diagnostic display sample of the realtime WFA prototype for IAH runway 15L/33R.

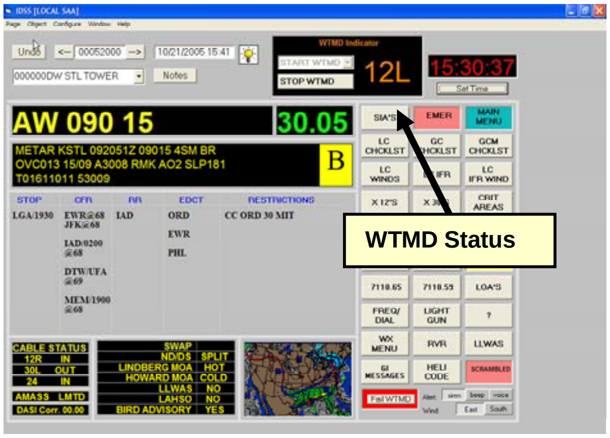

Figure 9. Overview of ACE-IDS display for STL with WTMD status field.

5. EXTENDING THE BASELINE WFA

Areal Wind Input

The primary safety vulnerability of the WFA is sudden wind shifts that cannot be anticipated by the airport ASOS and are not adequately forecast by RUC. Although the rate of false green status was found to be extremely low, the STL WFA evaluation (with ASOS and LIDAR verification) yielded several false green error events due to cold-frontal passages. Additional evaluation of WFA for STL for other periods using only ASOS as validation uncovered several more false green error events (at similarly very low false green error rates) due to convective outflows, or gust fronts. A time series of WFA performance for one such event is shown in Figure 10, with an associated NEXRAD reflectivity depiction of strong approaching convection shown in Figure 11. The ASOS crosswind during this event is seen to change by nearly 20 knots over a 2-minute period.

As mentioned earlier, final authority to enable WTMD will rest with ATC supervisors, who would be aware of convective activity in the day's operations and would be trained to transition out of WTMD procedures in the same manner in which they are trained to make other changes to ATC operations to mitigate the effects of convective activity. Even so, work was done to investigate the use of an automated procedure that could be added to WFA that would detect such threats. Algorithms were developed that would examine NEXRAD-based inputs of high resolution vertically-integrated liquid (HRVIL) and outflow detections from the Machine Intelligent Gust Front Algorithm (MIGFA) within various regions of interest (ROI) from 11 to 32 km in radius, centered on STL. The algorithm would issue an override of green status if HRVIL VIP levels greater than 3, or if a MIGFA detection or forecast, was present within the ROI. Analysis indicated that use of such procedures would eliminate 67% to 80% of the false green errors for STL over a one-year period. The effect of such algorithms on WFA benefit (i.e., would such a procedure unduly eliminate green periods not associated with false green events?) is still being investigated

Another possible data source that could be used to automatically detect adverse discontinuities in the local area wind is the Terminal Winds Analysis, which is in operational use as part of the Integrated Terminal Weather System (ITWS). This product provides a three dimensional gridded wind analysis for the airport terminal environment based primarily on local wind estimates derived from the TDWR and NEXRAD Doppler radars, as well as surface and aircraft wind reports. The Terminal Wind analysis provides winds at a 2-km horizontal resolution over a 40 km x 40 km area, at an update rate of 5 minutes. Its lowest two levels would fall within the lowest 1000 ft of interest to WTMD. Investigation of the use of this data source in ongoing.

Finally, a third potential candidate for this purpose is a frontal analysis and prediction product under development at MIT Lincoln Laboratory for the prototype National Corridor Integrated Weather System (CIWS). This product relies on multiple interest images of satellite, radar, and gridded surface data fields to detect and track synoptic scale wind shifts.

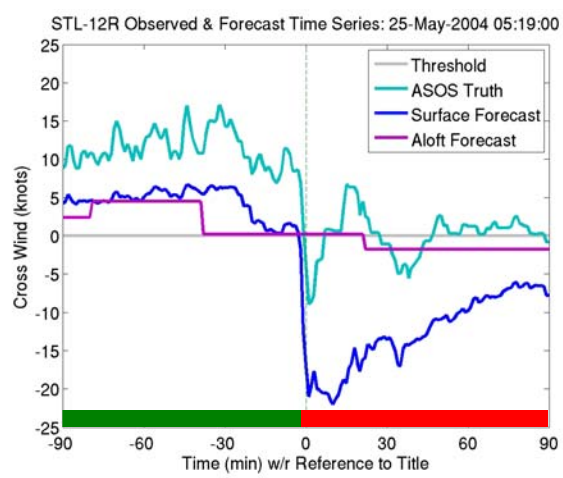

Figure 10. Time series of STL-12R WFA performance and ASOS observation for 3-hr period centered on 0519 UTC 25 May 2004. The final red/green WFA alerts are shown in the bottom solid bar.

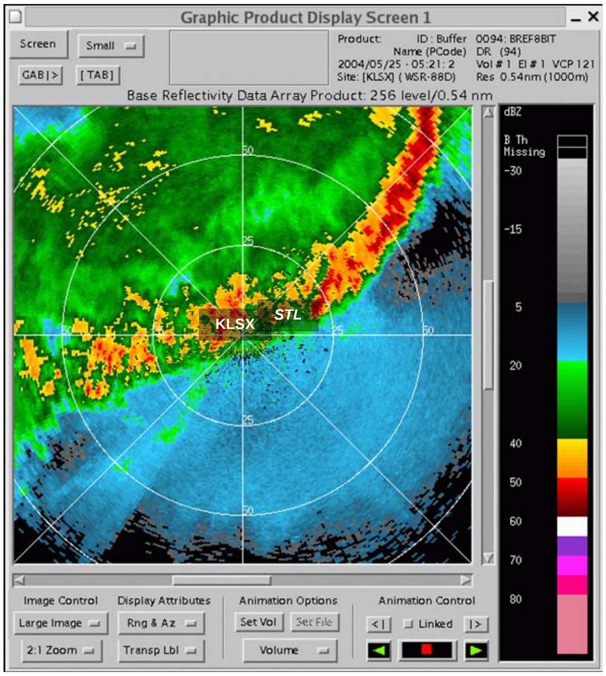

Figure 11. Base Reflectivity from the KSLX Nexrad radar for 0521 UTC 25 May 2004. The location of the STL airport is also indicated.

Additional WTMD Airports

The WTMD program has designated 10 airports whose wind climatology, runway geometries, and air traffic characteristics render them candidates to derive benefit from the procedure. A list of these 10 airports is shown in Table 4. The surface component of the WFA has been tuned for all 10 sites and the quality of the resulting models over a one-year period (using only ASOS surface winds as truth) has been examined. All sites are found to have roughly the same false green error rate of STL or less. STL is seen to be in the middle of the pack as far as potential benefit. BOS and SFO have the highest green minute rates (over 0.40) and the lowest missed green rates. This analysis is highly preliminary, as the performance of the RUC for these sites also needs to be examined, especially for areas near the coasts (where initialization data over open ocean is sparse) and at locations in rugged terrain (such as SFO and SEA) where small-scale local orographic wind effects may not be adequately resolved by the mesoscale model. Investigation of these issues is also ongoing.

Table 4. Names of the additional WTMD airports.

BOS	Boston
DTW	Detroit
EWR	Newark
IAH	Houston
MEM	Memphis
MIA	Miami
PHL	Philadelphia
SEA	Seattle
SFO	San Francisco
STL	St Louis

6. CONCLUSION

A conceptually simple, reliable, high-update model of future runway-specific crosswinds has been developed to provide an indication of anticipated wind conditions favorable for WTMD procedures. It is expected that the use of these reduced aircraft separation standards will provide a substantial reduction in wake vortex related delay. The formal requirements of the WFA are to be specified in early 2008, for subsequent certification and implementation.

This baseline WFA, and the experience gained in its development, evaluation, and implementation will also serve as a platform for an approach to mitigating wake vortex related spacing delays for the arrival portion of the overall problem. This is expected to be more challenging, as it involves a domain of concern that is spatially much larger and temporally much longer, due to the need to safely and efficiently manage aircraft approaches to the runways.

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