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Abstract

An analysis has been performed on data generated from the two most recent field deployments of the Aircraft Wake VOrtex Spacing System (AVOSS). The AVOSS provides reduced aircraft spacing criteria for wake vortex avoidance as compared to the FAA spacing applied under Instrument Flight Rules (IFR). Several field deployments culminating in a system demonstration at Dallas Fort Worth (DFW) International Airport in the summer of 2000 were successful in showing a sound operational concept and the system's potential to provide a significant benefit to airport operations. For DFW, a predicted average throughput increase of 6% was observed. This increase implies 6 or 7 more aircraft on the ground in a one-hour period for DFW operations. Several studies of performance correlations to system configuration options, design options, and system inputs are also reported. The studies focus on the validation performance of the system.

Introduction

NASA's Terminal Area Productivity Program (TAP) was established to investigate and develop technologies to increase the efficiency of airport terminal operations. New technologies must meet current safety criteria as a minimum. The Aircraft Wake VOrtex Spacing System (AVOSS) is a project under TAP to demonstrate safe aircraft spacing reductions based on predicted wake behavior and actual wake observations. The FAA prescribes aircraft spacing criteria for operations conducted under IFR. The weight categories of the leading and following aircraft are incorporated into these criteria, but the influence of ambient weather conditions is neglected [1]. The criteria are overly conservative in many weather conditions, such as high crosswinds that push the wakes laterally from the path of an approaching aircraft. Changes in the spacing criteria have had a substantial impact on airport operations, as observed soon after the FAA spacing criteria were changed to create a new category for the Boeing 757 in 1994. Los Angeles International Airport is believed to have had a 12% capacity decrease after the new criteria were put into effect [11].

The AVOSS uses wake behavior predictions derived from the ambient weather conditions at the airport and aircraft data to provide a reduced spacing from the current minimums. Field sensors validate the predictions with observations and provide safety feedback for the system. The AVOSS architecture is discussed in detail in [1]. Field deployments in 1999 and 2000 at the Dallas Fort Worth International Airport (DFW) have been successful in demonstrating the feasibility of the AVOSS concept in reducing aircraft spacing and achieving higher terminal throughput. Descriptions of the DFW field deployments are given in [1] and [2]. AVOSS performance statistics and system design tradeoff studies appear in [3] and [4]. This paper updates the performance results from the DFW deployments and expands on previous system tradeoff studies. The focus of the new studies is the validation and safety checking of the wake predictions, which have not previously been investigated.

Terms

Safety Corridor- Spatial limits about the nominal flight path of an approaching aircraft defining a region free of wake hazards, and used to compute wake durations.

Residence time- Time from wake generation or beginning of a wake observation until the wake exits the safety corridor or has dissipated to a non-hazardous circulation strength

Lateral drift- Horizontal movement of a wake vortex

Sink- Vertical movement of a wake vortex

Demise- Decay of wake vortex circulation strength below a threshold value representing a minimum hazard

Buffer- The difference between a predicted and observed wake residence time

Exceedance- A difference between observed and predicted wake residence times where the observed time is greater than the predicted time

Factor- The name given to each mechanism of wake hazard removal (drift, sink, demise)

Taumin- A configuration parameter that represents a lower limit for wake predicted and observed residence times

Drift Lockout- A condition in the AVOSS logic that causes wake drift to be ignored as a wake transport factor

AVOSS System Description

The AVOSS architecture has remained consistent with previous descriptions [1], and is shown in Figure 1. The system deployment included all the subsystems shown with the exception of the ATC interface. Some candidate aspects of an ATC interface were modeled to provide more realistic performance metrics. An example of this is rounding spacing values output by the AVOSS to one half-nautical mile increments, representing a value that could be operationally useful. On intervals of every half-hour, the weather subsystem provides three files containing vertical profiles of atmospheric winds, temperature, and turbulence statistics. These profiles, along with parameters from an aircraft database provide the input to the prediction subsystem. The prediction subsystem consists of wake evolution models [6, 7] that provide aircraft-specific predictions of wake lateral drift, vertical sink, and circulation. These three wake behavior parameters are referred to as factors. The subsystem integration component computes durations of wake hazards (residence times) from these predictions and outputs the results to a file. Residence time represents the time elapsed between wake generation and when the wake

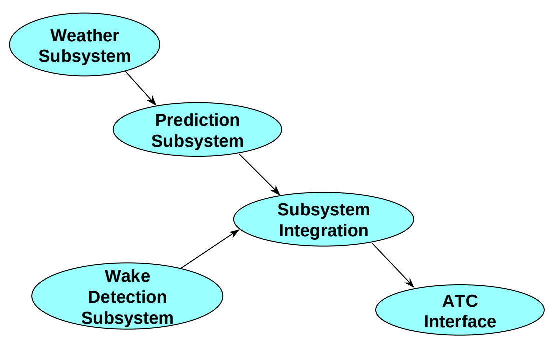

Figure 1 AVOSS system architecture

ceases to be a hazard to aircraft. A wake may cease to be a hazard by moving out of an approaching aircraft's path or dissipating to a circulation strength that does not present a hazard to the aircraft (demise). Residence times are computed for each wake factor and for both the port and starboard wakes.

Residence times are computed by comparing predicted or observed wake tracks to the dimensions of a safety corridor. The corridor provides spatial limits for wake trajectories. Upon reaching one of these limits, the wake is no longer a threat to a following aircraft. The wake may exit the corridor via lateral drift or sinking beneath the corridor floor. Residence time computations are performed at discrete “windows” of the safety corridor. Details of the safety corridor may be found in [2].

The AVOSS logic includes a variety of tests to determine if valid predicted residence times can be computed. Weather quality flags appear in each profile file generated by the weather subsystem. The AVOSS uses the flags to insure that a certain percentage of the data in each file is valid. A wind, turbulence, and temperature profile must exist for the same prediction interval for AVOSS to run and generate a predicted wake track. If the wind or turbulence files fail the quality check, the prediction generated is flagged and will not be used for validation. The temperature profile is not required to pass a quality check for validation due to low system sensitivity to this input [4]. A quality failure of the wind profile will cause the AVOSS logic to prevent spacing reduction based on lateral residence times.

Another condition that results in invalid data is caused when the crosswind is light and/or variable. When this occurs the predicted drift residence times are set to an invalid flag value (9999), since the winds could easily change and carry a wake that exits the safety corridor back into the path of an approaching aircraft. A sensitivity window of +/-1 m/s is used to determine if the crosswind mean +/- crosswind standard deviation intersects the window. The condition in which the result of the wind computation intersects the window is called drift lockout.

Finally, flags in an input configuration file can cause the AVOSS logic to set the drift, sink, or both residence times to the invalid flag value.

Net residence times are computed for each defined window and for each aircraft type expected in the traffic mix for a particular airport (See the Appendix for a description of the net residence time computation). The net residence time represents the significant wake hazard duration as computed from the port and starboard wake, and each wake factor. Since the net residence time is the necessary delay between two aircraft passing through a given computation window, it “sets” the minimum spacing for that window. The highest net residence time over all the computation windows for a particular aircraft is used to compute the “top of approach” spacing. The top of approach spacing is the separation necessary at the beginning of the approach to satisfy the minimum spacing at all computation windows along the approach. The spacing varies depending on relative aircraft speeds and ambient headwinds. The highest top of approach spacing among all the aircraft types (e.g. B747-400) in a particular category (small, large, B-757, heavy,) is then set as the minimum spacing for all aircraft in that category and is output to a file. The file reports the AVOSS spacing in a matrix indexed by aircraft category, allowing the spacing for a particular pairing of leading and following aircraft to be determined. The format is shown in Table 1.

Small aircraft are not considered as generators since the wakes of small aircraft are not operationally significant to the other categories. Field data [2]

Table 1 AVOSS Spacing Output Format

Generator ⇒ Follower ⇓	Large	B-757	Heavy
Small	AVOSS spacing (nm)	AVOSS spacing (nm)	AVOSS spacing (nm)
Large	AVOSS spacing (nm)	AVOSS spacing (nm)	AVOSS spacing (nm)
Heavy	AVOSS spacing (nm)	AVOSS spacing (nm)	AVOSS spacing (nm)

indicated that the wake sensors were not capable of measuring circulations at the low strengths significant to small follower aircraft; so spacing reductions are not made for small followers based on demise.

AVOSS outputs a statistics file that includes a runway throughput value (in units of aircraft per hour) computed using the AVOSS spacing. The throughput value represents a maximum possible arrival rate, and its computation uses probabilities of arrival of each expected aircraft type. Also, the spacing values are rounded and a time delay to account for variance in Air Traffic Control (ATC) operations is included [1]. The statistics file also includes various validation statistics reported in the next section.

The wake detection subsystem provides observed residence times that correspond to the predicted residence times computed at various sensor locations. The observed residence times are collected in "wake files" and used for validation. A program called "compare.exe" reads the files of predicted wake residence times and the wake measurement files from field sensors. The predicted residence times are compared to measured residence times to generate validation statistics. The difference between the observed and predicted residence time is the buffer. Compare.exe runs on each sensor file collected during the half hour prediction interval. Several wake files for each sensor may exist in a given prediction interval.

The compare logic matches observed wake residence times to predicted times based on file timestamps, sensor and prediction window location, and aircraft type. If a sensor file is missing any of the information above, or only has invalid flags for all residence times, the file is not used. The statistics file tracks the number of invalid wake files. Once a valid set of predicted and observed residence times is matched the following buffer time is computed:

Buffer = predicted residence time – observed residence time

The buffers are categorized as positive, class 1, class 2, hard, and soft. The categories exist to facilitate the analysis of the significance of each wake case. Positive buffers represent the prediction algorithm over-estimating the wake residence time and therefore do not present a safety concern.

In class 1 cases, both the predicted and observed residence times are less than a configuration input called Taumin. Taumin represents a likely aircraft spacing given a minimum runway occupancy time (ROT) for a particular airport. The ROT is the minimum time from aircraft touch down to runway exit. AVOSS spacing output is limited to a lower bound due to the minimum ROT. The value chosen for Taumin during the latest deployment and used in this study was 50 seconds. Predictions and observations that are both less than Taumin cannot influence spacing and consequently have no affect on operational safety. Taumin is therefore used to limit predictions and observations in the validation logic. For example, a predicted drift of 20 sec with a Taumin of 50 sec would result in the drift residence time being computed using 50 sec. The same limiting operation is applied to observed residence times.

Class 2 cases represent the predicted and observed residence times that correspond to spacing values greater than the default FAA spacing. No provision exists in the AVOSS to provide spacing greater than the FAA criteria.

Negative buffers (exceedances) are classified as "hard" or "soft". A hard buffer occurs when a sensor quantifies the predicted factor that sets the residence time. Hard exceedances bear the most operational significance since they represent a specific disagreement in the predicted bounds on wake behavior and a sensor observation of the same behavior. Soft exceedances result from buffers computed using residence times of different wake factors. Since soft exceedances are not a direct disagreement between a wake prediction and observation, they must be investigated on a case-by-case basis to determine their significance.

The type and placement of the field sensors used for weather measurement and validation is discussed in [2]. Two lidar systems, one pulsed and the other continuous wave (CW), were placed on the side of the approach path to runway 17C at DFW. The CW lidar offers higher resolution at short ranges (< 300m), so it was positioned to scan a "slice" of the safety corridor 84 meters north of the approach end of the runway. At this location the glideslope is at an altitude of approximately 60 feet, the safety corridor floor is at ground level, and the wakes measured are all in ground effect. The pulsed lidar scanned three regions 1080 meters, 1702 meters, and 2262 meters north of the runway threshold. Most data was collected at the 1702-meter scan plane. Wakes measured with the pulsed lidar could exit the corridor via all factors. An anemometer array referred to as the windline was positioned 983 meters from the runway threshold. The safety corridor floor is above ground level at the windline location, but the windline can only give reliable measurements of wake drift. It

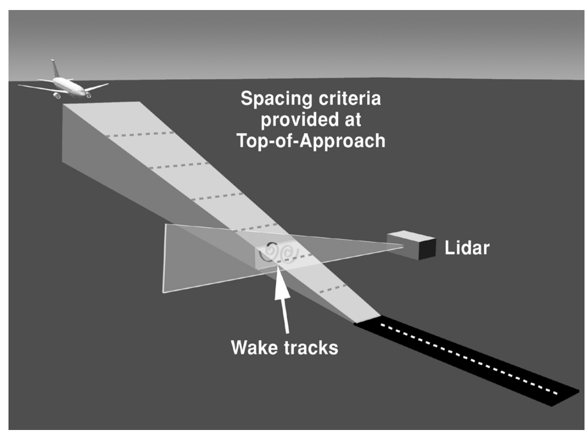

Figure 2 Safety corridor/sensor geometry.

was observed that wake sink usually set the spacing at the windline corridor location. This condition led to the special validation logic used for the windline. The sensor placement relative to the safety corridor is shown conceptually in Figure 2.

Re-Run of 1999 and 2000 DFW Deployments

In addition to the real-time AVOSS code that ran during the field deployments, AVOSS includes a "batch" version for use on a PC. The batch version reads a set of weather and wake files (real or artificial) and produces the same set of output files as those generated in real-time operation. To produce the results in this report, the batch version of AVOSS was executed using all of the input weather and wake sensor files collected from the 1999 and 2000 DFW deployments. The software version numbers used are summarized in Table 2. The 1999 data used was collected November 11 to December 3, and the 2000 data was collected May 1 through July 20. Re-execution of AVOSS on the data collected in the field insures a complete set of observations is used. A variety of issues in the field can cause wake or weather observations to be unavailable during real-time operation, but available for post-deployment analysis [3].

Table 2 AVOSS Software Version Numbers

avoss_go.exe	V1.0.0
avoss.exe	V2.5
Predictor algorithm	APA V3.1.0
Compare.exe	V1.5

The configuration input files were set to match the 2000 deployment setup. The results from both deployments were combined for the statistics in this report.

Table 3 is a summary of the number of weather observation files that passed the AVOSS quality criteria. The first column in Table 3 represents the total number of complete weather file sets for a given prediction interval. The next three columns show the number of each type of file that passed the quality check. The percentage in the last column is the percentage of files in column 1 that had both wind and turbulence files that passed the quality check. As shown, a high percentage of the available weather files were useful for validation.

Table 3 AVOSS Input File Utilization

Total runs	Runs with valid wind profile	Runs with valid turbulence profile	Runs with valid temperature profile	% Of valid input weather sets
2752	2602	2588	363	94

Throughput and Validation Performance

The predicted potential arrival rate using the AVOSS spacing and throughput performance model was approximately 33 aircraft per hour. The potential arrival rate with default spacing criteria was about 31 aircraft per hour, resulting in a 6% increase in mean runway capacity. The maximum throughput increase predicted was 16% over the throughput predicted using FAA default spacing. The United States airspace system is estimated to be operating at about 60% of its capacity [8]. Previous studies [9] predict that a 6% capacity increase at a 60% demand ratio would yield a 14% reduction in delay. Some slot-controlled airports such as La Guardia in New York are estimated to be operating at nearly 95% capacity [10].

At 95% capacity a 50-60% reduction in delay could be realized with the mean capacity gain predicted by AVOSS.

Validation performance feedback is also included in the AVOSS statistics file. Table 4 shows a breakdown of the predicted vs. the measured buffers. The total wake cases figure represents the total number of wake measurement files produced by all sensors.

Table 4 Validation Statistics Summary

	Number of Cases	Percentage of valid
Total wake cases	10712	
Valid wake Cases	2301	21.5%
Class 1 Events	1403	61%
Positive Prediction Buffers	720	31.3%
Hard Exceedances	19	0.8%
Soft Exceedances	159	6.9%

Table 5 Validation Statistics by Sensor

	Windline	CW Lidar	Pulsed Lidar	Total
Total wake cases	7911	1708	1093	10712
Valid wake Cases	1126/ 14%	389/ 23%	786/ 72%	2301
Class 1 Events	304/ 27%	337/ 87%	762/ 97%	1403
Positive Prediction Buffers	702/ 62%	12/ 3%	4/ 0.5%	718
Hard Exceedances	n/a	19/ 5%	0	19
Soft Exceedances	120/ 11%	21/ 5%	18/ 2%	159

The next row is a count of the files from this total that were valid. As shown, 61% of the cases were class 1, 30% were positive buffers, and 7% were exceedances. In 91% of the cases, the wake behavior was safely bound or not operationally significant.

The same buffer categories are then broken out by sensor in Table 5. A general observation of interest is that the pulsed lidar had by far the highest percentage of valid wake files. Another observation is that almost all of the positive prediction buffers are from the windline.

Figures 3 and 4 show the frequency of various magnitudes of negative buffer times for each sensor. As shown in Table 5 and Figure 4, all hard exceedances were measured with the CW lidar. In these cases, the predicted demise was less than Taumin, and 75% of the observed demise times exceeded Taumin by less than 10sec. The CW sensor is located where the corridor floor is at ground level, effectively disabling sink as a transport factor. In addition, the winds triggered the drift lockout logic in 63% of the cases, disabling drift as a transport factor. So the performance may be expected to decline with two out of three factors disabled in the predictions. The question remains as to causes of the error between the demise predictions and measurements for these hard exceedances. AVOSS predictions occur each half-hour, but wake measurements correspond to aircraft arrivals and occur at various times in a particular half-hour interval. Considering the delta in time from the prediction to the observation as the prediction age, two- thirds of the exceedances occurred when the prediction age was more than 10 min. Over one-third occurred when the prediction age was more than 20min. As illustrated in Figures 5 and 6, exceedance frequencies and magnitudes generally increase with prediction age, as expected. Note that a value for

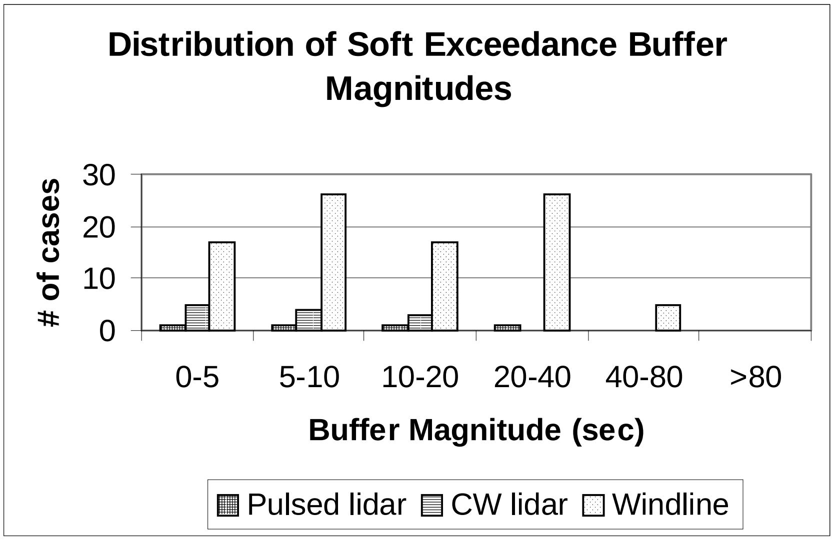

Figure 3 Soft exceedance buffer distribution.

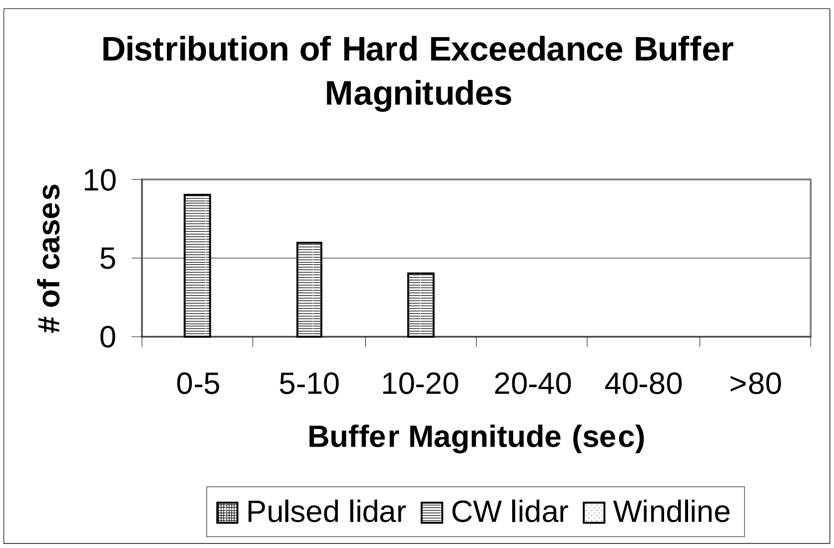

Figure 4 Hard exceedance buffer distribution.

Taumin of 60 sec instead of the 50 sec used would eliminate most of these hard exceedances.

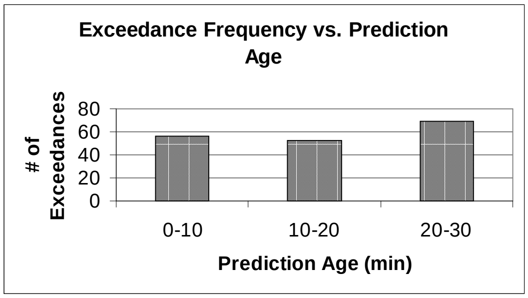

Figure 5 Exceedance frequency vs. prediction age.

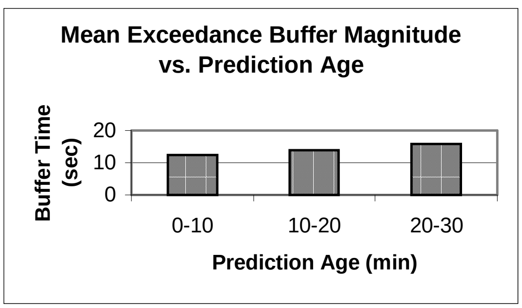

Figure 6 Exceedance buffer magnitude vs. prediction age.

The sensors provide a demise time that is the time for the wake to decay to a level of circulation that is not a threat to the following aircraft. An alternate demise time is provided that is the time for the wake to decay to a level that is not distinguishable from background turbulence. AVOSS can use either time as the observed demise wake factor. The value used for the non-hazardous circulation (a system input parameter) is 120 m^2/s. The threshold circulation used by the sensor system to compare a wake against background atmospheric turbulence can be set manually or computed automatically. Typical values used in the deployments were 90 m^2/s (pulsed lidar) and 100 m^2/s (CW lidar). The latest deployment configuration used the background turbulence-based time for the demise, since this factor was available more reliably from the sensors. In all cases where the circulation-strength based demise time was available from the sensor, its value was less than the background turbulence based demise time. Two exceedance cases would have been eliminated and several buffers reduced using the circulation-based demise time.

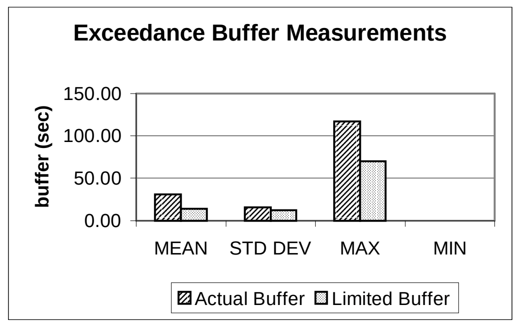

Figure 7 Exceedance buffer measurements.

In all of the hard exceedances, every prediction was less than Taumin and therefore limited to 50 sec. Figure 7 is a graph of the reported exceedance buffer magnitudes (called "limited" since measured from Taumin) and the actual buffer magnitudes computed from the raw prediction values for all the exceedances measured (hard and soft).

The mean buffer magnitude approximately doubles when the prediction was not "clamped" to Taumin. No value appears for the minimum exceedance magnitude in Figure 7 due to an exceedance of 0.03 sec measured in the 1999 data. Since Figure 7 is only a comparison of buffers computed from net residence times (see Appendix), an examination of all the buffers that could be computed from the exceedance data was performed. The results are summarized in Table 6. Entries in Table 6 filled with "No data" indicate that one or both of the residence times were invalid for a particular sensor and factor so no buffer could be computed. Significant mean buffer values for the drift and demise factors are given in Table 6. More data would be required to characterize the system performance for the sink factor, since only two data points were available. Further study is required to identify the causes and amounts for each source of error in the system. The error between a wake residence time observation and prediction can be summarized as the sum of four sources of error in the system, as shown in equation (1):

$$e_{sys} = e_{ic} + e_{wx} + e_{pred} + e_{sensor} \qquad (1)$$

where "e" denotes error, "sys" indicates the total system, the subscript "ic" indicates wake initial conditions, the subscript "wx" indicates weather estimation, "pred" represents the prediction algorithm, and "sensor" indicates the sensor system. Note the data for Table 6 contains the exceedance cases only, so the disagreement between the predictions and observations is for a small subset of system operations. Software modification would be required to output all the measured buffers, which should be compared for a complete analysis of system accuracy. However, the exceedances represent a critical subset of system operations, where the system is inaccurate in a manner that could impact safety, so examining this subset of system operation is relevant.

Weather Correlations to Predictions

To characterize the contribution of errors in weather estimation to the system error, the exceedances in demise and drift were examined. Only the cases in which a buffer was computed from the same observed and predicted factor were used. The measurements that fit this description are primarily the windline buffers for drift, and the CW lidar hard exceedances for demise.

The buffer magnitudes were compared to the corresponding wind and

Table 6 Exceedance Buffers-All Wake Transport Factors

Factor	Drift		Sink		Demise	
	Mean Buffer Value (sec)	Buffer Standard Deviation (sec)	Mean Buffer Value (sec)	Buffer Standard Deviation (sec)	Mean Buffer Value (sec)	Buffer Standard Deviation (sec)
All sensors	27.8	16.9	-3.2	9.4	18.4	19.5
Windline	28.3	16.7	N/a	N/a	N/a	N/a
CW lidar	19.9	18.8	No data	No data	20.4	13.0
Pulsed lidar	No data	No data	-3.2	9.4	16.2	24.7

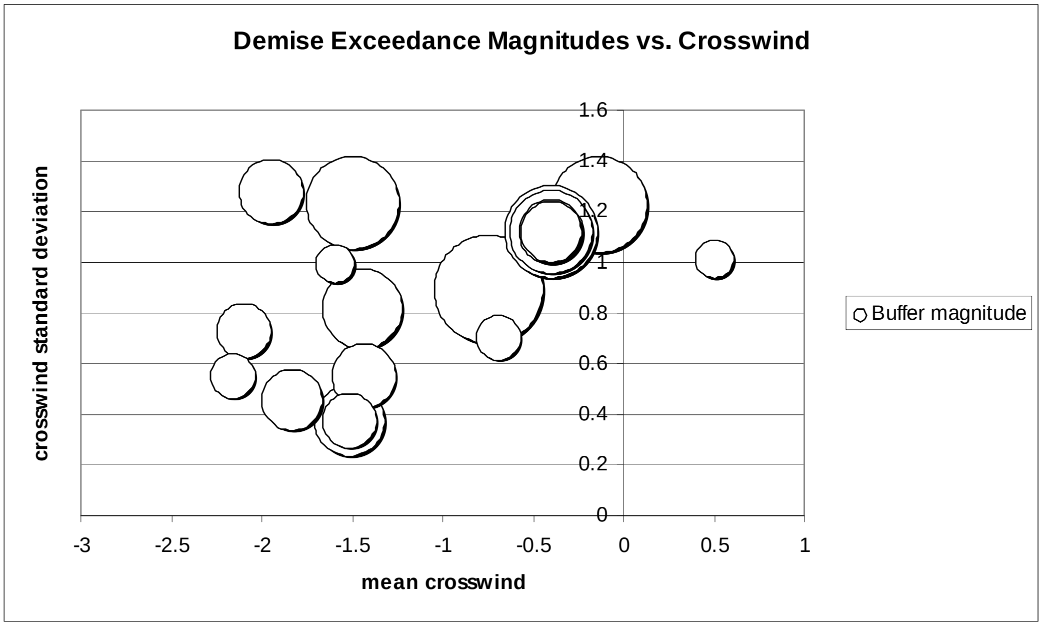

Figure 8 Demise exceedance magnitudes vs. crosswind.

turbulence profile data to identify correlations between the ambient weather conditions and the system error. Figures 8 and 9 show the demise buffer magnitudes as a function of crosswind and Eddy Dissipation Rate (EDR), respectively. Figures 10 and 11 show the same plots for the drift data.

As shown in Figure 8, the largest exceedance buffer magnitudes (largest bubbles) occur at mean crosswind values between 0 and 1 m/s, and standard deviations of around 1 m/s. Another group of exceedances occur between mean crosswind values of -1.5 to -2 m/s, and are relatively independent of the standard deviation. The fact that almost all exceedances are during negative mean crosswinds may be due to prevailing S-SW wind that was observed during the lidar operating hours. This wind direction would also tend to push the wakes toward the CW sensor location, which may have influenced the amount of time the sensor was able to track the wake. It may be expected that most of the demise exceedances occurred in mean crosswinds of 1.5 m/s or less, since a high mean crosswind would cause a condition where the drift instead of the demise would be set as the predicted residence time. All of the larger exceedance magnitudes occurred with crosswinds characteristic of the drift lockout condition, which forces demise to be the only factor used to determine spacing and available for validation.

A weather input that has a direct influence on the demise prediction [5] is the EDR, and Figure 9 shows that almost all exceedances lie between EDR values of 0.002 m^2/s^3 and 0.008 m^2/s^3. These values represent typical daytime levels of turbulence in the atmosphere. The maximum error buffers seemed to fall around EDR = 0.004 m^2/s^3. Further study will determine if this result identifies a region of input values that degrade the system performance.

To reduce clutter, only exceedance buffers larger than 30 sec are shown in Figure 10. Most of the larger drift exceedance magnitudes occur at small values of crosswind standard deviation. The region between +/- 1 m/s of mean crosswind has no exceedances due to the drift lockout logic. Since almost all of the exceedances are on the edge of this region, the data supports a slight expansion of the thresholds for drift lockout, as this would eliminate most of these exceedances. Figure 11 shows that all of the drift exceedances occurred at lower values of EDR than the demise exceedances. As expected, higher values for EDR would tend to speed the demise of wakes. This, in turn, would reduce the effectiveness of the drift-dependent windline.

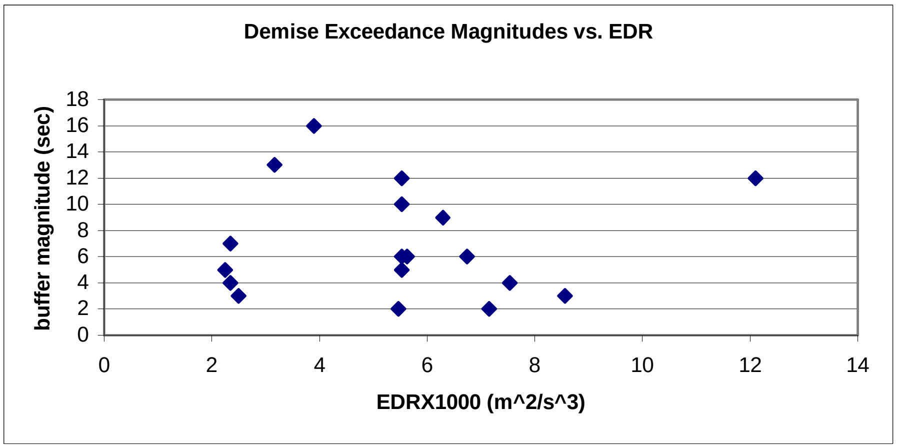

Figure 9 Demise exceedance magnitudes vs. EDR.

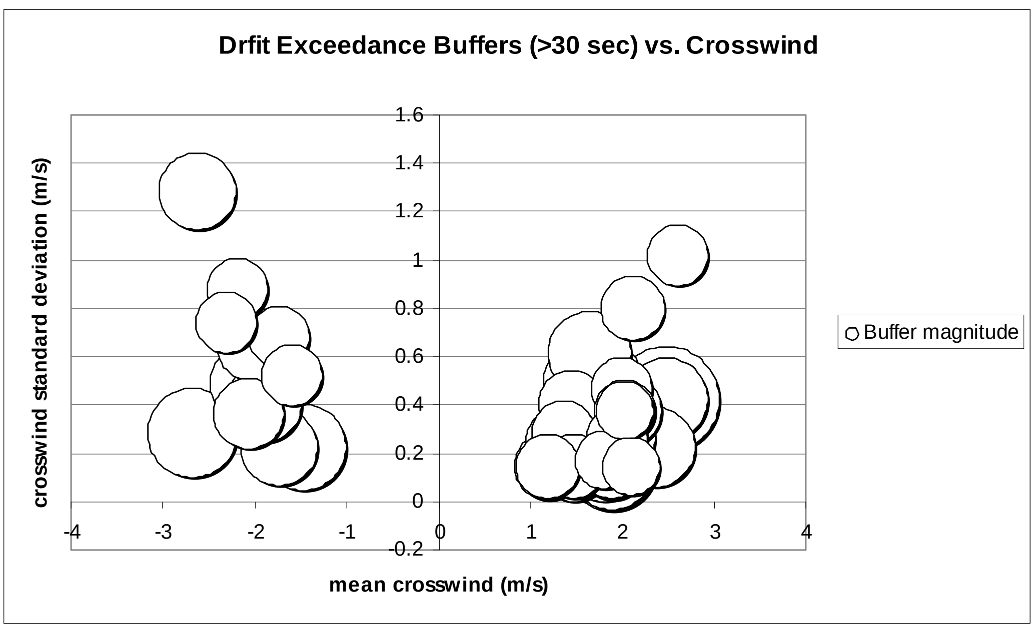

Figure 10 Drift exceedance buffers vs. crosswind.

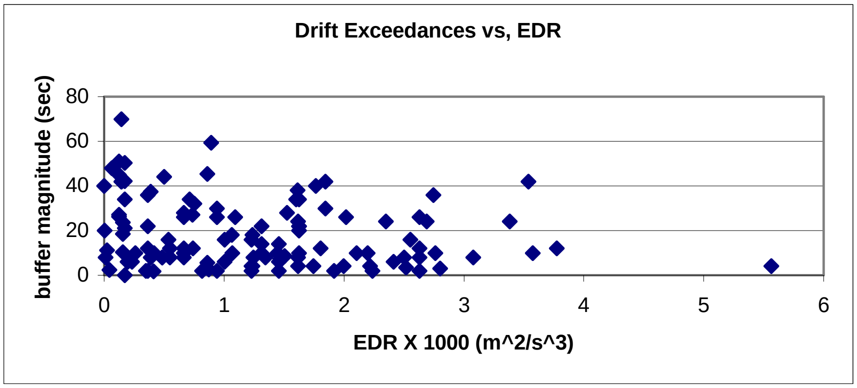

Figure 11 Drift exceedances vs. EDR.

Another ambient weather condition that was compared to the exceedance statistics is headwind. Headwind effects are not modeled in the prediction or sensor algorithms. Figure 12 shows the drift exceedances plotted against headwind. The trend line in Figure 12 shows a general decrease in buffer magnitude with increasing headwind. This may be expected since higher headwinds will tend to speed a wake's demise. Although not shown, the same trend was observed when plotting the demise exceedance buffer magnitudes as a function of headwind.

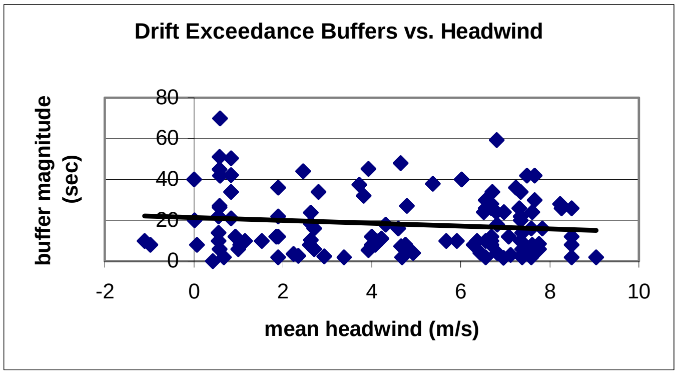

Figure 12 Drift exceedance buffers vs. headwind.

System Tradeoff Studies

The current AVOSS implementation includes many system configuration options to facilitate design tradeoff studies. The basic procedure is to vary parameters in an input configuration file, run AVOSS in batch mode, and examine the output statistics. The result is a quick assessment of a design option impact on the overall system performance. Three studies were conducted to examine the performance sensitivity of AVOSS to the drift and sink wake transport factors. The studies expand on previous sensitivity studies ([3] and [4]) by examining the configuration effect on the validation statistics.

Experimental Design

For the sink study, a sink rate parameter is available that allows the user to reduce the predicted sink rate by the input percentage. The reduction occurs before the vertical residence time is computed. The default value for this parameter is 100%, or no reduction from the predicted sink. A value of 0% effectively disables the sink as a wake transport factor, as the wake will never be predicted to sink out of the safety corridor. The sink rate parameter is transparent to the validation logic. The sensitivity to the wake sink factor study performed in [3] was expanded to determine the throughput performance for other sink rates. The 1999 deployment was executed in batch mode with sink rates of 0%, 10%, 25%, 38%, 44%, 50%, 80%, and 100%. The 2000 deployment was only executed with sink rates of 0% and 100% to support the remaining sensitivity studies discussed below.

The second study examined the impact of disabling lateral drift as a wake transport factor. Flags in the AVOSS configuration file can be set to disable lateral drift, vertical sink, or both for the wake predictions. The result of setting these flags is to reset the appropriate predicted residence times to an invalid flag value before the spacing is calculated. The compare logic (see Appendix) also recognizes the state of the flags to set the appropriate observed residence times to the invalid value before a buffer computation is performed. Lateral drift only was disabled for the test.

Finally, AVOSS computes lateral residence times using the worse case prediction derived from the mean, mean minus standard deviation, and mean plus standard deviation crosswind statistics. The default is to use one standard deviation for the statistics, but a configuration parameter (called nsigma) allows for a multiple of two or three times the standard deviation to be used. Higher multiples of the crosswind standard deviation represent a higher level of crosswind uncertainty. The system performance sensitivity to crosswind uncertainty was examined using values of 2 and 3 for nsigma.

Sink Sensitivity Results

Figure 13 shows the percent increase in throughput as a function of the sink rate. As shown, the throughput is not

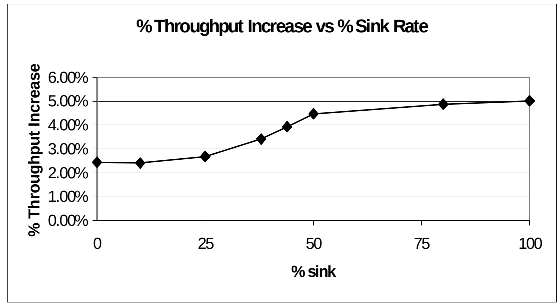

Figure 13 Throughput increase vs. sink rate, 1999 data.

impacted by more than a half a percent to a sink rate reduction of 50%. Following the plot from right to left, the throughput then decreases fairly linearly to about a 25% sink rate reduction, where the performance loss levels off.

Table 7 is a summary of the differences in validation statistics for each study. The first group with the heading "Default" represents the unaltered, default deployment configuration. The major effect of disabling sink on the sensor validation was the reclassification of approximately 50 class 1 buffers to positive buffers for the pulsed lidar. This reclassification occurred in cases where the predicted sink set the residence time in the default run. With the sink disabled, the residence time was reset to a factor that was greater than the observed residence time. Neither class 1 nor positive buffers present a safety concern for system operations. This characterization of the performance sensitivity to wake sink identifies design margins that will be useful is specifying future systems.

Drift Sensitivity Results

The mean throughput increase with the drift factor disabled was reduced to 3.7%, almost half of the mean with all factors enabled. The maximum average throughput increase was reduced by more than half to a value of 6.3%. The exceedance statistics were affected in several ways by disabling the drift transport factor. As shown in Table 7, no windline exceedances are present since these are computed solely from drift. Since the observed drift residence time is reset to the invalid flag when drift is disabled, any wake observation where drift sets the residence time will be invalid. This is the reason for the lower overall numbers in some of the buffer categories shown in Table 7. The hard exceedances, which have the most operational significance, are affected only minimally by disabling the drift transport factor.

Crosswind Uncertainty Sensitivity Results

Running AVOSS with nsigma=2 caused only a minor reduction in the mean and max percent throughput increase. The mean increase was 5%, as compared to 6% with nsigma=1 (default statistics), and the maximum increase was 14%, compared to 16% in the default case. With nsigma=3 the mean increase drops slightly to 4%, and the maximum remains about 14%.

These results imply that a significant window of crosswind uncertainty can be used with a minimal impact on throughput performance. Increasing the crosswind uncertainty had no effect on

<u>Table 7 Wake Validation Performance with Varied System Configurations</u>

Default	Class 1	Positive Buffer	Hard Exceedance	Soft Exceedance
Windline	263	469	0	91
CW Lidar	197	5	19	12
Pulsed Lidar	287	2	0	4
Total	747	476	19	107
Sink Disabled	Class 1	Positive Buffer	Hard Exceedance	Soft Exceedance
Windline	263	469	0	91
CW Lidar	197	5	19	12
Pulsed Lidar	235	56	1	1
Total	695	530	20	104
Drift Disabled	Class 1	Positive Buffer	Hard Exceedance	Soft Exceedance
Windline	0	0	0	0
CW Lidar	78	6	23	0
Pulsed Lidar	275	4	0	14
Total	353	10	23	14
Nsigma=2	Class 1	Positive Buffer	Hard Exceedance	Soft Exceedance
Windline	166	618	0	39
CW Lidar	196	8	19	10
Pulsed Lidar	287	2	0	4
Total	649	628	19	53
Nsigma=3	Class 1	Positive Buffer	Hard Exceedance	Soft Exceedance
Windline	93	713	0	17
CW Lidar	196	8	19	10
Pulsed Lidar	287	2	0	4
Total	576	723	19	31

the 19 hard exceedances reported in Table 7. This result is expected since all but one of these exceedances was determined by demise instead of drift. With each increase in crosswind uncertainty, there was an increase in positive buffers for the windline. The positive buffers came from a reclassification of class 1 and exceedance events. Again this result is expected since the worst-case wake drift is used for the predicted residence time. Keeping the observed drift residence times constant, an increase in the predicted residence times would tend to reduce class 1 and exceedance buffer events and increase the positive buffer events. The pulsed lidar statistics were not affected since these exceedances were not computed using drift. The implication is that a higher crosswind uncertainty can be assumed with little negative impact on system performance, and a neutral or positive impact on validation results.

Lessons Learned

Future implementations of the AVOSS would benefit from strategic placement of the validation sensors, based on the lessons learned to date. A sensor that quantifies a particular wake transport factor well should be placed in a location where that factor has been shown to set the spacing in most predictions. However, tradeoffs between sensor installation and airport operational considerations will have to be made, and the limitations of a given sensor installation must be quantified and incorporated into system design margins. Improvements in sensor technology or wake tracking algorithms would provide more useful observed data, allowing for improvements in the validation logic. Two sets of validation logic, one for safety checking and one for system diagnostics and development should be investigated. In addition, refinements in the demise definition would reduce the hard exceedances observed in this study.

Work needs to be done in characterizing and quantifying each source of system error in Equation 1. A modification to the compare code that outputs all valid buffers for each wake factor would allow sensitivity studies on input parameters to be conducted with a full set of data, instead of just the exceedances. It has been suggested [4] that a localized prediction of crosswind variance and vertical shear would provide substantial benefits to prediction accuracy. These measurements would require new applications of the current sensor technology. A previous study at John F. Kennedy (JFK) airport [3] showed promise for using the lidar sensor to measure ambient weather conditions. The existing data should be analyzed further to determine correlations in the weather conditions or sensor operations with large or small buffer magnitudes.

Conclusions

The latest field deployments of the AVOSS were successful in demonstrating the concept of reduced wake avoidance spacing based on ambient weather conditions. A significant increase (6% on average) in runway throughput was predicted using the AVOSS spacing outputs. Validation of the wake behavior predictions with a variety of sensor systems showed the predictions to safely bound the wake behavior or not be operationally significant in all but 19 of 2301 cases. Sensitivity studies were performed which focused on the validation performance of the system. The conclusions of the experiments are summarized as follows:

1. The majority of the reported exceedances occurred in conditions of low mean crosswind but high crosswind standard deviation, where the system logic prevents the use of wake drift to derive reduced spacing.
2. Up to 50% uncertainty in the wake sink factor can be tolerated with a minimal impact on predicted throughput and validation, but higher uncertainties reduce the throughput mean increase by half.
3. Disabling wake drift as a transport factor reduces the throughput performance by about 50%, while having little affect on the exceedances measured in 1999 and 2000 DFW deployments.
4. Relatively large (up to three times the measured standard deviation) bounds of crosswind uncertainty can be tolerated with only a small decrease in throughput performance.

The observations in the studies have implications on the requirements definitions for future operational systems. System performance is influenced by complex interrelationships between system design options, configuration, and inputs. Validation performance in particular is influenced heavily by sensor placement. The limitations of a given sensor placement should be quantified to assess the impact on system operation. In addition, substantial penalties in predicted performance result from ignoring a wake transport factor.

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Appendix

In this section details are given for the computation of predicted and observed residence times. Special logic to handle sensor operational limitations is also described, and a specific validation example is provided to illustrate the need for caution when interpreting the results using this system logic.

Residence Time Computation

Each wake sensor file includes residence times that are computed from the measured track. These times are broken out by each wake and each wake factor as follows:

HP,VP,DP,HS,VS,DS

where "H" denotes horizontal, "V" vertical, "D" demise, "P" port wake, and "S" starboard wake. The values are in seconds and represent the time the wake was a hazard due to each factor. For example, "HP" is the time in seconds a wake generated on the port side of an aircraft took to exit the safety corridor by drifting horizontally. "VS" is the time a wake generated on the starboard side of the aircraft took to sink beneath the safety corridor floor. A value of "9999" for any residence time is reserved as an invalid flag. If a wake reached its demise value before drifting out of the corridor the sensor system would report "9999" for the wake's horizontal residence time, for example. This residence time format is paralleled in the predicted residence time file, and the following description of the residence time computation applies to both predicted and measured data.

The residence times for each wake and wake factor are combined to yield the net residence time computed with the following equations:

Port residence time = min(HP,VP,DP)

Starboard residence time = min(HS,VS,DS)

Residence time of pair = max(port

residence, starboard residence)

If both port and starboard wakes have a valid residence time for at least one factor, the residence time of the pair will be used by the compare logic for buffer computation.

A sensor often tracks only one wake, and in the interest of utilizing all the available data, logic exists in the compare code to determine if the single observed wake is sufficient for validation. In a calm wind a pair of wakes will sink at a relatively constant separation proportional to the generating aircraft's wingspan until reaching an altitude approximately equal to this initial separation. Then the wakes are influenced by the proximity of the ground, which causes them to drift horizontally in opposite directions away from and perpendicular to the aircraft flight path. The presence of a crosswind may cause the upwind wake to drift in the opposite direction, causing it to remain in the safety corridor lateral limits for a longer duration. The observed track file is examined and the drift rate of each wake is computed using linear regression. If a wake is determined to be drifting opposite in direction to its no-wind drift at a rate greater than a threshold set in the system configuration, the wake is "critical". If the only observed wake is determined to be critical, the net residence time is the residence time of this critical wake (either port or starboard).

Due to the critical wake logic, it is possible that a buffer between a predicted and measured residence time is not computed from the same transport factors in a hard buffer. The logic allows a hard buffer to be computed from a factor that sets the observed residence time and a different predicted factor that sets spacing. As long as the critical wake has a valid observation for the factor that set spacing the buffer is classified as hard.

Special consideration is given to observations made by the windline. The windline currently provides reliable data for wake drift only. Due to this limitation, the residence time equation for both windline predictions and observations is:

Residence time = max(HP,HS)

The windline logic is only used for validation; the residence time used for spacing computations is computed with the same logic in all windows.

It was observed at the DFW windline location that the wake sink consistently provided the smallest predicted residence time. Since the sink is not used in the buffer calculation for windline sensor cases, all windline comparisons are classified as soft.

Validation Case

The current logic was designed with two goals. The first goal is to provide data that can be used to validate the prediction algorithm and facilitate tradeoff studies performed in the course of system evolution. The second goal is to provide a first cut at including some automatic safety checking that would be required in a system put to operational use in the field. Therefore, exceedances do not necessarily indicate an unsafe event. Similarly, all soft exceedances should not be considered to be acceptable for safe operations, as illustrated in the following example:

Table A.1 is a validation case from the deployment re-run data (7/12/00, 19:26:57). In this case the spacing is set by the predicted demise value of 53.4 sec. The residence times observed for the port, and starboard wakes are 64 sec, and 19 sec, respectively. The resulting net observed residence time is therefore 64 sec. In the observed track file the port wake drift rate was opposite in sign to the no-wind drift rate and had a magnitude close to, but not over, the critical wake threshold (0.5 m/s). The starboard wake was observed to drift out of the corridor well in advance of its observed residence time and would not have been a hazard to an approaching aircraft. The port wake drifted out of the corridor but then drifted back in, presenting a hazard until it had reached demise. The buffer is classified as soft since there is no valid starboard demise time, and both wakes are critical. (If neither wake satisfies the test for criticality the default of both wakes being critical is used.) Since the starboard demise was not valid, two scenarios could have existed. The starboard wake could have had a demise time less than the port, and the buffer would be hard with the same value as computed, or the demise time could have been greater than the port, and the buffer would also be hard and a new value based on the starboard demise. If no starboard residence time were measured, the wake file would not have been used. Valid residence times for both wakes must be present to perform a validation if both wakes are critical. Also, if the residence times were as they appear in Table A.1, but the port wake passed the criticality test, the buffer would still be considered soft. This outcome is due to the logic default of both wakes critical when valid residence times exist for both wakes. Future implementations of the logic that may use the hard exceedance as a signal to return to default spacing would need to revise the critical wake determination logic so potentially unsafe events such as those just described could not occur. Separate logic to perform safety checks and system diagnosis may be necessary.

Table A.1 Wake Validation Case

Wake residence time	Port drift	Port sink	Port demise	Starboard drift	Starboard sink	Starboard demise	Residence time
Predicted	9999	9999	53.4	9999	9999	53.4	53.4
Observed	9999	9999	64	19	9999	9999	64

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An analysis has been performed on data generated from the two most recent field deployments of the Aircraft Wake VOrtex Spacing System (AVOSS). The AVOSS provides reduced aircraft spacing criteria for wake vortex avoidance as compared to the FAA spacing applied under Instrument Flight Rules (IFR). Several field deployments culminating in a system demonstration at Dallas Fort Worth (DFW) International Airport in the summer of 2000 were successful in showing a sound operational concept and the system’s potential to provide a significant benefit to airport operations. For DFW, a predicted average throughput increase of 6% was observed. This increase implies 6 or 7 more aircraft on the ground in a one-hour period for DFW operations. Several studies of performance correlations to system configuration options, design options, and system inputs are also reported. The studies focus on the validation performance of the system.

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