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Development Status**

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## NASA AIRCRAFT VORTEX SPACING SYSTEM DEVELOPMENT STATUS

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### Abstract

The National Aeronautics and Space Administration (NASA) is addressing airport capacity enhancements during instrument meteorological conditions through the Terminal Area Productivity (TAP) program. Within TAP, the Reduced Spacing Operations (RSO) subelement at the NASA Langley Research Center is developing an Aircraft VOrtex Spacing System (AVOSS). AVOSS will integrate the output of several systems to produce weather dependent, dynamic wake vortex spacing criteria. These systems provide current and predicted weather conditions, models of wake vortex transport and decay in these weather conditions, and real-time feedback of wake vortex behavior from sensors. The goal of the NASA program is to provide the research and development to demonstrate an engineering model AVOSS in real-time operation at a major airport. The demonstration is only of concept feasibility, and additional effort is required to deploy an operational system for actual aircraft spacing reduction. This paper describes the AVOSS system architecture, a wake vortex facility established at the Dallas-Fort Worth International Airport (DFW), initial operational experience with the AVOSS system, and emerging considerations for subsystem requirements. Results of the initial system operation suggest a significant potential for reduced spacing.

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### Acronyms

ATC	Air Traffic Control
AVOSS	Aircraft VOrtex Spacing System
AWAS	AVOSS Winds Analysis System
CTAS	Center-TRACON Automation System
CW	Continuous Wave
DFW	Dallas-Fort Worth International Airport
EDR	Eddy Dissipation Rate
FAST	Final Approach Spacing Tool
FOQA	Flight Operations Quality Assurance
GPIP	Glide Path Intercept Point
GSA	Glide Slope Angle, degrees
GWVSS	Ground Wind Vortex Sensing System
ITWS	Integrated Terminal Weather System
NWS	National Weather System
QAR	Quick Access Recorder
RASS	Radio Acoustic Sounding System
RSO	Reduced Spacing Operations
TAP	Terminal Area Productivity
TASS	Terminal Area Simulation System
TDWR	Terminal Doppler Weather Radar
TKE	Turbulent Kinetic Energy
WVL	Wake Vortex Lidar

### Symbols

b	aircraft wing span
b'	distance between cores of the wake pair
$d_{i,j}$	required spacing for aircraft pair i,j
h	height of wake above ground, meters
$p_{i,j}$	probability of aircraft category i leading category j
M	mass, kg
S	following distance, meters
t	time
T	non-dimensional time
V	aircraft speed, m/s
$X_{GPI}$	Glide Path Intercept Point on runway surface, meters
$X_{GSI}$	Distance from runway of initial glide slope intercept, 11128 meters in current configuration

$X_T$	The transition point, meters. This is the distance from the runway where the corridor width begins to increase and the corridor floor transitions from ground level to a function of position from the runway
$Y_{lim}$	Y coordinate of lateral corridor limit, meters. This is 1/2 the total width of the corridor
$Z_{lim}$	Z coordinate (altitude above ground) of the corridor floor, meters
$Z_{FP}$	Z coordinate of the expected flight path, meters
$\Gamma$	wake circulation strength, $m^2/s$

AVOSS Overview

The present NASA development effort is funded by the Terminal Area Productivity (TAP) program. Within TAP, the Reduced Spacing Operations (RSO) subelement at the NASA Langley Research Center is developing an Aircraft VOrtex Spacing System (AVOSS). This development is focused on a year 2000 demonstration, in a relevant airport environment, of a real-time wake vortex spacing system. The system demonstration will include all systems operating in a real-time mode, up to but not including the Air Traffic Control (ATC) interface. This includes atmospheric profile measurements by a meteorological subsystem, wake vortex behavior predictions by the predictor subsystem, and wake vortex measurements to confirm the predictions. The system integration element will link all subsystems for automated system operation. Actual aircraft spacing reductions will not be made as an element of the demonstration. The objective of the development effort and demonstration is to bring the maturity levels of all systems to the point that the concept can be proven in an operational environment, with all variables present, and that the system is ready for handoff to the FAA and industry for operational test bed deployment. The system to be demonstrated will emphasize the scientific validity of the weather profile measurements and wake predictions, and not the final engineering required for prototype operational equipment. As such, certain features such as system self-test and ATC interfaces may be absent or implemented only to the degree required for demonstration of the system concept.

The basic AVOSS architecture is unchanged from previous descriptions<sup>1,2,3</sup> and shown in Figure 1. This architecture supports the basic functional requirement of calculating the separation required

to prevent aircraft encounters with wake vortices, given the current and expected meteorological parameters. The meteorological subsystem uses sensors and modeling techniques to describe the vertical profiles of the wind, turbulence, and temperature from the surface to the glide slope intercept altitude. A statistical description of relevant variables is provided to minimize spatial variations and permit prediction of the worst-case wake behavior that may occur during an operational time period. The wake predictor uses this weather profile and descriptions of the aircraft fleet at the airport to predict wake drift rates, sink rates, and decay rates for each modeled aircraft type. The wake behavior is compared to pre-defined safety corridor dimensions and a wake demise definition to derive required aircraft separation intervals. Wake vortex sensors are used to verify that the wakes are behaving within the range of predicted values, and disable reduced spacing if they are persisting longer than expected.

AVOSS Configuration

The current AVOSS "Version 1" configuration focuses on the approach application of AVOSS, and provides separation criteria by aircraft category (small, large, heavy) for a 30-minute period based on measured vertical wind profiles, an aircraft data base, and approach safety corridor and demise definitions. The separation criteria are based on the time required for the wakes from each aircraft to sink or drift out of the safety corridor, or decay to a "demise" circulation value, discussed below. Wake behavior is calculated at a set of approach "windows" from the glide slope intercept altitude to the runway threshold. Each

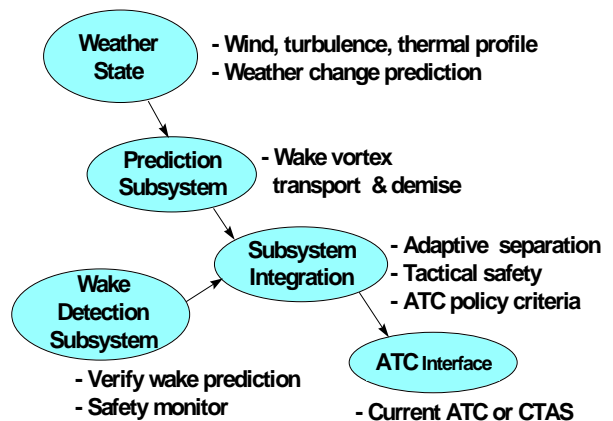


Figure 1 - AVOSS Architecture

window models the wake at a different location and altitude on the approach. Two types of spacing matrices are provided by the current AVOSS, a spacing matrix at each approach window and an "approach spacing" matrix that provides the top-of-approach spacing required to meet the wake spacing criteria along the entire approach. The latter matrix includes the effects of changing spacing on final due to different aircraft speeds. For example, 4 mile spacing may be required at the outer marker to provide 3 mile spacing at the threshold when the following aircraft is faster than the lead aircraft. Currently the output is in nautical miles, although time is used internally and can be provided to appropriate ATC systems. The program also applies a minimum threshold spacing for runway occupancy time considerations. This value is currently provided in a parameter file in nautical miles.

The current system configuration provides considerable flexibility to change the number of aircraft modeled by simply editing a data base that is read at run-time, or to change the number of aircraft categories, or use distance or time-based outputs. The number of approach windows used to model the wakes can be changed at run-time by specifying the distance from threshold of any windows to be added to the default set. This feature can be used to increase the window density near the altitude of any unusual meteorological conditions, or to accommodate field logistics when wake sensors are moved from one site to another.

The basic system operation begins with reading the aircraft data base, creating a default set of six approach windows from the runway threshold to the glide slope intercept point, creating any additional windows required, then initiating the wake and spacing calculations. The default windows are most dense near the runway threshold due to rapidly changing boundary conditions and ground effects on the wake, and spaced farther apart at higher altitudes. Table 1 shows the characteristics of the default windows,

including distance from threshold, glide slope altitude, altitude of the safety corridor floor, and the width of the corridor, all in meters. Although no windows are currently located between the threshold and the touchdown location, the software allows a window to be specified down to the point where the glide slope intersects the runway surface. The window at 982 meters corresponds with a wake sensor array deployed at the Dallas-Fort Worth Airport.

The window characteristics are computed by AVOSS when the window is created at the beginning of program execution, based on the values of distance-from-threshold and the corridor option number in a system parameter file. The glide slope intercept point is assumed to be 11.1 km (6 nm) from the runway at an altitude of 600 meters (1968 feet). Two options are defined to explore the sensitivity of AVOSS performance to the size of the safety corridor. Both options put the floor at ground level from the runway to 843 meters, using only wake decay and lateral drift to reduce spacing in this region. The corridor is 91.5 meters (300 feet) wide from the runway threshold to 843 meters, then fans out. For reasons to be discussed below, at the glide slope intercept point the width abruptly increases to 20 km.

#### Safety Corridor Definition

Prior AVOSS publications<sup>1,2</sup> described the corridor in relation to the outer and middle marker locations. Lessons learned in field activities suggested standardizing the corridor shape based on distance from the runway. The current definition of the corridor shape is expressed in a runway axis system with the origin on the runway centerline at the threshold, the positive X axis along the extended centerline toward the outer marker, the Y axis positive to the right of the approach path, and Z axis positive upwards. Lateral corridor limits are expressed in the Y coordinate and altitude limits in the Z coordinate.

Distance from Threshold	Glide Slope Height above Runway	Altitude of Corridor Floor (option 1)	Altitude of Corridor Floor (option 2)	Width of Safety Corridor
0	17	0	0	91.5
430	39	0	0	91.5
843	61	0	0	91.5
982	68	6	46	95
5000	279	188	238	197
11128	600	464	530	20000

*Table 1 - Default Approach Window Characteristics (meters)*

Definition of the safety corridor begins with establishment of the nominal approach path. A value of 3.0 degrees is used for glide slope angle (GSA) for runways 17C and 35C at DFW. The glide path intercept point on the runway ( $X_{GPI}$ ) is -320 meters for runway 17C. The negative value indicates that the intercept is on the pavement, as opposed to being outside the threshold, and the negative value must be used in the equations below.

$$X_T = \text{int} \left[ X_{GPI} + \frac{60.9756}{\tan(GSA)} \right] \quad (1)$$

$$Z_{FP} = (x - X_{GPI}) \tan(GSA) \quad (2)$$

Equations 1 and 2 calculate the location where the glide slope height is 200 feet above the runway ( $X_T$ ) and the assumed aircraft flight path altitude ( $Z_{FP}$ ) at any location on the approach.

The lateral limits are (equation 3):

$$\begin{aligned} & \text{if}(x < X_T), \text{then}(Y_{\text{lim}} = 45.73) \\ & \text{if}(x \geq X_T), \text{then}(Y_{\text{lim}} = 45.73 + 0.012695(x - X_T)) \\ & \text{if}(x \geq X_{GSI}), \text{then}(Y_{\text{lim}} = 10000) \end{aligned}$$

The corridor vertical limit has two options.

Option 1 (equation 4):

$$\begin{aligned} & \text{if}(x < X_T), \text{then}(Z_{\text{lim}} = 0) \\ & \text{if}(x \geq X_T), \\ & \dots \text{then}(Z_{\text{lim}} = Z_{FP} - (60.9756 + 0.00725[x - X_T])) \\ & \text{if}(x \geq X_{GSI}), \\ & \dots \text{then}(Z_{\text{lim}} = Z_{FP} - (60.9756 + 0.00725[X_{GSI} - X_T])) \end{aligned}$$

Option 2 (equation 5):

$$\begin{aligned} & \text{if}(x < X_T), \text{then}(Z_{\text{lim}} = 0) \\ & \text{if}(x \geq X_T), \\ & \dots \text{then}(Z_{\text{lim}} = Z_{FP} - (21.3 + 0.00471[x - X_T])) \\ & \text{if}(x \geq X_{GSI}), \\ & \dots \text{then}(Z_{\text{lim}} = Z_{FP} - (21.3 + 0.00471[X_{GSI} - X_T])) \end{aligned}$$

Note that the corridor options 1 and 2 differ only in the corridor floor shape. Both options place the corridor floor at ground level from the runway to the transition point, taper the floor from that point to the glide slope intercept point, then maintain a constant distance between flight path and the floor beyond the glide slope intercept. Option 1 is the most conservative, with the floor tapering from ground level at the transition point to about 136 meters (450 feet) below flight path at the glide slope intercept. Option 2 steps the floor to 21.3 meters (70 feet) below glide slope at the transition point and increases this to 70 meters (230 feet) below flight path at the glide slope intercept. Current results are being achieved with option 2.

### Wake Spacing Calculation

The actual wake spacing calculations begin by computing the wake trajectory and decay time history for each aircraft in the data base at each approach window. A weather profile is read which describes the needed meteorological variables. Table 2 shows the first and second order effects on the wake factors that may reduce spacing. The cross wind variable is described in terms of the mean component and the turbulent component (variance). This cross wind variance is computed from the multiple available sensors in the field<sup>4</sup> and determines the uncertainty in wake behavior for the specified time period. Early results were obtained with a 15-minute weather profile averaging period, which has since been changed to a 30-minute period. The weather statistics at the altitude of the flight path at each approach window are used to run the wake vortex prediction algorithm<sup>5</sup>.

Wake Factor	First Order Influences	Second Order Influences
Lateral Transport	<ul style="list-style-type: none"> <li>• Cross-wind profile</li> <li>• Ground effect</li> </ul>	<ul style="list-style-type: none"> <li>• Aircraft variables</li> <li>• Stratification</li> <li>• Turbulence</li> </ul>
Vertical Transport	<ul style="list-style-type: none"> <li>• Aircraft variables</li> <li>• Ground Effect</li> </ul>	<ul style="list-style-type: none"> <li>• Turbulence</li> <li>• Stratification</li> <li>• Cross-wind shear</li> </ul>
Decay	<ul style="list-style-type: none"> <li>• Turbulence</li> <li>• Ground Effect</li> </ul>	<ul style="list-style-type: none"> <li>• Aircraft parameters</li> <li>• Stratification</li> </ul>

Table 2 - Primary and Secondary effects on Wake Behavior.

The wake predictor provides a time history of the wake motion and decay, which is passed to an algorithm that compares the trajectory to the safety corridor limits to provide wake residence time values. Three residence time components are calculated internally, a lateral residence time, a vertical residence time, and a demise time. These describe the time required for the wake to exit the lateral corridor limit, the vertical corridor limit, or to decay below the demise value, respectively. The three times are independently computed for the port and starboard wake of each aircraft, producing six values. Values that cannot be determined are filled with the value "9999", which is used throughout the system to indicate invalid sensor data or wake residence time. This will always be the case for the vertical transport time near the threshold, since the wakes can never sink below ground level. The value 9999 is also used if the predictor algorithm does not return a valid wake time history, the time history terminates while the wake is still in the corridor above the demise strength, or uncertainties in meteorological parameters do not allow reliable wake prediction. The six residence time components (lateral, vertical, and demise of two wakes) are combined in the following order to produce a single residence time for the aircraft. First, the residence times of the port and starboard wakes are separately determined. This is simply the minimum value of the three basic components. For example, using a lateral residence time of 65 seconds, a vertical residence time of 9999, and a demise time of 70 seconds will produce a wake residence time of 65 seconds. Lastly, the maximum of the port and starboard wake residence times is taken to determine the wake pair residence time. A port vortex residence time of 65 seconds combined with a starboard residence time of 9999 would produce a time of 9999 for that aircraft, which would prevent spacing reduction.

Provision of wake spacing criteria that are useful to ATC for a significant period of time does not require prediction of the wake residence time for one particular aircraft. What is required is the prediction of the potential range of wake residence times. The principle factors effecting the predictions include variations or uncertainty in cross wind, turbulence, and initial wake position and strength. Version 1 AVOSS models the cross wind uncertainty effect by running the wake predictor algorithm three times, once with the mean cross wind profile and once each with the mean plus the cross wind variance and the mean minus the cross wind variance. The worst-case

wake residence time from these three conditions is used to calculate spacing. Conceptually, if the mean cross wind is being influenced by thermals or other short scale phenomena that create gusts and lulls in the wind, the separation provided will be safe even if an aircraft pair lands during one of the lulls in the wind.

These calculations are repeated for each aircraft type at each window. The resulting residence times are used for two purposes. One is to combine with assumed aircraft speeds to compute the distance-based spacing at each window. The threshold window spacing is limited to a minimum value for runway occupancy considerations and the current separation standards are applied as a maximum value. The maximum limit is needed since a number of factors can prevent wake behavior prediction in some situations. The invalid residence time value (9999) translates into very large spacing values when converted to distance. The second use of the residence time set is to compute the time interval for each aircraft pair at the beginning of the approach, referred to as the "spacing point", required to meet all wake constraints. This is accomplished by first constructing a 3 x n array at each window that represents the three follower categories (small, large, heavy) and the n number of aircraft in the data base treated as generator aircraft. The time spacing behind each generator aircraft type is converted to a time required at the spacing point, considering the maximum speed of each follower aircraft category, the approach speed of each generator, and the distance from the spacing point to the window. Only the maximum speed of all aircraft in each follower category is required since this produces the most-conservative adjustment to the approach spacing. The head wind component from the vertical weather profile is used in these calculations to estimate groundspeed. Once the spacing point time behind each aircraft is determined for all windows and for all follower categories, the worst case time is chosen. For example, assume that the time required behind a B-767 for a large follower at the spacing point is 80, 75, 60, 50, 50, 55 seconds, respectively, to meet the wake conditions at windows 1 through 6, where window 1 is at the threshold. For the "approach spacing", AVOSS will apply 80 seconds to large aircraft following the B-767 at the top of the approach. The current Version 1 software applies a very simple, constant airspeed assumption for this compensation. A more sophisticated airspeed deceleration profile will be pursued for the final demonstration system.

The reason for computing an approach spacing that considers all approach windows is two-fold. First, it provides a system-level method to assess the sensitivity of real-world spacing changes to advancements in the state of the art in weather profiling or wake modeling. Advances that can refine one wake prediction factor at one altitude (see Table 2) may or may not have a significant effect on total spacing, depending on whether the factor improved was limiting the approach spacing. An example is cross-wind effects on wake lateral motion at altitudes above a couple of hundred meters, which generally does not effect overall approach spacing due to the more-effective wake sink at those locations. Second, the approach spacing output can provide guidance to ATC on the actual spacing required as aircraft intercept the localizer on approach.

Finally, the generator types are grouped into weight categories to provide a category-based output. For each follower the worst-case time of all large generators is applied, as is the worst-case time for all heavy generators. The resulting time array is converted to distance for output. The final result is a set of 3 x 3 arrays of separation distances. One array is provided for each window alone, and a final array for the approach spacing required at the spacing point. The wakes generated by small aircraft are not modeled, so spacing behind small generators is not provided. The 3 x 3 arrays describe the three generator types (large, B-757, and heavy) and the three followers (small, large, and heavy).

Several special situations exist in the calculation of wake residence time and spacing. These are (1) corridor width at the glide slope intercept point, (2) use of demise for small followers, and (3) cross wind variance that exceeds the mean. The corridor width abruptly increases for any approach window located at or farther from the runway than the glide slope intercept. The effect of this width increase is to effectively disable any spacing reduction due to lateral motion of the wake. Any spacing reduction at this altitude then will be due either to the wake sinking below the flight path of the follower, or to demise of the wake. The purpose of this limitation is to enable the computed spacing at this altitude to be used as aircraft are intercepting the final approach localizer prior to being established on the localizer. Application of the approach spacing can be made outside the outer marker location as long as the aircraft are at the glide slope intercept altitude prior to intercepting the localizer.

The second special case is to prevent application of demise to small followers. As will be shown below, very weak wake strengths, which may be too low to detect with available sensors, may be a factor to small followers. The demonstration AVOSS, therefore, does not consider wake demise when computing spacing for small followers. Any spacing reduction for small followers must be due to wake motion out of the approach corridor.

The third special condition applies to light wind conditions with considerable variability. Conceivably, the mean wind could provide sufficient wake drift to reduce spacing, and the mean minus the variance, if large, could have the opposite cross wind sign and sufficient strength to also reduce spacing. In reality, however, this condition indicates that little or no cross wind may exist, which could stall the wake in the corridor. A test is applied within AVOSS to prevent reducing spacing at a window, due to lateral drift, if the cross wind variance exceeds the magnitude of the mean cross wind. This feature also prevents spacing reduction due to the wakes drifting out opposite corridor walls in very light mean wind. Such a situation would be inappropriate for separation reduction, as even a slight unexpected breeze could stall a wake near the runway.

The spacing matrix produced by this process is intended for use during the next operational period, where the duration of this period is defined by the averaging interval of the weather profile input. The primary function of the wake vortex sensors is then to provide wake residence time values to compare to the residence time predictions. Ideally, the residence time predicted by the mean wind will correlate well with the observations, while the scatter in the observations should fall within the range of residence times provided by predictions using the wind variance. The Version 1 AVOSS uses the wake sensors for display and scientific comparison purposes. An operational system should provide logic to disable reduced spacing when observed residence time values exceed mean predictions and begin to approach the worst-case prediction.

## Dallas-Fort Worth International Airport Wake Vortex Facility

The initial subsystem integration for a working AVOSS system took place at the Dallas-Fort Worth International Airport (DFW) in September, 1997. The purpose of the deployment was to perform the initial subsystem tests and system integration to begin AVOSS system testing and refinements. While the actual deployment took place over an approximate three week period, the established field systems and networks have been in continuous use since January 1998 to permit data collection and real-time AVOSS operation from the NASA Langley Research Center. The data being collected is archived to evaluate modified AVOSS algorithms and accumulate long-term system performance data.

The meteorological systems at DFW are similar to the system deployed for data collection at Memphis<sup>6</sup> in 1994 and 1995. A site near the north end of the airport (Figure 2) contains an acoustic sodar and a radar profiler with Radio Acoustic Sounding System (RASS). A site near the south end of the airport contains a second acoustic sodar and a 45-meter tower equipped with anemometers, including 10 Hz sonic anemometers at 5 and 40 meters altitude, and temperature and humidity sensors. Other sensors, primarily used for initialization and validation of numeric atmospheric models, are situated at both sites. These sensors include rain gauges, soil temperature and moisture, and solar flux instrumentation. The data from the sensor suite can provide turbulence measurements up to 40 meters altitude, and wind profiles from the surface to several kilometers. All meteorological sensors are linked to a network operated by MIT Lincoln Laboratory in the Integrated Terminal Weather System (ITWS) office suite located near the center of the airport complex. The data is combined with Terminal Doppler Weather Radar (TDWR) wind profiles provided by ITWS within an AVOSS Winds Analysis System (AWAS) algorithm developed by Lincoln Laboratory<sup>4</sup>. The product provided to AVOSS is a vertical profile of the mean cross wind and its variance, mean head wind, turbulence, and temperature.

The wake vortex sensing subsystem consists of a Continuous Wave (CW) lidar deployed by Lincoln Laboratory<sup>7</sup>, a pulsed Wake Vortex Lidar (WVL) deployed by NASA Langley<sup>8</sup>, and a Ground Wind Vortex Sensing System (GWVSS) deployed by the Volpe National Transportation Systems Center<sup>9</sup>.

All wake sensors are tasked with providing wake time history data (lateral, vertical, and strength) in a common data format immediately following the loss of the wake from each aircraft. Data that cannot be measured by any particular sensor is filled with the system invalid data value. The wake sensors are also linked to the wake vortex network within the ITWS office suite. An event correlation function is implemented by Lincoln. This function takes the wake file from the sensor and examines real-time ATC radar beacon data to determine the aircraft type and aircraft time-of-passage through the sensor scan plane. The wake file is then modified to embed the aircraft type and adjust the time labels to place each wake observation into absolute time from aircraft passage. This adjustment is needed because the wake sensors themselves generally cannot determine the aircraft passage time. Following the deployment the lidars were removed and the GWVSS continues to provide wake data.

The wake vortex predictor system is embedded in the AVOSS processor. The current, first-generation, wake predictor is based on extension of prior work<sup>5,10,11</sup>. This predictor has shown good correlation with observations in many situations, mostly out-of-ground effect cases, but has several known limitations. Among these is the absence of vertical wind shear terms, which can prevent wakes from sinking or cause them to rise<sup>12,13</sup>, lack of specificity of the turbulent scale lengths required to model wake decay, an assumed hard linkage between wake sink rate and wake circulation<sup>14</sup>, and a rough approximation to wake decay in



Figure 2 - DFW Airport Wake Sites



ground effect. The in-ground-effect decay model simply applies the out-of-ground effect decay rate derived from the Greene model<sup>10</sup> for the first numerical interaction, then holds a constant decay rate for the remainder of the trajectory. To better match the predicted strength to observed data, the computed initial strength of wakes created at very low altitudes is scaled as a function of initial altitude. Methods of parameterizing vertical shear effects and ground effects based on physical understanding of the processes involved are being aggressively pursued at this time and will be implemented in the Version 2 AVOSS code in late 1999. Although the existing predictor algorithm has certain limitations, it is believed to be representative of wake behavior in most situations and appropriate for this phase of AVOSS development.

During the 1997 deployment to DFW, the AVOSS processor was physically located within the ITWS office suite at the airport and connected to the Lincoln wake vortex network. The AVOSS processor was relocated to Langley Research Center after the deployment. A dedicated data line to DFW provides the network connection. A shared disk space on the DFW wake vortex network is used to place meteorological sensor data, AWAS wind profiles, and wake trajectory files that have been labeled by the event correlation process. AVOSS reads files from this disk, performs the wake prediction and approach spacing calculation function, and archives all input data and resulting predictions. AVOSS also provides a display of the meteorological data, the predicted and observed wake behavior, and the resulting separation matrices.

#### Dallas-Fort Worth Deployment Results

The results of the initial AVOSS integration and testing at DFW will be described in terms of lessons learned and quantitative performance results.

#### Lessons Learned

The initial system integration and operation at DFW was highly successful from the perspective of establishing a facility for on-site and remote AVOSS testing, verifying the methods for interfacing all subsystems for real-time operation, testing individual subsystems, gathering a data base of meteorological and wake vortex data for predictor algorithm refinement, and exposing the multiple teams and disciplines to the requirements

of an integrated field system. Although a several-week deployment is too short for meaningful performance data or testing in a wide variety of weather conditions, the observed performance was encouraging. Wake data was collected at several altitude levels, including periods when the Lincoln lidar was positioned between the runway threshold and the touchdown zone to measure wake behavior at very low altitudes. This data is required for validation of in-ground-effect decay algorithms under development.

The meteorological sensors and the AWAS wind profile captured the important first order effects of the atmosphere. Qualitative comparisons of raw sensor data and the AWAS wind profile consensus showed good agreement in most cases, with disagreement between the sensors reflected in higher wind variance values as intended. Sensor disagreement can occur as gust fronts pass the airport and affect the various sensors at different times, or in situations where the output of one sensor is degraded for any reason. The AWAS winds were reliably provided to AVOSS. However, the need for several weather system refinements was identified. First, the AWAS wind profile frequently indicated high values of cross wind variance at an altitude of about 60 meters. This was due to effects of losing the high quality and high update rate tower data above 43 meters, and relying on other sensors for wind data. Wind variance calculations also provided high values above altitudes of about 300 meters due to a reduction in sodar data quality at the higher altitudes. Since the deployment, techniques have been identified to correct the 60-meter variance calculation. Long-term AVOSS operation is suggesting that wake sink, rather than lateral motion, is usually effective at higher altitudes. This result may eliminate the need for cross wind variance at higher altitudes.

The wake vortex sensors reliably provided wake vortex time history files to AVOSS and the event correlation process correctly labeled most files with aircraft type and passage time. Several situations arose that suggested system refinements for the AVOSS demonstration. The event correlation technique relies on ATC radar beacon returns, which have accuracy limitations on the order of 6 to 10 seconds when used to estimate the time of passage of an aircraft past a geographic location. A 10 to 13 second uncertainty in wake residence time may require a spacing increase on the order of one-half mile, so more accurate means may be required to fully realize the benefits of an

operational system. In this first field test the wake sensor teams were asked to provide wake tracks in a coordinate system relative to the sensor itself, with coordinate transformations to the runway axis system and wake residence time determination accomplished at the AVOSS processor. This technique proved to have multiple disadvantages. First, the system was not adaptive to last-minute changes in lidar van location that were dictated by wind and runway changes or ground conditions at planned sites. Any site changes required changes to the AVOSS itself and careful configuration control. Second, post-processing of the wake files is complicated by the need to provide offsets to file data that vary with the date and time of the data. Third, examination of the file could not quickly reveal whether the wake sensor was performing the intended function of verifying wake residence time. Residence time can be determined from the data only if the wakes are tracked long enough to reach demise strength or exit the safety corridor. In this first experience with real-time wake processing, many wake tracks terminated too early to determine corridor residence time.

Several system modifications were made as a result of the DFW experience. The most significant was code implementation of the "Version 1" AVOSS features described earlier in this paper. The code taken to the field had implemented a spacing matrix that provided a spacing value for each aircraft make and model, using a wake decay value that was unique to each follower aircraft model. With 20 aircraft in the data base this version produced a 20 x 20 spacing matrix. The target ATC system for that implementation was the Active Final Approach Spacing Tool (FAST) element of the Center-TRACON Automation Tool (CTAS). Prior to the deployment, but with insufficient time for code modification, the scope of AVOSS was refined to target a manual ATC environment for earlier acceptance and use. Following deployment, Version 1 was implemented to provide the 3 x 3 category matrix and the other features described above. A revised wake sensor requirement has been put in place which requires that the wake time history file directly provide the lateral, vertical, and decay residence time of both wakes, and that the wake position be provided in runway axis coordinates. The Volpe GWVSS, which has remained at DFW, began providing the revised file format in early 1998. Changes to the lidar systems will be tested locally prior to the next deployment at DFW. This revised AVOSS code began routine

operation in January 1998, and is the source of the quantitative results presented in the next section.

### Quantitative Results

An initial assessment of system performance was conducted using an archived data set from the meteorological subsystem at Dallas. AVOSS Winds Analysis System (AWAS) data from enhanced software began flowing to Langley in January 1998. AWAS files from January 23 to May 31, 1998 were examined by a project meteorologist to remove bad data. Data was considered bad when sensor outages or systematic errors were contaminating the AWAS profile or the meteorologist did not consider the data to be representative of the ambient conditions. The resulting weather data set represented 88 days of the 129 day period, or 68% availability of representative data. The data from these 88 days was filtered to only keep time periods between 8:00 AM and 10:00 PM local time, approximating the busiest traffic period. Next, the remaining data was filtered to select the periods when the ceiling was at or below 5000 feet (1524 meters) or the visibility was less than 5 miles (8 kilometers). This was done to approximate the time periods when instrument procedures are being used, which is when the AVOSS capability is most required. The resulting data set consisted of 255 airport operational hours. The AVOSS software was run with this input data set, and the output separation matrices were analyzed to determine the distribution of spacing values.

The results indicated that the average spacing reduction (weighted by the ratio of small, large, and heavy followers at Dallas) was 1.2 nautical miles (2.2 km) behind B-757 and 1.4 nautical miles (2.6 km) behind heavy aircraft. The average spacing behind large aircraft was not significantly reduced, as expected, since there are no wake constraints behind large aircraft for large and heavy aircraft followers. These results must be validated with wake sensors present to substantiate the wake predictions, and over longer operational periods, but indicate a significant potential for reduced spacing.

A first-order approximation of the increase in throughput due to the AVOSS spacing matrices was calculated by determining the average inter-arrival interval given the predicted spacing and an assumed speed for each follower category. This throughput approximation does not model delivery accuracy of aircraft nor the likely need to round

AVOSS spacing criteria to an integer or one-half mile interval spacing values for ATC use. The average arrival time interval is given by:

$$\bar{t} = \sum \frac{p_{i,j} d_{i,j}}{V_j} \quad (6)$$

where the summation is across all generator categories (i) and all follower categories (j),  $p_{i,j}$  is the probability of the pairing (i,j),  $d_{i,j}$  is the required spacing for this pairing, and  $V_j$  is the speed of the follower (j). The probability of a pair is simply the product of the fraction of each generator and follower category. The assumed traffic mix is representative of DFW, and consists of 25% small aircraft, 60% large aircraft, 10% B-757, and 5% heavy aircraft. The B-757 is treated as a large aircraft when it is the follower. Assumed approach speeds are 120 knots (61.8 m/s), 140 knots (72.1 m/s), and 150 knots (77.2 m/s) for small, large, and heavy aircraft, respectively. The inverse of the average arrival spacing time was then taken as the single runway acceptance rate. The default spacing matrix produced a single runway acceptance rate of 44 aircraft per hour in this approximation. With the average spacing values produced by AVOSS, the arrival rate increased to 48 aircraft per hour, for an increase of 9 percent. This represents an average increase. At times no increase is possible while at others larger spacing reductions are provided. The throughput increase becomes larger as the traffic mix shifts toward more heavy aircraft operations. For example, an arbitrary change in the traffic mix to 10% small, 50% large, 15% B-757, and 25% heavy results in a throughput increase from 40.9 to 47.6 aircraft per hour, or 16.5 percent.

#### Future Project Efforts

The AVOSS deployment to DFW and the lessons learned from analysis of the resulting data have been highly beneficial for focusing the final two years' effort. The following activities are underway to refine the product to be demonstrated in the year 2000.

#### Wake Prediction

Numerical wake modeling with Langley's Terminal Area Simulation System (TASS) Large-Eddy Simulation model<sup>12,15</sup> are focused on providing the needed sensitivity studies and relationships between wake motion and decay behavior and specific atmospheric parameters. The TASS

model is being used both in 2-dimensional and 3-dimensional runs. TASS results have identified eddy dissipation rate (EDR) as an appropriate decay predictor and vertical shear as significant in predicting wake sink rate changes. TASS is being used to conduct specific sensitivity studies to fill gaps in available field data, in support of efforts to develop real-time wake prediction algorithms. The product of these efforts<sup>16</sup> will be a second-generation wake predictor algorithm for use in the demonstration system. Recent advances in decay modeling and weather system capability are creating an opportunity to use AVOSS for departure spacing, and may expedite adaptation of AVOSS to parallel runway wake issues. A key issue in the AVOSS departure application is the lack of a predictable flight path as aircraft liftoff and climb. This factor prohibits reduction in spacing due to wake motion, unless highly specialized departure procedures are introduced.

#### Weather System

A number of techniques for reducing the cost and complexity of the weather system are being investigated. As discussed above, ongoing AVOSS performance analysis with DFW field data suggests some relaxation in wind profile measurement requirements at altitude. A specific requirement to sense situations that may prevent normal wake sinking may be substituted instead. The current techniques for estimating vertical cross wind variance<sup>4</sup> relies on the availability of multiple wind sensors. A simpler technique, employing long-period turbulent kinetic energy (TKE) measurements is being investigated as an alternative. A TKE time period on the order of 30 to 60 minutes should capture the effects of thermals that affect the variation in wake drift rates, and can be measured by a single sensor on a meteorological tower. Methods of automatically estimating vertical profiles of both TKE and EDR are being investigated as a low-cost method to predict wake decay and motion uncertainty. Finally, a significant effort is underway in short-term forecast (nowcast) of relevant meteorological parameters<sup>17</sup>. A nowcast model funded by AVOSS has recently begun running operationally, and has the potential to diagnose and predict all required meteorological parameters with accuracy as good as the variability from one sensor to another, using existing National Weather Service (NWS) meteorological products as the initialization. This effort may significantly reduce the cost of an operational AVOSS.

## Performance Studies

The current performance studies will be repeated as additional weather data, refined predictor algorithms, and other system refinements become available. The current study is limited by the lack of vertical wind shear terms or explicit ground effect decay terms in the wake vortex predictor. The detailed design of the demonstration AVOSS will be modified to take advantage of the current performance study results while attempting to reduce the cost and complexity of the system. Examples include dual use of the wake lidar as a weather sensor. The results of the final performance studies, expected to be conducted in 2000, will provide guidance for cost/benefit studies and configuration of an initial operational system.

## Wake Sensors

The wake vortex sensing system is reasonably mature at this point and suitable for AVOSS demonstration and initial test-bed operation. Continuous wave lidars have been in use for many years for research measurements of wake behavior, and the current MIT Lincoln Laboratory implementation<sup>18</sup> provides automated wake detection and active tracking, as well as near-real time production of wake motion and strength data files. The NASA pulsed lidar has been tested with the Lincoln CW system and ground wind line at the John F. Kennedy International Airport and provides wake data that compares favorably with those sensors.

Although final sensor requirements can only be established with FAA and industry consensus and using cost/benefit analysis of options, the following basic wake sensor requirements are suggested:

1. No health hazards to humans or wildlife.
2. No adverse environmental impact or aviation systems interference due to radio frequency interference (RFI) or noise.
3. Practical siting requirements (on-airport to maximum extent, minimal constraints from terrain interference, minimal land required).
4. Automated operation and self-test.
5. Economical coverage of approach corridor from glide slope intercept to runway for test bed system, perhaps limited to last 2 or 3 miles of the approach for operational system.
6. Ability to operate in normal airport wind, precipitation, cloud, visibility, and ambient noise conditions.
7. Ability to provide positive measurement of wake lateral and vertical residence times and

demise time of wake vortices in the approach corridor. The integrated sensor system should enable AVOSS to determine residence and demise time with accuracy on the order of 10 seconds relative to aircraft passage.

8. Ability to track wakes down to a wake strength of about 75 to 90 m<sup>2</sup>/s (see demise section below) in the presence of atmospheric turbulence.
9. Acceptable life-cycle costs and component reliability, requiring infrequent visits for service or calibration.

Although the existing lidar sensors meet many of these suggested requirements, particularly items 1 through 3, some improvements in items 4 through 9 will be required for a practical operational sensor. While not an inherent limitation of the sensors, the research systems in use have, at times, provided wake track files that either terminated prematurely or had an insufficient number of data points to fully validate wake demise or corridor exit. Insufficient wake track duration can be caused by a combination of poor signal-to-noise ratio in very clean air environments, masking of the wake signature by background atmospheric turbulence, low scan rates, and signal processing techniques. The current sensor implementations occasionally provide wake track files that terminate at high circulation values on the order of 150 to 200 m<sup>2</sup>/s. Currently there is no process for determining if a sudden wake track loss is due to sudden destruction of the wake (Crow instability or bursting) or sensor limitations. Requirement 8 may require revision, given that wake strength thresholds below 100 m<sup>2</sup>/s have generated false wake detection in turbulent or windy conditions during the AVOSS deployments to Memphis and DFW. Use of the wake sensor to determine the time required to decay to a more practical detection value will be considered as a means to verify wake decay predictions.

The current lidar sensors are not all-weather devices, in the sense that the maximum wake measurement altitude is limited to the degree that the laser beam can penetrate cloud layers, and the lidar range is equivalent to the visual range in fog. These lidars can only provide full approach path coverage when the laser can penetrate to the glide slope intercept altitude. Figure 3 shows that even this limitation will allow use of AVOSS in many instrument approach operations. This figure shows the results of obtaining weather observations at 9 sites (Atlanta, Boston, Chicago, Detroit, Dallas-Fort Worth, Los Angeles, Newark,

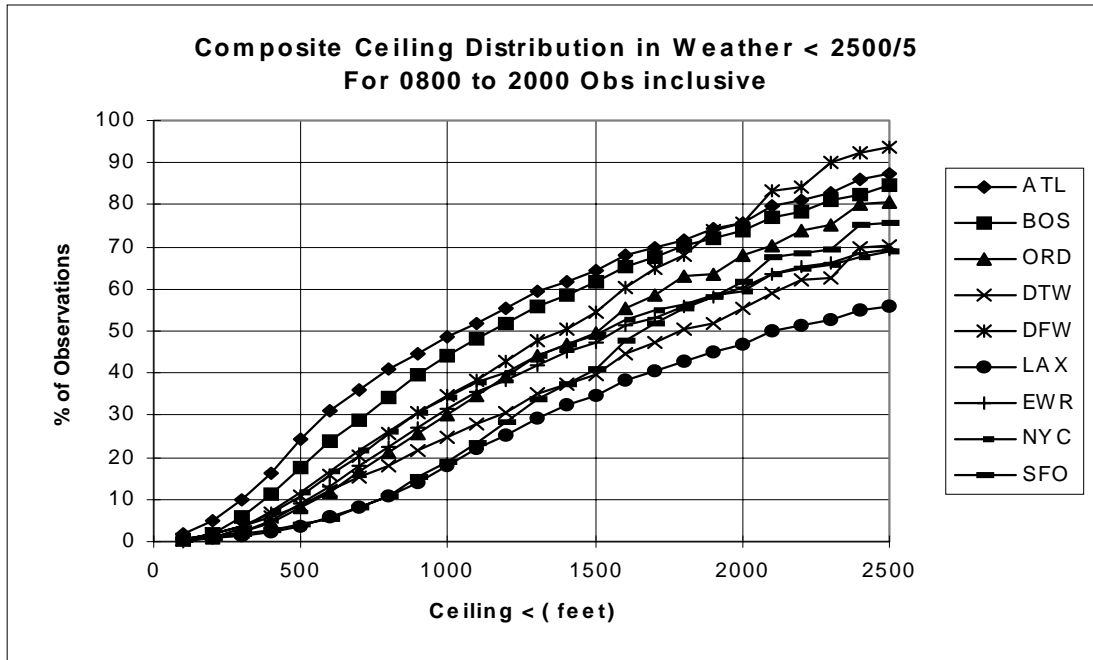


Figure 3 - Conditional Ceiling Distribution for Weather less than 2500/5.

New York City, and San Francisco) for the years 1961 through 1990, and selecting those observations for the local hours 8:00 AM to 8:00 PM that met the criteria of a ceiling below 2500 feet or a visibility less than 5 miles. This selection is meant to approximate the times when AVOSS would be beneficial during the busiest traffic periods. The selection is conservative, as instrument operations at airports such as DFW and Chicago commence at higher ceiling values. This selection of observations was then examined to determine the distribution of ceiling values.

The results suggest that, for the periods that AVOSS is needed, a wake sensor limited by ceiling would be adequate in roughly 30% to 60% of the observations, depending on the site chosen and assuming the glide slope intercept takes place at an altitude of 490 meters (1600 feet). If initial AVOSS operations improve the confidence in the wake predictions at the higher approach altitudes such that only the final 500 feet of descent need be monitored, then a wake sensor limited by ceiling would suffice in 75% to 97% of instrument operation conditions, depending on the airport location. Meaningful capacity gains and early operational experience with AVOSS can therefore be achieved with existing sensor technologies, but cloud penetrating sensors are required for AVOSS availability in all instrument approach conditions. Research is underway at Langley to investigate alternative, cloud-penetrating sensors such as radar<sup>19</sup>.

The time accuracy requirement of item 7 is motivated by the effect that time uncertainties will have on applied wake spacing. Once an aircraft passes a point on the approach, the next airplane following distance (S) must provide the appropriate arrival time interval (t) at the follower's speed (V) to satisfy the generator's wake residence time requirement.

$$S = Vt \tag{7}$$

$$dS = Vdt$$

Given speeds of about 70 meters/second on final approach (136 knots), a change of separation time of 10 seconds produces a spacing change of 700 meters, or about 0.38 nautical miles. This result suggests that system uncertainties, such as the accuracy of determining time-of-passage of an aircraft through an approach window or the accuracy of measuring wake residence time in the corridor, on the order of 10 to 20 seconds, may require a 0.4 to 0.8 mile buffer to be added to all wake spacing distances predicted by AVOSS. Since the difference between current spacing criteria and the minimum that AVOSS might produce, given runway occupancy time considerations, is on the order of 1 to 4 miles, small uncertainties in individual components may erode much of the potential system benefit.

### Operational Deployment Considerations

With the AVOSS development program approaching a final concept demonstration, consideration of the requirements for an operational system are appropriate. At the conclusion of the TAP program a physically implemented AVOSS will be operating real-time and demonstrated in a relevant airport environment. Long-term meteorological system data, being collected at DFW since January 1998, will be available to perform detailed system performance and cost/benefit studies in support of an operational decision. As a minimum, the following factors should be considered when implementing the first wake vortex spacing system.

#### Incident Analysis

Nuisance wake turbulence encounters occur today in routine operations, and can be expected to continue to occur after the introduction of wake vortex spacing systems. In most cases the wake encounters are not significant. There are no known aircraft accidents due to wake encounters on final approach when the ATC Handbook and Aeronautical Information Manual guidelines were being followed. The few recent accidents that have occurred involved follower aircraft below the flight path of the generator in calm evening or night time atmospheric conditions favorable to long-lived wakes<sup>20</sup>. Flight crews will likely be highly sensitive to any turbulence encounters as AVOSS is introduced. In one recent wake vortex simulation study<sup>21</sup>, pilots sometimes rated wake encounters as unsatisfactory when in fact wakes were not even present in the simulation. Failure to baseline the current environment will lead to a real risk of attributing events to AVOSS that may not be wake encounters at all or would have been encountered without AVOSS present.

To quantify existing safety levels and verify that AVOSS maintains or improves safety, some means of quantifying wake encounters, both before and after the introduction of a spacing system, is needed. This quantification may take several forms, including a formal pilot reporting system for wake encounters, or analysis of flight data on a regular basis. Examination of flight data recorder or Quick Access Recorder (QAR) data under Flight Operations Quality Assurance (FOQA) would enable derivation of exceedance statistics for key wake encounter parameters such as roll angle or control deflection. If the data is tabulated by altitude bins, separately for each major aircraft

type, a picture of the disturbances encountered on approaches could be developed. Although the data will include events other than wakes, the overall statistics should not change adversely or should improve as AVOSS is introduced. This data would serve a valuable additional function in establishing a boundary between routine disturbances encountered and objectionable encounters, which in turn would aid development of wake sensor minimum performance standards.

#### Phased Introduction

A measured approach to introducing a wake vortex spacing system into the operational ATC system will be required. The domain to consider has at least four factors: the aircraft types that reduced spacing is applied to, the weather conditions under which the reductions are allowed, the degree of wake monitoring applied, and cost/benefit tradeoffs. The AVOSS is inherently a system that depends heavily on meteorological conditions. As a result, a cautious introduction of operational capabilities is appropriate to observe system behavior in a wide range of conditions and to detect rare events. Due to the limited time available for full-system field testing during the TAP program (a total of perhaps six weeks of full-system operation) some aspects of system operation will require further validation in an operational test bed.

Initial system operation should gradually introduce aircraft categories from the least susceptible to the more susceptible. Initially the test-bed system should run in a heavily-monitored mode until subsystem performance is validated, and a significant quantity of various meteorological conditions have been experienced. Spacing for heavy aircraft following other aircraft could then be reduced when appropriate, then spacing for large aircraft following others. Small aircraft should receive reduced spacing only when a very high confidence in all subsystems is achieved, due to their vulnerability to inadvertent wake encounters.

The meteorological conditions under which the AVOSS is available may also require phased introduction. Vertical profiles of wind and turbulence will be more easily forecast in well-mixed boundary layers, typical of many daytime conditions, and will be a greater challenge to measure and forecast during transitions to and from certain nighttime conditions. Likewise, events such as frontal passages will create additional weather system challenges. Refinement of the

weather system for all-weather operation is beyond the scope of this project and will require field testing in a wide range of events. The initial system operation may be limited to daytime conditions in the absence of frontal boundaries or convective cells, expanding into more challenging conditions as experience is gained.

### Demise Definition

Wake vortex demise may govern aircraft spacing when the wind is not transporting wakes away from the flight path. Demise may be the only practical means of establishing spacing in a departure application, due to uncertainties in aircraft flight path. Demise is defined as the point where wake strength has reached a value that resembles background turbulence and is no longer operationally significant to following aircraft. Establishment of demise is critical for several purposes:

1. Provide a minimum performance specification for wake vortex sensors.
2. May significantly effect system performance.
3. Provide a basis for establishing separation standards for future large aircraft.

One method of providing a rough estimate of turbulence strength that may be significant to aircraft is to calculate potential encounter wake strengths with the current separation standards. This analysis was performed using the decay rates observed in field tests at Idaho Falls<sup>22</sup> in 1990. In these tests, the wakes from a Boeing 727, 757, and 767 were sampled by an instrumented tower at various wake ages, by varying the altitude and offset of the aircraft during multiple tower passes. The wake age is non-dimensionalized using the time required for a wake to sink a distance equal to the initial spacing of the two wake cores. Initial wake circulation strength is given by

$$\Gamma_0 = \frac{9.81M}{1.224Vb'} \quad (8)$$

where Mass (M) is expressed in kilograms, true airspeed (V) in meters/second, and initial wake spacing, or distance from the left wake to the right wake (b'), in meters. Sea level air density is used in this equation (1.224 kg/m<sup>3</sup>). Initial wake spacing

(b') is related to wing span (b) by

$$b' = \frac{\pi}{4}b \quad (9)$$

The initial sink rate of a wake pair in still air is governed by the circulation and wake spacing according to:

$$\dot{h}_0 = \frac{\Gamma_0}{2\pi b'} \quad (10)$$

These approximations for initial wake characteristics have proved adequate for initialization and validation of computational fluid dynamics code for wake behavior prediction, regardless of aircraft configuration<sup>23</sup>. Combining equations 8, 9, and 10 gives the initial sink rate:

$$\dot{h}_0 = \frac{8x9.81M}{1.224\pi^3Vb^2} \quad (11)$$

The time required to sink one wake spacing, assuming neutral stratification, is then:

$$t' = \left(\frac{\pi}{4}b\right) / \dot{h}_0 = \frac{1.224\pi^4Vb^3}{32x9.81M} \quad (12)$$

The non-dimensional time T is simply

$$T = t/t' \quad (13)$$

Typical values of aircraft parameters and t' are given in Table 3. In this sample one unit of non-dimensional time represents 14 to 26 seconds of real time. Data from Idaho Falls<sup>22</sup> was normalized during the study of reference 24. A decay rate that bounded observed data from the three aircraft types is given by:

$$\Gamma_T = \Gamma_0 \left(1 - \frac{T}{8}\right) \quad (14)$$

This equation bounded the observed data, with most wakes decaying considerably faster. At this decay rate the wakes will reach one-half strength in 4 non-dimensional time units, or 56 to 106 seconds of real-time.

Aircraft	Span (m)	Speed (m/s)	Mass (kg)	t' (s)
Boeing 727-200	32.9	70	68000	13.9
Boeing 767	47.5	70	122000	24.0
DC-10-30	50.3	75	168000	21.6
Boeing 747-400	64.3	75	286000	26.5

Table 3 - Typical time values for one non-dimensional time.

A data base of 38 aircraft, ranging from commuter aircraft to the B-747-400, was used to calculate initial wake strengths and the time separation that results from the current wake spacing criteria and follower speeds of 120 knots (61.8 m/s) (small category), 140 knots (72.1 m/s) (large category) and 150 knots (77.2 m/s) (heavy category). The data base included 21 large and 16 heavy aircraft types. Initial wake strength and the non-dimensionalization were calculated from the maximum landing weight and nominal approach speed provided in the data base. The wake strength of all 38 aircraft was then computed at the time that a small, large, or heavy follower could encounter the wake with today's spacing standards. Table 4 shows these encounter wake strengths. For the large and heavy generator categories, the minimum, mean, and maximum wake strengths presented to each follower category are tabulated. For example, the 21 large aircraft produced a mean encounter for small followers of 22 m<sup>2</sup>/s with a minimum of 0 and a maximum of 100 m<sup>2</sup>/s. Encounters of small aircraft wakes are not tabulated. The documented decay rate of (1-T/8) is shown as well as a higher decay rate of (1-T/6).

This calculation suggests that, in the event of an inadvertent wake encounter with the separation criteria in use today, and subject to the approximations used, small aircraft will generally be exposed to insignificant wakes on the order of 30 m<sup>2</sup>/s, with wake encounters on the order of 100 m<sup>2</sup>/s possible with very long lived wakes from

a few aircraft types. Large aircraft can be exposed to encounters on the order of 100 m<sup>2</sup>/s, with 200 m<sup>2</sup>/s possible in some situations. Heavy aircraft can be exposed to encounters on the order of 100 to 200 m<sup>2</sup>/s, with 300 m<sup>2</sup>/s possible in rare situations. Note that the spacing currently required behind the B-757 results in much weaker wake encounters than would be the case from either large or heavy generators, for the assumptions used. The maximum wake strength encountered was very sensitive to the denominator in equation 14, with no encounters exceeding 105 m<sup>2</sup>/s for a decay rate of (1 - T/4).

For comparison, the initial wakes strengths of several aircraft, given minimum and maximum landing weights, falls in the following range:

- Beech Bonanza light single: 25 to 40 m<sup>2</sup>/s
- Cessna 310 light twin: 30 to 50 m<sup>2</sup>/s
- King Air turboprop: 42 to 67 m<sup>2</sup>/s
- Twin Otter turboprop: 46 to 74 m<sup>2</sup>/s
- BaE Super 31 turboprop: 50 to 73 m<sup>2</sup>/s
- Dash-8 turboprop: 91 to 131 m<sup>2</sup>/s
- MD-81: 165 to 265 m<sup>2</sup>/s
- Boeing 727-100: 172 to 272 m<sup>2</sup>/s

These results tend to fall in agreement with the work of Stewart<sup>21</sup>, which suggests that pilots of large aircraft would object to encounters of most wakes, while the reaction of heavy aircraft to substantial wakes is not objectionable.

		Follower Category					
		Small		Large		Heavy	
Generators		1-T/6	1-T/8	1-T/6	1-T/8	1-T/6	1-T/8
Large	Minimum	0	0	7	38	15	44
	Mean	4	22	66	104	76	112
	Maximum	33	100	159	196	169	204
B-757		0	0	0	51	0	73
Heavy	Minimum	0	0	0	3	6	128
	Mean	1	27	34	112	114	206
	Maximum	23	126	140	238	239	331

Table 4 - Potential Encounter Circulation Strength with Current Separation Standards.



Based on this analysis, and until additional work leads to a consensus regarding the turbulence intensity that begins to become operationally significant, the AVOSS development will proceed with a wake demise definition of 90 m<sup>2</sup>/s for both large and heavy following aircraft. This value then becomes a minimum detection requirement for any wake sensor that will be used to validate AVOSS demise predictions. The demise definition will initially be applied only to the large and heavy following traffic, with no spacing reduction being given to small followers unless the wakes have drifted out of the safety corridor. Additional AVOSS performance may be achieved, following initial operational experience and industry agreement, if the demise definition can be made a function of aircraft class, and by applying the demise definition to small followers. Application to small aircraft would likely require a separate standard for the turbo-prop aircraft typically used in commuter carrier service, and for the short wing-span small aircraft that are highly sensitive to encounters.

### Summary

This paper has described the current status of the NASA Langley AVOSS development. The AVOSS system architecture, a wake vortex facility established at the Dallas-Fort Worth International Airport (DFW), initial operational experience with the AVOSS system, and emerging considerations for subsystem requirements have been addressed. Significant advances are being made in modeling wake vortex behavior in the atmosphere, meteorological system development and nowcasting, wake sensors, and system integration. As advancements are made, they are being implemented into the current AVOSS development facility for performance testing with field data. A concept development AVOSS system is currently running at the DFW airport, sans lidar wake sensors, and long-term performance studies suggest the opportunity for significant spacing reductions and throughput increase. The remainder of the AVOSS project will be devoted to implementing the second-generation wake vortex prediction algorithms, tailoring and simplifying the meteorological subsystem to facilitate a cost-efficient operational system, and validating the system in real-time operation with all sensors and variables present.

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