4th FAA/Eurocontrol R&D Conference Santa Fe, New Mexico Dec. 2001

The Effect of Aircraft Wake Vortex Separation on Air Transportation Capacity

Dr. George L. Donohue
Department of Systems Engineering and Operations Research
George Mason University
Fairfax, Virginia 22030-4444
gdonohue@gmu.edu

David K. Rutishauser
NASA Langley Research Center
Hampton, Virginia 23681-2199
d.k.rutishauser@larc.nasa.gov

ABSTRACT

The wake vortex separation problem has been known for over 30 years. The current system of static restrictions and approach separation criteria reduces the air transportation system capacity under IFR conditions. In the US, these static restrictions are frequently ignored under VMC conditions by assigning aircraft separation responsibility to the pilot once he has the airport runway in sight. The current system leads to 1) frequently imposing excessive separation under IMC and 2) infrequently allowing inadequate separation under VMC.

The recent NASA/FAA research on wake vortex separation has made significant progress on both theoretical understanding and empirical measurement of the aircraft wake vortex behavior interacting with the atmospheric boundary layer. An overview of the NASA Aircraft VOrtex Spacing System and analysis of field results are included in this paper. The current state-of-the-art indicates that new sensors and vortex prediction and warning algorithms should be incorporated into FAA weather and ATM decision support system software in order to recover critical lost air transportation capacity while at the same time maintaining or increasing safety.

Runway wind directional variability is intrinsic to the random nature of the atmospheric turbulent boundary layer. This inherent uncertainty in wind vector presents challenges to accurately predicting runway wind direction out to 30 minutes. The prediction time is required to begin the spacing of arriving aircraft approximately 200 miles from the airport due to the aircraft maneuver restrictions. The atmospheric turbulent boundary layer Turbulent Kinetic Energy (TKE) level or eddy dissipation level is a more stable scalar quantity and is more reliable in predicting the conditions for wake vortex breakup and accelerated circulation decay. Based upon both the experimental results observed in the NASA DFW experiments and theoretical considerations, it is recommended that **WARNING** of wake vortex circulation intensity above background be the criteria for any wake vortex ATC system, **NOT a PREDICTION** of wake vortex location relative to the runway centerline for initial system implementations. This should be true under most windy conditions. Under low wind, stable IMC conditions, the wind conditions may be more predictable and centerline Prediction may be more successful.

BACKGROUND

Research on aircraft wake vortex physics, detection, characterization and aircraft safe separation has been ongoing for over 30 years. A major conference was sponsored by the FAA, NASA, NCAR, NOAA, ALPA, AOCI, NTSB and AOPA in October of 1991 [7] and [8]. Fifty-five papers are presented in this two-volume set that provide an excellent review of the literature and state-of-the art in 1991. In

This research was conducted under contract to a MITRE sponsored research activity. MITRE does not necessarily endorse the results. This research also does not necessarily reflect the views of the FAA.

particular, the papers by Greene, et. al. [6] and Page, et. al. [14] present data and a number of lessons learned over the previous 20 years, a time of considerable research into aircraft wake vortex phenomena. Most of the physics that we are aware of today, after more than 10 years of additional research, was known in 1991, although considerable gains have been made in our ability to quantify and predict wake behavior.

The problem of a lighter weight aircraft (with a smaller wing span) encountering the wake vortex of a heavier aircraft (with a larger wing span) and suffering a roll upset has been known for a long time, Rossow [18]. The primary difficulty, occasionally resulting in a fatality, is a roll upset below 200 meters AGL, which the following aircraft is unable to correct prior to touchdown. Rossow suggests that a good rule of thumb is to ensure that the wake encountering aircraft not experience a roll rate greater than one half it's aileron roll control authority. Initially, it was believed that all aircraft vortices lasted for very long times and were resilient to viscous decay (i.e. $\sim 1/\sqrt{t}$), as described by the classic work of Lamb [12]. In the early 1970's, however, Crow [1] [2] showed that aircraft vortex pairing takes place due to small perturbations leading to large non-linear wake vortex break-up. Tow-tank testing by Liu [13] showed that the large, energy containing eddies in a homogeneous, isotropic background turbulence is a sufficient perturbation to lead to Crow instability breakup of aircraft trailing vortices. The wake vortex breakup was observed to be relatively insensitive to the dissipation level (i.e. small scale eddies). In hindsight, this should not have been a surprise since the larger energy containing eddies act as a larger perturbation to the vortex pairing instability, which turns the wake vortex energy against itself in self-destruction. The Liu data implied, therefore, that under most atmospheric conditions, the wake vortex life should not be governed by either laminar flow viscous decay or (once a threshold is exceeded) turbulent dissipation.

In 1991, it was still unclear how to properly model these interactions numerically and little was known about the effect of the ground boundary condition and non-isotropic, non-homogeneous turbulence of the atmospheric boundary layer. The description of the earth's boundary layer is now well described by Stull [19]. Considerable progress has been made since 1991 on the use of large, fast computers to use Large Eddy Simulation (LES) models that use most of the terms in the Navier Stokes equations with sub grid scale turbulent closure models to predict the interaction of the atmospheric boundary layer with landing aircraft wake vortices. Much of this effort is described by Proctor [15] and Proctor and Han [16]. It is found that LES 3-D models predict significant differences from the 2-D approximation models, illustrating the strong three dimensional nature of vortex-vortex pair coupling in a highly non-linear vortex annihilation process known as the Crow instability [1].

As early as 1991, most authors recognized that the background turbulence was at least as important to wake decay and aircraft separation as was advection by crosswinds, aircraft mass, aircraft landing velocity, aircraft wingspan and wing loading distribution. Almost 10 years ago, it was suggested by Evans and Welch [4] that the newly conceived FAA Integrated Terminal Weather System (ITWS) and the NASA Final Approach Spacing Tool (FAST) could be combined to significantly increase airport capacity by safely decreasing aircraft separation, especially under Instrument Flight Rules (IFR) where the FAA enforces wake vortex separation using simple, conservative criteria based solely on aircraft mass.

It was not until 1997 that the total national air transportation system capacity was recognized to be approaching a capacity crisis. Subsequently it was estimated to be currently operating at nearly 60% of maximum capacity (Donohue [3]). This was not a surprise to those familiar with the underlying theory of the NAS national network models. The NAS has been modeled by both MITRE and LMI as consisting of a network of queues. Queuing theory states that demand to capacity ratios in excess of 50% (surpassed in 1989) lead to a strong nonlinear (i.e. hyperbolic) increase in system delay.

It has been observed in both the 1991 conference and the more recent papers written by NASA that capacity increases of only about 10% can be expected by reducing wake vortex separation to approximately 3 miles (Hinton, et. al. [11]). (*A significant fraction of this capacity gain could be achieved by monitoring the background atmosphere's convective and turbulent state and providing a > 30 minute prediction of desired safe separation to Air Traffic Control (ATC)* *personnel.)* **This calculation underestimates the delay reduction value of a 10% capacity increase when an airport is operating near maximum capacity ratio because of the strong non-linear delay increase with high capacity fractions. A 10% increase in capacity can yield a 50% decrease in delay at 60% capacity fraction.**

Evans and Welch [4] also observed that the largest gains would probably be achieved in relaxing the IFR wake separation rules imposed by the FAA ATC. There is no theoretical reason to believe that wake vortex behavior is any different under fog and rain conditions than in clear weather. In fact, it is now known that FAA training that wakes always sink below flight path is **not universally correct**. Aircraft wake dynamics are strongly influenced by background atmospheric boundary layer conditions and there are numerous conditions that lead to wake vortex ascending rather than the conventional wisdom that wake vortices always descend. FAA pilot training material for wake turbulence avoidance should be modified to reflect this new understanding.

THE BASIC PHYSICS OF WAKE GENERATION AND BREAKUP

At the 1991 conference, it was largely the inability to analytically predict the interaction of wake vortices with the known large-scale structure of the atmospheric turbulent boundary layer that led to uncertainty as to the persistence of the vortices. Significant progress has been made in the interim years on creating numerical models of the Navier Stokes equations that allow the Large Eddy Structures (LES) to be represented with sub-grid scale models of the eddy dissipation functions. NASA has conducted sensitivity analysis of wake vortex interactions over a wide range of environmental parameters in order to develop a statistical envelope representation of aircraft wake vortex behavior in the presence of a range of temperature gradient stability condition (lapse rate), wind velocity profiles, aircraft mass, wing aspect ratio, fog and precipitation, etc. [17].

Proctor [15] and Proctor and Han [16] describe the modeling of the underlying physics of the atmospheric boundary layer / wake vortex interaction. The important non-dimensional parameters and simplified equations that need to be understood and used in estimating the wake decay are presented below and are taken from the collection of references cited in this report. It is important to note that the decay rates deemed to be important for this problem are the time for the Crow instabilities to form and tear the coherent wake apart (i.e. not viscous dissipation, unless the atmosphere is extremely stable with no wind and a very low eddy dissipation rate). This has been found to be the dominant mode of wake decay as observed both in the laboratory, Liu [13] and in the field, Crow [1] [2] Hinton, et al. [10] Page et. al. [14] and by LES numerical simulation Proctor and Han [16]. It is noted in [16] that for non-dimensional eddy dissipation rates greater than 0.001 (i.e. $\eta > 0.001$), the lidar wake decay data closely match the LES theoretical predictions and are **largely independent of the eddy dissipation rate above a finite threshold**. This behavior was also noted by Liu [13] in the laboratory.

Below this threshold, the wake vortex is persistent and presents a significant hazard to closely spaced aircraft where the following aircraft is of significantly lighter weight and has limited roll upset recovery capability. Once this background threshold is exceeded, however, wake vortices from even the heaviest aircraft are induced to interact with themselves in a highly destructive and non-linear fashion. This rapid decay of wake vortex circulation intensity is, therefore, largely independent of the more difficult to predict runway wind direction. **This fact could lead one to initially consider a wake vortex intensity warning system rather than a wake vortex location prediction system.**

CHARACTERISTICS OF WAKE VORTEX CIRCULATION STRENGTH AND DECAY RATE

As a starting point, one needs to understand that aircraft lift is directly related to the fluid circulation created by the wing. This circulation ($\mathbf{\Gamma_0}$) characterizes the strength of the horseshoe vortex that theoretically begins at the point of aircraft liftoff on the runway and extends through the two wing tips and through the axis of the wing throughout the entire flight until the arrival touch down point. To decrease the wing circulation is to decrease the airplane's ability to fly. The aircraft circulation strength is known from invisid theory to be directly proportional to the aircraft mass and inversely proportional to the aircraft velocity and wingspan (equation 1, in mks units).

$$\mathbf{\Gamma_0 \sim 12.5\ M / V_a B} \qquad \mathbf{(1)}$$

The next value we need to know is the characteristic time scale for the wake vortex to decay. The two counter rotating vortices rolling off the wing tips create a downwash velocity that pulls the wake vortex pair down after leaving the aircraft. A characteristic time scale can be defined as the time it takes for the vortex pair to descend one wing span and is referred to in this paper as (**t'**) and is shown in equation (2) to be proportional to the cube of the wing span, linearly proportional to the aircraft velocity and inversely proportional to the aircraft mass.

$$\mathbf{t' \sim B^3 V_a / M} \qquad \mathbf{(2)}$$

Knowing the aircraft specific characteristic time scale, we define a characteristic non-dimensional time (**t^***) as shown in equation (3).

$$\mathbf{t^* = t / t'} \qquad \mathbf{(3)}$$

If the ambient background turbulence eddy dissipation rate (**ε**) (equation 4) is measured to be above a threshold value, then the Crow instability is empirically observed to lead to a coherent circulation decay rate that is bound by equation (5).

The eddy dissipation rate is given as:

$$\mathbf{\varepsilon = 0.25\ q^2 / L} \qquad \mathbf{(4)}$$

for homogeneous, isotropic turbulence in the inertial sub-range.

A suggested threshold value for the triggering of the Crow instability is of the order of 10^{-4} m^2/s^3. An analysis of the turbulence climatology at Dallas Fort-Worth by MIT [25] shows that the eddy dissipation rate during typical operational hours is greater than 10^{-4} m^2/s^3 99% of the time. Once this background threshold is exceeded, the accelerated wake vortex circulation decay rate can be bound by the empirically observed equation (5) and is predicted to be below naturally occurring atmospheric turbulent levels near the ground in 8 to 9 non-dimensional time periods. [i]

$$\mathbf{\Gamma = \Gamma_0 (1 - t^* / 8)} \qquad \mathbf{(5)}$$

A very conservative safe separation distance can be determined by the time it takes for the preceding aircraft's wake to decay to an observed typical atmospheric background circulation level of 70 m^2/s (**Γ_{bg}**). One can rearrange the above equations to solve for this dimensional time in seconds as shown in equation (6).

$$\mathbf{t_{\Gamma bg} = 8t'(1 - \Gamma_{bg} / \Gamma_0)} \qquad \mathbf{(6)}$$

Table 1 uses published aircraft mass, wingspan and landing speed data and the above equations to compute important wake decay parameters for a representative range of commercial aircraft. Table 2 is a summary of the current FAA IFR wake separation criteria and Table 3 is a modified table taken from [10] to illustrate the predicted circulation strength using equations (1) (2) (3) (5) and the miles-in-trail separations from Table 2.

TABLE 1. Typical Aircraft wake vortex Parameters

Aircraft	Mass (Kg)	App. Spd. (m/s)	Wing Span (m)	Γ_0 (m^2/s)	t' (sec)	$t_{\Gamma bg}$ (sec)
B747-400	232,000	75	64	600	32	230
B777-200	185,000	66	61	570	31	220
A340-200	200,000	64	60	650	26	190
B767-300	123,000	68	48	470	23	160
B757-200	117,000	63	38	610	11	80
B727-200	70,000	65	33	400	13	90
B737-200	40,000	64	28	280	13	80
CRJ-700	27,000	63	23	230	11	60
Dash-8	13,000	56	26	110	29	90

Table 2. FAA Threshold spacing criteria (nmi)

	LEADING A/C			
FOLLOWING A/C	**SMALL**	**LARGE**	**B757**	**HEAVY**
SMALL <18,600 Kg	**2.5 to 3**	**4**	**5**	**6**
LARGE <116,000 Kg	**2.5 to 3**	**2.5 to 3**	**4**	**5**
HEAVY >116,000 Kg	**2.5 to 3**	**2.5 to 3**	**4**	**4**

Table 3. Potential <u>Maximum</u> Encounter Circulation (Γ) with Current Separation Standards assuming $\Gamma = \Gamma_0(1 - t^*/8)$ (m^2/s). Background Lidar measurement threshold is approximately 70 m^2 / s

	LEADING A/C			
FOLLOWING A/C	**SMALL**	**LARGE**	**B757**	**HEAVY**
SMALL <18,600 Kg	**70**	**100**	**70**	**130**
LARGE <116,000 Kg	**70**	**200**	**70**	**240**
HEAVY >116,000 Kg	**70**	**200**	**70**	**330**

The value of 70 m^2/s is used for any computed value <70 m^2/s since this value was typical of background atmospheric turbulence observed by lidar during DFW field operations, suggesting that this may represent a safe definition of demise.

Note that this criteria is very inconsistent and that it would allow small aircraft to encounter as much as 130 m^2/s circulation strength behind a Heavy aircraft while restricting Large and Heavy aircraft to encountering a range of 70 m^2/s to a 330 m^2/s.

Based upon an extensive review of this literature and the above observations, it should be noted that the current separation criteria are frequently over conservative except for the rare occurrence of no wind, and stable temperature stratification. According to Stull [19] this condition normally does not occur until after dusk, when the solar heating subsides and the atmospheric boundary layer becomes quiescent.

Relaxation of these IFR separation criteria, due to a better atmospheric monitoring system can have a significant effect on total system capacity, and therefore delay, at today's demand to capacity ratio. In addition, it is now both theoretically predicted and empirically observed that certain atmospheric conditions lead to wake vortex rise rather than fall. FAA wake avoidance guidance to pilots is to ALWAYS stay above the previous planes glide slope and land long if there is a potential wake vortex encounter. This is not always correct guidance. NASA has reviewed the DFW data to determine when wake vortex rise occurred. The operational significance of these events is discussed in the next section.

NASA AVOSS EXPERIMENTS AT DALLAS-FORT WORTH AIRPORT (DFW)

As part of a program to address reduced terminal capacity during IFR operations, NASA developed a proof-of-concept Aircraft VOrtex Spacing System (AVOSS). AVOSS uses current terminal weather observations and short-term predictions to anticipate wake behavior for the purpose of providing safe wake spacing criteria that is an improvement on the FAA spacing criteria shown in Table 2. The AVOSS was successfully demonstrated in a real-time field deployment at DFW during the summer of 2000. A brief overview of the AVOSS architecture and operation, performance results, and lessons learned is provided in this section.

The AVOSS architecture is shown in Figure 1. The weather subsystem was developed in cooperation with the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, North Carolina State University, and the National Oceanographic and Atmospheric Administration (NOAA). The system consisted of two instrumented towers, Doppler radar and sodar profilers for measuring winds aloft, and a radio acoustic sounding system (RASS) to measure temperatures aloft. At 30-minute intervals, data from these sensors as well as two Terminal Doppler weather radars were integrated into vertical profiles of winds, temperature, and turbulence using a fusing algorithm developed at MIT Lincoln Labs [23]. This data is used as a short-term forecast of the weather that is input to a state-of-the-art wake-prediction model [24]. This model provides estimates of wake transport (lateral and vertical) and strength. NASA Langley used the Terminal Area Simulation System (TASS) Large Eddy Simulation code developed by Proctor to systematically study the effects of ground interaction, turbulence, wind, wind gradients, and thermal structures on wake decay and motion in support of the predictor model development [21 & 22]. The final predictor is similar in form to the older Greene wake vortex decay model [5]. It was decided to shift from using Turbulent Kinetic Energy (TKE) in the Greene model to Eddy Dissipation Rate (EDR) due to insensitivity in selecting the integral scale (L) that is required in the use of TKE, Hinton, et. al. [11]. Numerous other changes to the Greene model were made to model ground interactions. The 30-minute interval was considered to be an acceptable amount of time for a persistence-based forecast of the weather while providing realistic lead-time for anticipated enroute controller planning. Northwest Research Associates developed the prediction subsystem, with participation from NASA and the Naval Postgraduate School.

The subsystem integration logic applies the estimates of wake behavior to a corridor of airspace about the nominal flight path (the center of the localizer and glide slope). Wakes can cease to be a hazard by drifting or sinking out of the corridor or by decaying to a circulation strength comparable to background turbulence. The dimensions of the corridor are based on a 3-sigma buffer applied to observed aircraft position dispersion data from radar tracking data [9].

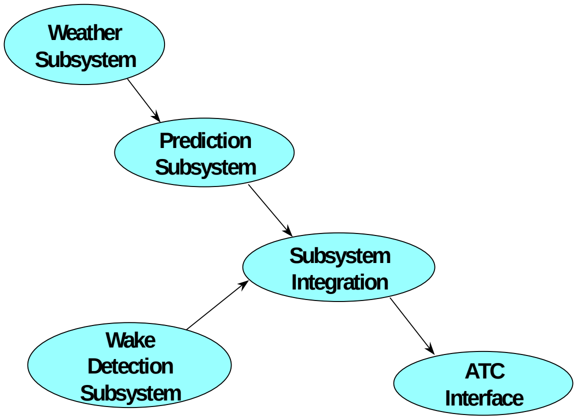

Figure 1. AVOSS architecture.

To determine the AVOSS recommended spacing, the wake hazard times are computed for each aircraft type (e.g., B-747) present in the traffic mix for a given airport. The computations are performed at various points along the approach corridor to capture the changes in wake behavior with altitude. The wake factor (position or strength) that first clears the corridor at those points sets the wake existence time for that aircraft at that point. The worst-case spacing for each aircraft type is then taken as the required spacing for that aircraft's category (e.g., heavy). Using the average approach speeds for each aircraft type and the predicted headwinds, the wake hazard times are converted to minimum spacing values (in nm) for each leader/follower pair. This results in the most conservative spacing being applied. The spacing is output as a category-indexed table in nautical miles.

The wake detection subsystem consists of various wake sensors that track the wakes from the approaching aircraft and provide time histories of wake position and strength as well as observed wake hazard times. These are used as a safety check and to validate the predictions. Figure 2 conceptually shows the safety corridor and a sensor placement. The subsystem used in the DFW deployment consisted of a continuous-wave (CW) lidar system operated by Lincoln Labs, a pulsed lidar operated by NASA, and a ground wind vortex-sensing system (GWVSS), or windline operated by Volpe. The CW lidar has the best range resolution but is limited to about 300 meters in range, so it was used close to the runway threshold in the field deployments. The pulsed lidar can measure wakes out to several kilometers, but has poorer range resolution (~30 meters). The wind line is a row of pole-mounted anemometers, so it has limitations as to where it can be installed in an airport environment, and wakes must sink into the sensor before they can be measured. The advantage of the wind line is its modest cost and low maintenance.

The AVOSS demonstration did not include an ATC interface, although a model that accounts for the performance impact of interfacing to ATC was included to add utility to the results. The model includes rounding of spacing values to ½ nautical mile increments and a buffer to simulate variances in aircraft delivery to the top of approach. Performance statistics were collected for continued system evaluation and development. Further details of the AVOSS design can be found in [9], [10], [11], and [26].

Analysis of the field data from the 1999 and 2000 DFW deployments reveals the maximum Instrument Flight Rules (IFR) throughput gain averaged 6%, while ranging from 0% to 16% [20]. The gain is computed by comparing the throughput using the AVOSS spacing recommendation to that achieved with the default FAA spacing. The 0% gain indicates that on some days the AVOSS did not recommend reducing the default spacing. The 16% gain in throughput is approximately equal to the maximum gain possible when comparing the default spacing to the minimum runway occupancy time (ROT) limited spacing.

Sensitivity studies of the predicted throughput based on omitting various wake behavior factors in the spacing computation have revealed that ignoring one of the three factors (drift, sink, or decay) reduces the average throughput gain by half. A test re-run of the 2000 DFW deployment computing spacing based only on demise showed a drop in the average throughput gain from 6% using all factors to 0.7% using only demise. Further investigation revealed that wake demise was the factor that set the spacing computation in almost half the predictions. The dramatic drop in average throughput gain was due to the assumed aircraft mix at DFW, which had a low frequency of arrivals for the categories of aircraft that had the largest impact on the spacing. An operational implementation of the AVOSS concept that included a demise-only based spacing can be expected to have reduced performance as

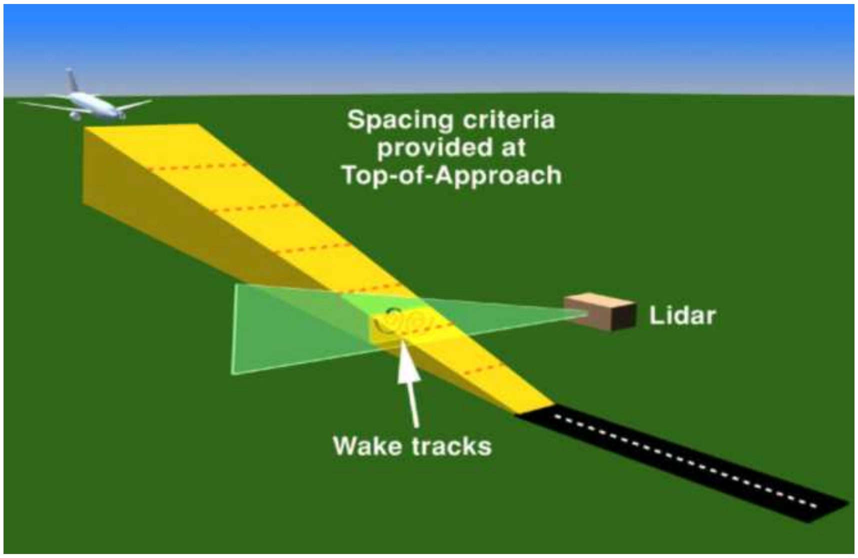

Figure 2. Safety corridor and sensor placement concept.

compared to the demonstrated system that is highly sensitive to the mix of aircraft types at a given location.

Field data from the DFW deployments was also used to validate the AVOSS predictor algorithms. Of 2301 wake measurements that were compared with the predictions, 99% indicated AVOSS reduced separation could be applied based solely on the predicted behavior (i.e. observed wake hazard times did not exceed the predictions). In almost 2/3 of the cases, AVOSS recommended the minimum separation possible (ROT limited) with no sensor measurements contradicting the recommendation. The 1% of cases where observed wake hazard times exceeded the predicted times were all exceedances of less than 20 seconds, with half under 5 seconds. These cases are not necessarily an indication that an inadvertent wake encounter would have occurred, since the wake hazard time is taken when the wake is observed to be clear of the safety corridor or indistinguishable from background turbulence. As designed, an aircraft would have to be flying with a significant deviation from the localizer or glide slope course to encounter the wake, which is unlikely given FMS-coupled approaches and typical pilot performance. Figure 3 further illustrates this point by showing the wake lateral and vertical positions at the time exceedance events were recorded.

All of the events shown were exceedances because the observed time for a wake to reach demise was higher than predicted. The vertical dotted lines in the figure are the lateral limits of the safety corridor, and the circle is centered at the nominal following aircraft position, with diameter equal to a B767 (heavy category) wingspan. The data is taken at a position where the corridor floor is at ground level. The diamonds and dots are the estimates of the wake core positions from the CW lidar. The diamonds denote wakes that were observed to rise. If it is assumed (arbitrarily) that the wake core must intersect the plane of the wing for an encounter to occur, only three or four wakes present a potential hazard. In addition, the strengths of all the wakes plotted range from 113 to 190 m^2/s, with a maximum circulation in the circle of 150 m^2/s. Referring to Table 3, these values are well under the maximum potential wake encounter strengths at the present separation criteria for large and heavy followers, with the exception of

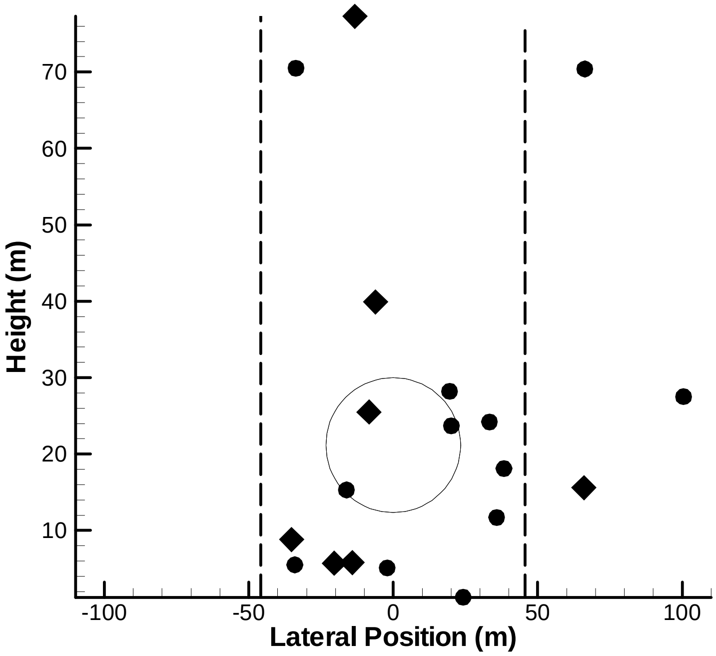

Figure 3. Wake positions during exceedance events recorded during the 2000 AVOSS deployment.

following a B757. Note that the current version of AVOSS never reduced separation for small category followers based on demise.

Of the 389 measurements from the 1999 and 2000 deployments made by a sensor that could determine a rising wake, 75 or 19% of these cases were observed. These cases were all measured with the CW lidar that was positioned where the wakes were in ground effect. No reliable data of wakes rising out of ground effect was found in the deployment data. Of the 75 rising wake observations, 7 cases fell into the category of exceedances, as shown in Figure 3. The fact that most of the rising cases did not produce exceedances implies that the rising behavior alone does not determine operational significance. Conversely, 7 of 19 or 37% of the measured exceedances were rising cases. Since these exceedances were measured in a position where wakes could not sink below the floor of the safety corridor, the rising behavior in ground effect may have an indirect effect on the vortex decay that contributed to the number of cases. An enhancement to the prediction algorithm to model rising wake behavior and its effects on vortex decay may improve system performance.

INTEGRATION OF DYNAMIC WAKE VORTEX SEPARATION INTO THE NAS ARCHITECTURE

One of the critical issues has been the selection of an "Operationally Acceptable Strength" (OAS) circulation threshold (Γ_{bg}) or demise threshold. It was initially set at 90 m^2/s. It has been empirically observed at DFW with two different lidar systems that many wakes decay to below the measured background circulation strength of ~ 70 m^2/s within about 70 seconds of aircraft passage**. This data combined with the AVOSS validation data mentioned previously suggest that Runway Occupancy Time (ROT) should be the FAA IFR limiting spacing criteria under most meteorological conditions if a wake vortex warning condition were available.** This assumes of course that the surveillance systems are upgraded to multilateration or GPS accuracy at 1-second update rates to the aircraft and that controller buffer zones (of up to 1 mile) are greatly reduced. **Until these changes are made, the wake vortex separation criteria will mostly influence the ATC system capacity under IFR conditions since the pilot is typically assigned separation responsibility under VMC**.

NASA understands and the data clearly indicate that wake prediction is a **stochastic measurement and prediction problem.** An improvement to the current prediction algorithms that is being investigated is to design them to output wake behavior statistics. The current algorithms output a mean vortex position and strength, with no variance statistics or confidence values assigned to the mean. A statistical prediction would facilitate development of performance specifications for an operational system, since the predicted probability of a wake encounter could be computed. Many of the validation cases reported from the DFW deployment represented scenarios where one wake factor, such as sink, did not behave as predicted while the wake was rapidly decaying or drifting, or in some cases even sensor errors such as merging the track of the wakes from two separate aircraft, falsely indicating a long-lived wake that climbed back up to the glide slope. Initial indications from field experience suggest that phenomena that cause one wake factor to last longer than predicted will simultaneously accelerate the effect of other factors. For example a thermal that prevents a wake from sinking will introduce rapid demise, and shears that can prevent wakes from sinking cause rapid lateral drift. NASA is aware that more fine-tuning and safety analysis needs to be done on the envelope prediction algorithms before Full Scale Development (FSD) or deployment.

The emphasis that I am placing on wake vortex decay as the critical separation criteria is somewhat different than most other authors on this subject. The primary focus of the FAA and the European ATC authorities has been on vortex movement by background wind convection. This is certainly an important phenomenon in affecting aircraft wake vortex encounter. The AVOSS data at DFW clearly indicate, however, that wake vortex convection by the large-scale structure of the atmospheric boundary layer is stochastic in nature and difficult to predict with much certainty, although AVOSS represents a major first step towards automating the assessment of the wind variance and using it in wake predictions to bound the potential drift. **More importantly, however, it is also observed that the wake vortex decay is usually quite rapid and may dominate wake vortex separation criteria independent of wake vortex predicted position.**

It is also quite clear that any wake avoidance system's performance quality will be based upon the quality of the micro-meteorological measurement and predictions. The NASA AVOSS demonstration used the prototype ITWS installation at DFW. It augmented the ITWS sensor suite with a number of extra instruments, the most notable of which were the turbulent eddy dissipation rate measurements that are required for the wake drift and decay rates in the prediction code. Both the MIT/LL CW and the Coherent Technologies Inc. pulsed solid-state lidar's are capable of estimates of Turbulent Kinetic Energy (TKE) or eddy dissipation rates (η) out to distances of approximately 1 km. The Solid-state laser system of CTI is a better candidate for practical field deployment and should be considered as being added into the suite of sensors that are fused in the ITWS system. In addition, the ITWS system should incorporate the NASA wake drift and decay prediction algorithms.

The information display stations designed for ITWS are in the correct locations and provide the correct Human Machine Interface (HMI) for wake turbulence avoidance as well as wind shear and microburst avoidance. ITWS provides all of the intra-airport communications and data dissemination functions that will be required for any wake vortex sensing and aircraft warning system. Finally, the ITWS program is well underway and the addition of a system upgrade is already in the life-cycle program plan. This fact minimizes the considerable difficulty of establishing a new program with a new funding line. Figure 4 illustrates the NAS 4.0 Air Traffic Management technology insertion schedule that could allow dynamic aircraft separation to be computed and displayed to the air traffic controller. Either URET or CTAS algorithms could be modified to accept ITWS/AVOSS inputs to guide aircraft final approach spacing at high demand to capacity ratio airports. At the earliest, these systems are scheduled for national deployment by the end of CY 2004.

An ITWS meteorological measurement system (augmented with a better one kilometer scanning turbulence measurement sensor and wake decay prediction algorithm) will be required at the high capacity fraction airports in order to provide the wake separation conditions to the ATC controller. The ITWS wind shear and microburst displays are of the proper nature and in the proper locations to provide separation guidance. Figure 4 illustrates the NAS 4.0 schedule for the introduction of the ITWS system. It can be seen that full deployment of the ITWS system is scheduled for CY 2003. Due to the increasing awareness of the impact that weather has on the capacity of the NAS, the ITWS Pre-programmed Product Improvement Program should be funded beginning in the 2002 budget.

In order for the capacity enhancing capability that a dynamic wake vortex separation system can provide to high capacity fraction airports, a production quality lidar and wake circulation prediction algorithms should be incorporated into the existing ITWS prototypes as soon as possible. Experience gained with these systems, especially at New York and DFW, should be incorporated into the ITWS Pre Planned Program Improvement (P3I) development program beginning in 2004.

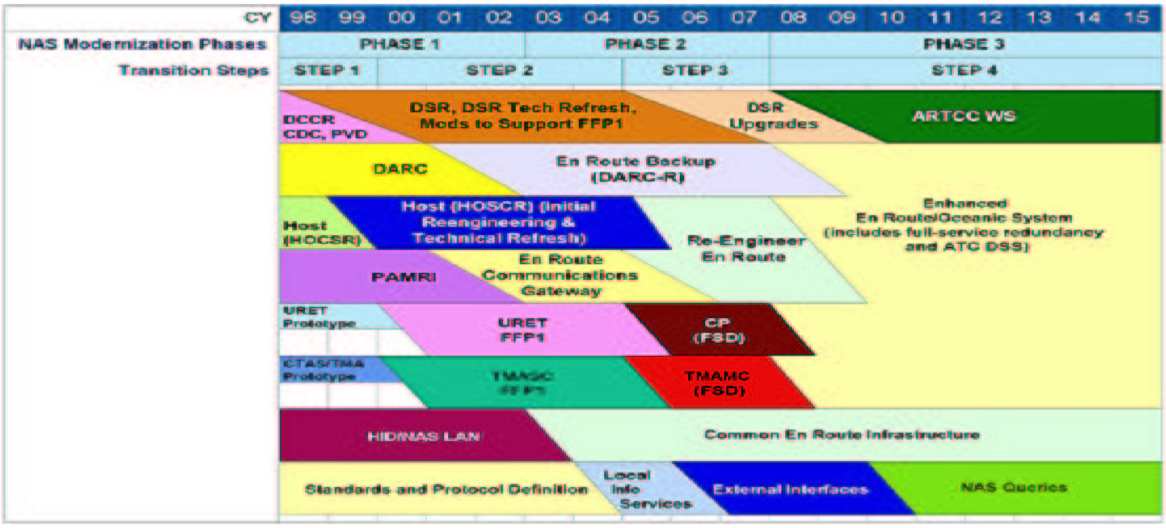

Figure 4. NAS 4.0 deployment schedule for ATM systems required to provide ATC separation guidance to the controller.

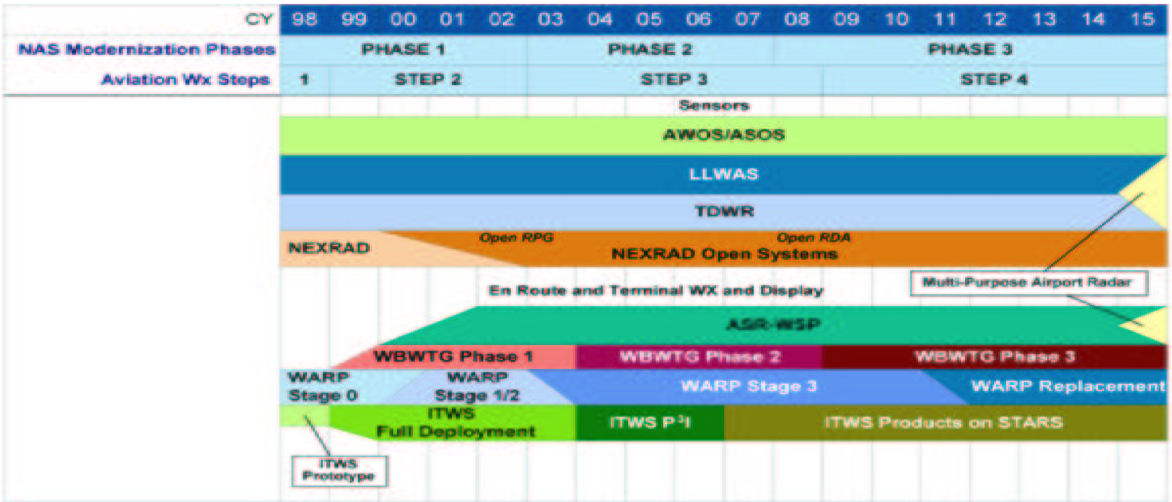

Figure 5. NAS 4.0 Deployment schedule showing ITWS prototype and P3I programs.

CONCLUSIONS

1) Aircraft wake dynamics are strongly influenced by background atmospheric boundary layer conditions and ground proximity. There are numerous conditions that lead to wake vortex ascending rather than the conventional wisdom that wake vortices always descend. It is not clear that these rising wakes can remain hazardous, so no procedural or training changes can be suggested at this time. Light aircraft landing long after heavy aircraft touchdown is still probably good advice. FAA pilot training material for wake turbulence avoidance should be modified to reflect this new understanding.

2) For atmospheric turbulent boundary layers with eddy dissipation rates below about 10^{-4} m^2/s^2 threshold, the wake vortex may be persistent and presents a significant hazard to closely spaced aircraft where the following aircraft is of significantly lighter weight and has limited roll upset recovery capability. Once this background threshold is exceeded, however, wake vortices from even the heaviest aircraft are induced to interact with themselves in a highly

destructive and non-linear fashion. This rapid decay of wake vortex circulation intensity is, therefore, largely independent of runway wind direction. This fact would lead one to consider a **wake vortex intensity warning system** rather than a wake vortex location prediction system.

3) Runway wind directional variability is intrinsic to the random nature of the atmospheric turbulent boundary layer. This inherent uncertainty in wind vector impacts the ability to accurately predict runway wind direction out to 30 minutes. The prediction time is required to begin the spacing of arriving aircraft approximately 200 miles from the airport due to the aircraft maneuver restrictions. The atmospheric turbulent boundary layer Turbulent Kinetic Energy (TKE) level or eddy dissipation level is a much more stable scalar quantity and is more reliable in predicting the conditions for wake vortex breakup and accelerated circulation decay, although AVOSS used numerous dedicated wind profiling sensors to demonstrate considerable success in estimating the bounds of the cross-wind 30-minutes out. Based upon both the experimental results observed in the NASA DFW experiments and theoretical considerations, it is recommended that **WARNING** of wake vortex circulation intensity above background be the criteria for an initial wake vortex ATC system, **NOT a PREDICTION** of wake vortex location relative to the runway centerline.

4) The current state-of-the-art indicates that new sensors and vortex prediction algorithms should be incorporated into FAA weather and ATM decision support system software in order to recover critical lost air transportation capacity. The ITWS P3I program seems to be the most logical place to place such a program.

NOMENCLATURE:

B aircraft wingspan (m)
b vortex separation = $\pi B / 4$ (m)
L Integral scale of homogeneous isotropic turbulence
t^* non-dimensional time
t' time to settle one vortex pair spacing (sec) = $\Gamma_0 / 2 \pi b$
$t_{\Gamma bg}$ time for wake vortex to decay to Γ_{bg}
t time (sec)
q^2 TKE turbulent kinetic energy (m^2/ s^2)
V $\Gamma/(2 \pi b)$ (m/s) vortex downwash velocity
Γ circulation (m^2 / sec)
Γ_0 initial circulation = $M g / (b \rho V_a)$ (m^2/ s)
Γ_{bg} demise circulation = 70 m^2 / s
ε turbulent (eddy) dissipation rate (m^2/ s^2)
V_a aircraft speed (m/s)
M aircraft mass (kg)
ν kinematic viscosity
ρ air density = 1.224 Kg / m^3 sea level
η nondimensional eddy dissipation = $(\varepsilon b)^{1/3} V^{-1}$
Re Reynold’s Number = $\Gamma / \nu \approx 10^6$ for the atmospheric boundary layer
g acceleration of gravity

ACKNOWLEDGEMENT

The AVOSS experiment was conducted by NASA Langley Research Center and an independent evaluation was conducted by the first author for the Center for Advanced Aviation Development of the MITRE Corp. The authors benefited from substantial technical discussions with several of the NASA AVOSS personnel (especially Mr. David Hinton) and Mr. George Greene of the FAA (AAR 210). We also benefited from comments on an earlier draft from Dr. Tim Dasey of MIT/LL Weather Sensing Group. NASA provided numerous technical articles describing their work and provided preliminary access to their DFW AVOSS field data. Without this assistance, this paper would have not been possible. Any errors or omissions in this paper are the responsibility of the authors alone.

REFERENCES:

1. Crow, S.C, “Stability Theory for a Pair of Trailing Vortices”, *AIAA Journal, Vol. 8, pp. 2171*, 1970.

2. Crow, S.C and E.R. Bate, Jr., "Lifespan of Vortices in a Turbulent Atmosphere", *Journal of Aircraft* Vol 13, No. 7, pp. 476-482, 1976.

3. Donohue, G.L., "A Simplified Air Transportation System Capacity Model", *Journal of Air Traffic Control*, April-June 1999.

4. Evans, J.E. and J.D. Welch, "Role of FAA/NWS Terminal Weather Sensors and Terminal Air Traffic Automation in Providing a Vortex Advisory Service", *Proceedings of the Aircraft Wake Vortex Conference Vol. I*, pp 24-1 to 2-22, June 1992.

5. Greene, G.C., " An Approximate Model of Vortex Decay in the Atmosphere", *Journal of Aircraft*, Vol. 23, No. 7, July 1986, pp.566-573.

6. Greene, G.C., R.E. Dunham, D.C. Burnham, J.N. Hallock and V.J. Rossow, "Wake Vortex Research-Lessons Learned", *Proceedings of the Aircraft Wake Vortex Conference Vol. I*, pp 2-1 to 2-13, June 1992.

7. Hallock, J.N. Ed**.,** *Proceedings of the Aircraft Wake Vortex Conference, Volume I*, Papers 1-29, Final Report June 1992, NTIS Report DOT-VNTSC-FAA-92-7.I

8. Hallock, J.N. Ed**.,** *Proceedings of the Aircraft Wake Vortex Conference, Volume II*, Papers 30-55, Final Report June 1992, NTIS Report DOT-VNTSC-FAA-92-7.II

9. Hinton, D.A., "An Aircraft Vortex Spacing System (AVOSS) for Dynamical Wake Vortex Spacing Criteria", *AGARD 78th Fluid Dynamics Panel Meeting and Symposium on the Characterization and Modification of Wakes from Lifting Vehicles in Fluid*, Trondheim, Norway, 20-23 May 1996.

10. Hinton, D.A., J.K. Charnock, D.R. Bagwell and D. Grigsby, "NASA Aircraft Vortex Spacing System Development Status", *AIAA 99-0753, 37th Aerospace Sciences Meeting & Exhibit, Reno Nevada*, January 11-14, 1999.

11. Hinton, D.A., J.K. Charnock and D.R. Bagwell, "Design of an Aircraft Vortex Spacing System for Airport Capacity Improvement", *AIAA 2000-0622, 38th Aerospace Sciences Meeting and Exhibit, Reno, Nevada*, 10-13 January 2000.

12. Lamb, H., *Hydrodynamics*, 6th Ed., Dover, 1945, pp. 221-224 and 591-2.

13. Liu, H-T. , "Tow-Tank Simulation of Vortex Wake Dynamics", *Proceedings of the Aircraft Wake Vortex Conference, Volume II*, pp. 32-1 to 32-26, June 1992.

14. Page, R.D., K.L. Clawson, L.J. Garodz and R.P. Rudis, "Panel Discussion on Tower Fly-By Testing – 1990 Fall Series", Proceedings *of the Aircraft Wake Vortex Conference, Volume II*, pp. 49-1 to 49-53, June 1992.

15. Proctor, F.H., "The NASA-Langley Wake Vortex Modeling Effort in Support of an Operational Aircraft Spacing System", *AIAA-98-0589*, 1998.

16. Proctor, F. H. and J. Han, "Numerical Study of Wake Vortex Interaction with the Ground Using the Terminal Area Simulation System", *AIAA 99-0754, 37th Aerospace Sciences Meeting and Exhibit, Reno Nevada*, January 11-14, 1999.

17. Riddick, S.E. and D.A. Hinton, "An Initial Study of the Sensitivity of Aircraft Vortex Spacing System (AVOSS) Spacing Sensitivity to Weather and Configuration Input Parameters", NASA/TM-2000-209849, January 2000.

18. Rossow, V.J., "Prospects for Alleviation of Hazard Posed by Lift-Generated Wakes", *Proceedings of the Aircraft Wake Vortex Conference, Volume I*, pp. 22-1to 22-40, June 1992.

19. Stull, R.B., *An Introduction to Boundary Layer Meteorology,* Kluwer Academic Publishers, 1988.
20. O'Connor, Cornelius J., and Rutishauser, David K., "Enhanced Airport Capacity Through Safe, Dynamic Reductions in Aircraft Separation: NASA's Aircraft VOrtex Spacing System (AVOSS)", NASA/TM-2001-211052, August 2001.
21. Switzer, George F. and Proctor, Fred H., "Numerical Study of Wake Vortex Behavior in Turbulent Domains with Ambient Stratification", *AIAA 2000-0755, 38th AIAA Aerospace Sciences Meeting & Exhibit*, January 10-13, 2000, Reno, NV.
22. Proctor, Fred H.; Hamilton, David W.; and Han, Jongil, "Wake Vortex Transport and Decay in Ground Effect: Vortex Linking with the Ground", *AIAA 2000-0757, 38th AIAA Aerospace Sciences Meeting & Exhibit,* January 10-13, 2000, Reno, NV.
23. Cole, R., Denneno, A., Matthews, M., "The AVOSS Winds Analysis System", Project Report NASA/L-5, Lincoln Laboratory, Massachusetts Institute of Technology, April, 2001.
24. Robins, R. E., Delisi, D. P., "NWRA AVOSS Wake Vortex Prediction Algorithm Version 3.1.1", NWRA-CR-00-R229A, Northwest Research Associates, November 2000.
25. Perras, G. H., Dasey, T. J., "Turbulence Climatology at Dallas/ Fort Worth (DFW) Airport-Implications for a Departure Wake Vortex Spacing System", MIT/LL Project Report NASA/L-4, April, 2001.
26. Hinton, D. A., "Description of Selected Algorithms and Implementation Details of a Concept-Demonstration Aircraft VOrtex Spacing System (AVOSS)", NASA/TM-2001-211027, June 2001.

AUTHOR BIOGRAPHIES

George Donohue is a Professor of Systems Engineering and Operations Research at George Mason University. Formally, Dr. Donohue was Associate Administrator of Research and Acquisition for the FAA. Dr. Donohue is an AIAA fellow, and holds a Ph. D. in Mechanical and Aerospace Engineering from Oklahoma State University.

David Rutishauser joined the AVOSS team in July of 2000. Prior to joining NASA, Mr. Rutishauser worked at the Raytheon Systems Company as a hardware and software design and integration engineer. Mr. Rutishauser holds a Batchelor's of Electrical Engineering and a Master's of Electrical and Computer Engineering from the University of Dayton and Arizona, respectively. Mr. Rutishauser holds a private pilot certificate with an instrument rating.

---

[i] Discussion with George Greene indicate that this value of 8 to 9 seems to be a good decay rate for WV near the surface but a value of 16 to 18 may be the appropriate decay time for high altitude or low background turbulence conditions. The high altitude case is not deemed to be a safety hazard due to enroute spacing practices and the low density airspace conditions of the enroute environment. Under low background turbulent conditions near the ground, current wake vortex spacing may be not be changed.