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10.1 NOWCASTING REQUIREMENTS FOR THE AIRCRAFT VORTEX SPACING SYSTEM (AVOSS)*†

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1. INTRODUCTION

Aircraft wake vortices are counter-rotating tubes of air that are generated from aircraft as a consequence of the lift on the aircraft. The safety concern of wake vortices, particularly when lighter aircraft are following heavy planes, has caused the Federal Aviation Administration (FAA) to enact minimum separation requirements during the arrival phase of flight. These separation standards are imposed at the arrival threshold during Instrument Flight Rules (IFR) and are a significant constraint on arrival capacity at the largest U.S. airports. Any movement toward increasing air traffic efficiency, such as concepts toward free-flight, must address increasing runway capacity if they are to be fully effective. Decades of past wake vortex measurements clearly show that current wake vortex separations are overconservative in many weather conditions, and that adapting the separations to the current weather state could safely reduce these separations.

The Aircraft Vortex Spacing System (AVOSS) is a NASA Langley Research Center research effort toward developing the technology for an automated system for adaptively reducing aircraft wake separations (Hinton, 1996). Air Traffic Control (ATC) must have advance notice of future wake vortex separations in order to have aircraft available to take advantage of reduced arrival wake separations. This requires that meteorological variables that influence vortex behavior be accurately forecast, so vortex behavior models can provide the separation criteria.

This paper describes the known meteorological influences on vortex behavior and gives an overview of the AVOSS. Airport climatology is studied to discuss the prevalence of conditions that are conducive to capacity increases with AVOSS technology. Finally, additional constraints on AVOSS nowcasts are discussed.

2. WEATHER AND WAKE VORTICES

Aircraft wake vortices have cross-sectional scales that are on the order of a few tens of meters in diameter, with larger vortices being generated by larger aircraft. The cores of the wakes from each wing are initially separated by approximately 3/4 of the wingspan, and counter-rotate. The windfield from each vortex extends beyond the separation between the vortices, so they mutually advect one downward after generation. The initial strength (termed the vortex circulation) of each vortex is directly proportional to the aircraft weight, and inversely proportional to the air density, the aircraft airspeed and its wingspan. The vortex descent rate (typically 1-2 m/s) is directly proportional to the circulation of the opposing vortex, and inversely proportional to the distance between the vortices. At about a distance above the ground equivalent to the initial separation between the vortices, the presence of the ground begins to slow the vortex descent (the ground imposes the zero vertical motion boundary condition). Surface friction generates secondary vortices close to the ground that act to push the vortices away from one another in hyperbolic tracks relative to the ground. These secondary vortices can also push the vortices back upward again, creating a condition known as a vortex bounce.

Vortices will tend to be advected by larger scale atmospheric winds. The advection rates of vortices have been well documented and agree well with measurements of ambient winds at the same altitudes. In relation to the wake generated by a landing aircraft following a linear trajectory, the transport of the vortex away from the flight path of a following aircraft is

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mainly due to vortex descent and crosswinds. For aircraft that are landing or taking off, headwinds do act to slow or speed up the apparent descent of the wakes. However, at typical descent angles of landing aircraft (3 degrees), this is a minor influence. A 10 knot headwind will increase the apparent descent rate (at any fixed reference point) of a vortex not interacting with the ground by only a few centimeters/sec. However, over the short time periods that vortices live, updrafts may be sufficient to counteract vortex descent at a few hundred meters.

Studies have also suggested that a change in the vertical windshear (that is, the second derivative of the horizontal wind over height) can also have important influences on the vertical transport of the vortex. Detailed physical models suggest that there are regions of changing vertical shear which can serve to reverse vortex sinking, so that the vortex can "bounce", even away from the ground (Proctor, 1998). Vortex measurements at Dallas/Ft. Worth (DFW) Airport and Idaho Falls do show this vortex behavior, which may be due to a changing vertical windshear.

Vortices will decay in circulation after their generation, until they experience one of several forms of catastrophic demise or they become indistinguishable from typical atmospheric variations. Vortices have been measured that last only a few tens of seconds, and others have been measured to last several minutes (although the latter is unusual, especially if they encounter the influence of the ground). There are researchers who claim that vortices may not decay, despite decades of vortex measurements and successful flight operations to the contrary. For the majority who agree that vortex decay is the norm, there is far less certainty about the precise mechanisms and influences on vortex decay.

The primary meteorological influence on vortex decay is undoubtedly the degree of atmospheric turbulence. Small-scale turbulence (on the order of centimeters to a few meters) acts to decrease the intrinsic circulation of a vortex by entrainment at the periphery. In this way the vortex tends to decay from the outside inward, and there are numerous measurements to support this mechanism (Sarpkaya, 1998). Larger scale turbulence (from tens to hundreds of meters) promotes kinking of the vortex tube, which helps instigate Crow instability, whereby the two vortices join and mutually annihilate one another. The most commonly used model of vortex decay, the Greene model (Greene, 1986), expresses the vortex circulation as an exponential function of time, the rate of which is determined by the Turbulent Kinetic Energy (TKE). More recent studies are pointing to the use of eddy dissipation rate (ε) as a turbulence parameter more appropriate to vortex decay (Proctor, 1998).

An additional influence to vortex decay is the degree of atmospheric stability. Vortices that are descending into an atmosphere with opposing buoyancy forces can have accelerated decay, although this influence is much weaker than the effect of turbulence in the atmosphere.

Models have indicated that additional meteorological influences, such as rain and humidity, have little or no influence on the track or decay of wakes (Proctor, 1998). Measurement validation of these model results is still needed.

Finally, perhaps one of the most common forms of vortex demise is a phenomenon called vortex bursting, characterized by a sudden loss of vorticity. The mechanism for vortex bursting is not well understood, and since it does not necessarily occur along the entire vortex tube, the focus of study of vortex decay has to remain on more gradual weakening.

3. AVOSS CONCEPT

The basic output of AVOSS will be a set of separations between aircraft that will assure landings that are safe from wake turbulence. These separations need to be provided at least 30 minutes in advance in order for appropriate scheduling and planning to take advantage of any reduced separations. At this time arrivals are about 150 nm from the airport, just before the top of their descent in en-route airspace. Extending the time horizon of spacing forecasts to one to three hours as extensions to initial AVOSS capabilities is very important in maintaining capacity benefit. In the absence of these longer time forecasts, it is unlikely that sufficient up-front planning can be performed to ensure that enough aircraft are available to take advantage of the increased capacity.

Ideally the output separations will be sent to an air traffic automation system such as the Center/TRACON Advisory System (CTAS), where they will be considered along with other traffic constraints and provided as guidance information to controllers. There are several advantages to sending the separation information to CTAS. Among the most important are that non-integer separations can be provided, and that separations can be perhaps provided for each combination of leading and following aircraft type. The output of AVOSS can also be sent to a manual ATC system, but in this case it is likely that AVOSS will provide category-based separation matrices.

The separations are derived from the worst-case vortex behavior over the entire final approach path and potential weather conditions. Since presentations of future separations are required, this necessitates a weather forecast model that provides accurate nowcasts of the relevant meteorological variables discussed in section 2. The forecasted range of weather conditions are then provided to a vortex behavior model, which assesses the amount of time that a pair of vortices will remain a factor for following aircraft. This is done for each simulated aircraft type, and the vortex safety clearance times are then translated into separation distances.

AVOSS is also developing vortex-sensing technology that will be used in an operational system as a safety fallback, in the event that the forecast of required vortex separations are occasionally inaccurate.

4. HIGH BENEFIT WEATHER CONDITIONS

In the design of the AVOSS system and in directing the technology to the appropriate areas, it is important to understand the weather conditions where the most benefit can be received. To begin this process, hourly surface observations for a 9-year period (1984-1992) at the largest US airports were analyzed. Only observations during the typical capacity constrained operating hours of 6 am to 10 PM were considered.

Instrument meteorological conditions (IMC) are defined as weather conditions with a ceiling below 1000 ft or visibility below 3 miles. In considering the times when an AVOSS system could provide operational benefit, these criteria were relaxed, since restrictions at higher flight levels impose separations that cannot be made up at lower altitudes. In this study, the modified-IMC conditions were defined as a ceiling at or below 2500 ft or visibility at or below 5 miles. This may even be conservative for some facilities. As an example, DFW and ORD controllers state that their operations begin to be affected with ceilings of 3500 to 5000 ft.

The following conditions were considered in the analysis: rain (drizzle, light, moderate, and heavy), thunderstorms, fog, haze, snow and overcast. The term overcast is being used here when the observation meets the modified-IMC criteria but there were no additional precipitation or visibility remarks.

In considering the impact of these conditions on the predictability of vortex behavior, a key consideration is the anticipated variability of the conditions that affect vortex behavior, such as the wind. If the weather is spatially inhomogeneous, then the range of potential vortex behaviors is larger and the likelihood that AVOSS can provide operational benefit is reduced. Moderate to heavy rain tends to occur in storm cells that do not cover large areas, and are often accompanied by widely variable winds. Snow often occurs in localized bands, especially near many of the strongly affected airports such as ORD and DTW, and capacity during snow events are probably limited by other constraints such as runway preparation. For these reasons, periods of heavy and moderate rain, thunderstorms and snow were discounted from being high benefit AVOSS times. This is clearly an approximation, and there may be portions of this time that AVOSS can be useful.

The corresponding windspeed distributions for the remaining conditions were analyzed, and the results are shown in Figure 1. As expected, the fog and haze conditions are coincident with generally weaker winds, which reduces benefits due to vortex transport. These conditions are less likely to transport the vortices away from the approach corridor. In considering the usefulness of AVOSS in these conditions, vortex decay becomes most important. Fog conditions are generally associated with low turbulence and neutral stability, which are not conducive to vortex decay. For these reasons, fog is probably not a high benefit AVOSS time. In contrast, haze is generally associated with hot and turbulent conditions where vortex lifetimes should be greatly reduced, and therefore is likely a high benefit weather condition.

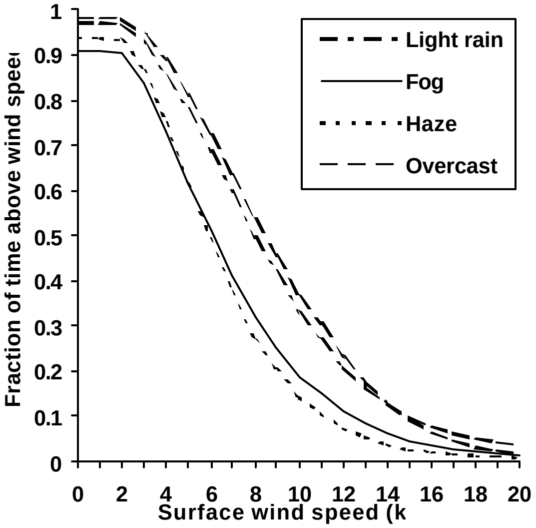

Figure 1. Fraction of operating time with surface wind speeds above various wind speeds for different types of weather conditions.

Figure 2 shows a chart of fraction of time that various US airports are operating under the modified-IMC conditions outlined earlier. The hollow-filled bars indicate this percentage. The solid-filled bars show the percentage that the airport is operating under light rain, drizzle, haze or overcast conditions. These are the remaining weather conditions that are likely to be high benefit AVOSS periods. As Figure 2 shows, a substantial portion of the modified-IMC periods, when airport capacity can be strongly limited, are likely to be improved by an arrival dynamic wake vortex separation system. A prime example is LAX, where about 75% of the modified-IMC time is conducive to AVOSS benefit. Even though a smaller fraction of this period will have weather conditions which allow separation decreases, the potential reductions in delay are huge for this system, at least on par with other highly touted systems such as the Integrated Terminal Weather System (ITWS) in reducing weather related delay. Actual dollar benefits are also strongly dependent on the traffic mix, capacity to demand relationship by time of day, and specific procedures at the airports.

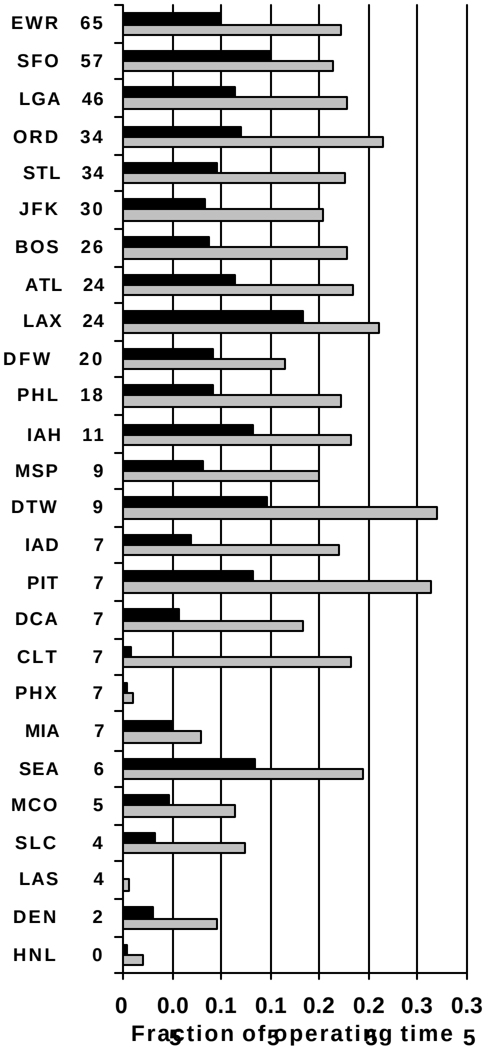

Figure 2. *Fraction of operating time in modified-IMC conditions (gray bars) and the percentage with reasonably high levels of benefits from an AVOSS system (black bars). The black bars consider haze, light rain, drizzle, or overcast weather conditions. The number next to the airport identifier indicates the number of airport delays of 15 minutes or more per 1,000 operations.*

5. NOWCASTING REQUIREMENTS

The discussion thus far has focused on the variables of interest to wake vortex behavior and a characterization of the weather conditions that will lend themselves to an adaptive vortex spacing system. Beneficial weather conditions include those that are either conducive to rapid vortex decay or transport, or have inherently less variability and thus have more predictable local conditions. Clearly vortices are affected by very local conditions, but this does not impose a requirement that the local conditions need to be specifically forecast. All that is necessary is that all of the local conditions are bounded within an appropriately forecast range of weather conditions. A forecast of, for example, wind conditions over the 30-minute to few hour forecast periods, is entirely worthless if only mean conditions are forecast. A useful forecast would specify a range of wind conditions. This range can be run through a vortex behavior model in several different combinations to find the worst-case vortex behavior.

If you consider only vortex transport away from the approach corridor, clearly the bottleneck region of the flight path is inside the middle marker to touchdown. This is because the ground prevents the vortex from descending, and so only a crosswind will transport the vortex away from the approach corridor.[1] It takes a minimum of about 3-4 knots of crosswind to ensure that both vortices will be moved out of the corridor (due to about an equal amount of competing lateral motion from the vortices). Using the currently defined AVOSS corridor width at touchdown, a 5 kt wind is sufficient to clear the vortices out of the corridor within a minute (about 3 miles of separation). However, since the clearance time is related to the reciprocal of crosswind speed, a one-kt difference (5 kts to 4kts) means a two-mile separation increase. This effect is greatly reduced for larger crosswinds, so that the difference in clearance time from an 11 kt to a 10-kt crosswind equates to about a 1/8 mile separation change. Since light winds are generally more common than strong winds, clearly a reduction in the wind forecast error has a strong effect on the minimum wind speed that will guarantee vortex clearance. Techniques for characterizing the wind variability in the AVOSS coverage area are currently under investigation, including techniques for using long period Turbulent Kinetic Energy (TKE) to estimate wind variability.

New models of vortex decay, particularly decay near the ground, are undergoing active development as part of the AVOSS effort and through several international efforts (Proctor, 1998). The sensitivity of these models to weather conditions has not yet been determined, so a quantitative assessment of the accuracy requirements for variables such as turbulence and stability cannot be well determined. The AVOSS system requires a vertical profile of eddy dissipation rate and the potential variability of that parameter.

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[1] Although vortices in ground effect clearly do decay quicker than vortices at higher altitudes.

AVOSS will cover all approaches to the airport, out until at least the outer marker. Each forecast will need to provide vertical profiles of the relevant parameters (wind, turbulence, temperature) which are representative of the conditions in this entire coverage domain. If there are systematic influences on the profiles at different portions of the coverage area, such as terrain or surface type (water vs. land), then separate profiles need to be provided for each of these regions. Wind variability must be provided as variance in the headwind and crosswind directions. The current thinking is that wind profiles will probably require a greater vertical resolution than turbulence and temperature profiles, and that the resolution will probably be non-uniform, with a higher resolution very close to the surface. The current AVOSS prototype at Dallas/Ft. Worth Airport provides profiles at 15-meter resolution up to 100 meters AGL, and 50-meter resolution above that level to the top of the coverage region (400 - 1000 m). The vertical resolution may not need to be quite as high as that, as long as regions of changing vertical shear are identified to an accuracy on the order of the vortex size (a few tens of meters). This kind of resolution can be reasonably obtained with existing FAA and commercial sensors, or can be provided as additional information from a long-range vortex sensor.

Table 1 provides a summary of the variables that need to be forecast as part of AVOSS.

Table 1.
Summary of required forecast variables.

Variable	Specifications
Crosswind Profile	• Ground to glide slope intercept altitude. • Vertical resolution better near the ground.
Wind variance or TKE	• Statistically captures all potential wind conditions in coverage area over forecast interval.
Detection of vertical wind shear or temperature inversion height	• Location of transition. • Magnitude.
Eddy dissipation rate (ε) profile	• Mean and variance of ε for forecast interval.
Indicator of discrete events	• Abrupt wind shifts. • Approaching convective activity.

6. SUMMARY

This paper has discussed the meteorological influences on wake vortex behavior, and the considerations for the nowcasting component of the AVOSS. Analysis of the weather conditions that are likely to be of most operational benefit with AVOSS technology were discussed, with the conclusion that light rain and drizzle, haze, and overcast conditions could provide significant operational benefit. Other conditions (thunderstorms and heavy rain) were discounted on the basis of insufficient predictability (in terms of vortex behavior), while the light wind, low turbulence conditions present in fog likewise removed that condition from strong consideration. A discussion of the impact of forecast accuracy was made, and coverage and resolution requirements were addressed.

A more detailed analysis of the specific benefits of an AVOSS system needs to be made. Clearly the information requirements of weather forecasts for AVOSS drops as longer time scales are considered. For AVOSS forecasts in the thirty-minute time range, detailed information must be provided about the separations that have to be used to ensure that aircraft are separated from wakes. This type of separation forecast means that the entire range of local meteorological conditions must be accounted for in the weather nowcast. For forecasts from one to several hours, it is probably sufficient that AVOSS forecast the average airport arrival rate. This will likely relax the requirements for these longer time forecasts. The forecast updates for longer-term forecasts will likely be larger, which increases the forecast parameter variability. However, since this information is strategic and not tactical, only the average parameter variability over the period accounted for in a 30-minute forecast need be specified.

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