An Aircraft Vortex Spacing System (AVOSS) For Dynamical Wake Vortex Spacing Criteria

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Summary

A concept is presented for the development and implementation of a prototype Aircraft Vortex Spacing System (AVOSS). The purpose of the AVOSS is to use current and short-term predictions of the atmospheric state in approach and departure corridors to provide, to ATC facilities, dynamical weather dependent separation criteria with adequate stability and lead time for use in establishing arrival scheduling. The AVOSS will accomplish this task through a combination of wake vortex transport and decay predictions, weather state knowledge, defined aircraft operational procedures and corridors, and wake vortex safety sensors. Work is currently underway to address the critical disciplines and knowledge needs so as to implement and demonstrate a prototype AVOSS in the 1999/2000 time frame.

1. Introduction

A continuing trend for increased air travel, combined with severe environmental restrictions on expansion or new airport construction, has led to more frequent flight delays and associated costs to the traveling public and to the air carriers. One response has been an increased interest in maximizing the efficiency of the runway capability that is available. The National Aeronautics and Space Administration is addressing the problem through its Terminal Area Productivity (TAP) Program. The major goal of the TAP program is to provide the technology base and systems to permit the same airport capacity levels during instrument meteorological conditions that are presently experienced during visual airport operations. Two major initiatives under TAP are the development of advanced Air Traffic Control (ATC) automation tools (reference 1) and wake vortex systems to improve terminal area efficiency and capacity. NASA Ames Research Center is the responsible center for development, testing, and demonstration of a Center-TRACON Automation System (CTAS), which includes a Traffic Management Advisor (TMA), a Descent Advisor (DA), and a Final Approach Spacing Tool (FAST). This automation provides aids to the controller to effectively schedule and sequence arrivals and minimize variations in desired inter-arrival spacing. This automation provides an opportunity to dynamically alter the wake vortex separation constraint as a function of the weather and the actual aircraft pair type (as opposed to broad weight categories). NASA Langley Research Center is performing the research and development to develop the automated wake system, known as the Aircraft Vortex Spacing System (AVOSS).

The impact of wake vortex on aircraft separation standards under instrument conditions results from multiple factors. During instrument flight conditions ATC has direct responsibility for aircraft separation and applies wake vortex constraints that are not weather dependent. Separation must therefore be based on worst case weight differences between and within aircraft weight categories and wake persistence observed during weather conditions favorable for long vortex life. Under visual conditions, responsibility for separation may be given to the pilot during the final approach phase. There are no minimum following distances that must be applied during visual operations and, in many cases, the primary constraint on following distance is runway occupancy time. In visual conditions that are favorable for rapid vortex demise or drift, or when following aircraft of very similar size and weight, pilots frequently apply less separation than would be required in instrument conditions. There is no fundamental reason to believe that vortices behave differently in visual and instrument meteorological conditions. By quantifying the atmospheric effects on wake behavior, the same reduced spacing should be possible in instrument conditions.

The purpose of the AVOSS is to integrate current and predicted weather conditions, wake vortex transport and decay knowledge, wake vortex sensor data, and operational definitions of acceptable strengths for vortex encounters (acceptable vortex strength definition) to produce dynamical wake vortex separation criteria. By considering ambient weather conditions the wake separation distances can be relaxed during appropriate periods of airport operation. With the appropriate interface to planned ATC automation (CTAS), spacing can be tailored to specific generator/follower aircraft types rather than several broad weight categories of aircraft. In a manual ATC, a simplified form of the AVOSS concept may be used to inform ATC when a fixed alternate, reduced separation standard may be used for the "large" and "heavy" aircraft categories.

2. Prior Research

The AVOSS prototype development will build on prior wake vortex research activities conducted by the Federal Aviation Administration (FAA), Volpe National Transportation Systems Center, and industry. In particular, reference 2

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provides a system concept that forms the foundation of the current system development. A detailed bibliography of prior research activities and a summary of the knowledge gained can be found in references 3 and 4. A number of developments have occurred since the earlier system concept definition that enhance the opportunity to realize a practical system. The current development effort is being conducted in a strong meteorological frame work. Many advances in weather sensors, wake sensors, computer capability required for computational fluid dynamic modeling, and ATC automation have occurred which will aid development and implementation of an Aircraft Vortex Spacing System.

3. AVOSS Concept

The philosophy behind the AVOSS system is to avoid aircraft encounters with vortices above an "operationally acceptable strength." This avoidance is obtained through consideration of two factors, wake vortex motion away from the flight path of following aircraft and wake vortex decay. Since these factors are highly dependent on ambient meteorological conditions, as well as the generating aircraft position and type, the wake vortex constraints on aircraft separation are expected to vary significantly with the weather. Since terminal area metering to meet airport acceptance rates occurs well before final approach, the AVOSS system must provide a predictive capability to realize reduced approach spacing. Initial predictions of wake vortex separation constraints 30 to 50 minutes in advance of the actual approach may be required to take full advantage of reduced wake constraints. This predictive requirement will drive all efforts in the primary work areas of meteorological sensors, ATC procedures, and system architecture.

The potential for an encounter will be determined through consideration of vortex motion and boundaries of the approach and departure corridors used by the aircraft. The approach corridor concept is required since wake separation requirements must be established well before the approach. This requirement does not allow use of actual aircraft position to provide separation between specific aircraft pairs.

The approach and departure corridors are sliced into a series of cross-sectional "windows", where the aircraft altitude varies at each window. The window concept provides a computational frame work for computing the varying vortex behavior at different heights above ground and for utilizing the varying meteorological conditions at those altitudes. The altitude or location on the approach or departure path with the longest lasting hazard will determine the separation required for the entire approach.

The term “operationally acceptable strength” indicates that vortex encounters will be permitted if the strength of the encountered vortex will have no adverse operational effect (pilot or passenger concern, increase in touchdown point dispersion, need to disengage autopilot, etc.) on the trailing aircraft. Such would be the case, for example, of a large turbojet transport encountering the wake of a small business-class jet. While the research is yet to define “operationally acceptable strength”, this strength will be well below the strength required to produce an upset. FAA and industry consensus will be essential to the establishment of this strength limit.

The general AVOSS structure is shown in figure 1. The meteorological subsystem provides current and expected atmospheric state to the predictor subsystem. The predictor subsystem, to be discussed in detail below, utilizes the meteorological data, airport configuration, and aircraft specifications to predict the separation time required for a matrix of aircraft. The sensor subsystem monitors actual wake vortex position and strength to provide feedback to the predictor subsystem and to provide a warning to ATC if a

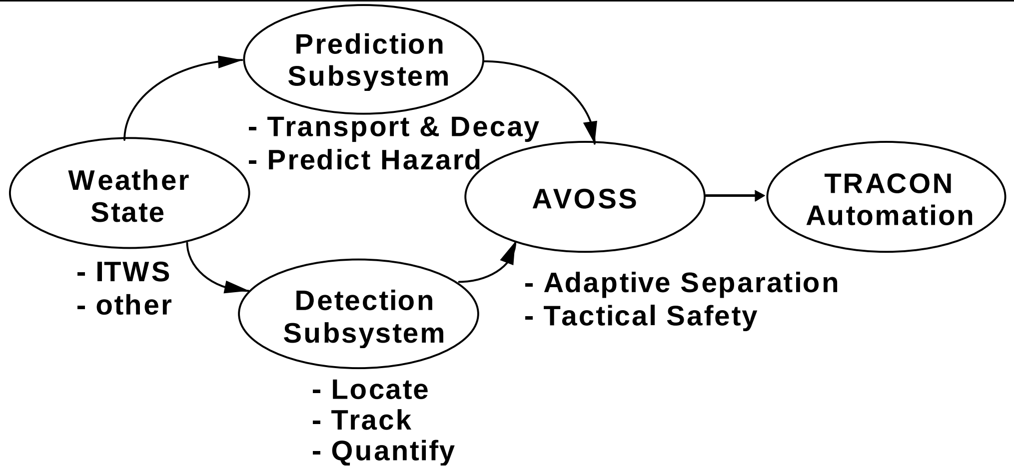

Figure 1 - AVOSS System Concept

spacing is sufficiently in error to require a wave-off.

Ground rules have been established for the development of an AVOSS. The ground rules are:

1. The development effort will be focused on a system that can be approved for operational use. This will require a large degree of robustness, reliance on readily available meteorological and wake sensors, graceful system degradation when sensors or subsystems fail, and cost realism.
2. The safety provided will be equal to or greater than the currently operational system.
3. The AVOSS will not require an increment in pilot skill levels or training requirements.
4. No aircraft structural or systems modifications will be required.
5. The AVOSS will not alter current pilot functions nor change airborne/ground responsibilities.
6. “Vortex-limited” spacing operations may require special ATC or flight procedures compatible with current skill levels. Examples may include executing straight-in Instrument Landing System (ILS) approaches and no intentional operations above glide slope by large or heavy aircraft.

As suggested above, the AVOSS system and ATC interface will require both technical processes and integration with operational practices. The technical aspects include understanding of vortex behavior under various atmospheric conditions, aircraft encounter dynamics, and sensor systems. The operational aspects include runway configuration and usage at a specific airport, the aircraft mix arriving during peak traffic periods, and procedures for vectoring aircraft to the localizer and on departure. The operational factors must be considered in the AVOSS implementation. For example, when all aircraft are constrained to full ILS approaches the precise knowledge of expected aircraft trajectory may allow AVOSS to provide the minimal spacing. When visual approaches are in use the relative uncertainty in aircraft trajectory may require reversion to a default spacing, or a less optimum spacing based only on vortex decay rates.

3.1 Predictor Subsystem Requirements and Architecture

The core of the AVOSS system is the predictor subsystem. This subsystem will accept weather state, a matrix of generating aircraft characteristics that relate to initial wake strength, dimensions of the operational corridor, and a matrix of limiting vortex strength for encounters with following aircraft. This data will be used in real-time to predict the inter-arrival time interval required, by the wake vortex constraint only, for each aircraft pair in the aircraft matrix. When weather conditions predicted to exist 20 to 50 minutes in the future are input, the predictor algorithms will provide the required spacing at that time. Uncertainty in weather state estimation and aircraft parameters must also be considered to provide an appropriately conservative separation prediction. The ATC system will use this data along with other constraints such as runway occupancy time and radar control precision to establish actual aircraft pair spacing. Two prediction horizons are required, an 30 to 60 minute prediction for flow rate metering and a shorter time prediction for final approach and departure control use.

The AVOSS predictor subsystem is being designed to the following requirements. The adequacy of these requirements will be substantiated or changed as required during the development process.

1. The predictor algorithm must provide separation of aircraft from significant vortices along the entire final approach path, from glide slope intercept to the runway. This range is needed due to the differences in atmospheric state and vortex behavior at various altitudes. The required aircraft separation must be predicted for a series of "windows" along the approach path. An approximately logarithmic altitude selection is suggested, with windows spaced to intersect the approach path at altitudes of 25, 50, 100, 200, 400, 800 feet, and the glide slope intercept altitude. The development research may indicate the need for greater or fewer windows.
2. The predictor algorithm must function without detailed knowledge of aircraft approach flap setting, airspeed, or weight. Only aircraft type and whether the operation is a takeoff or a landing will be used. The reason for this requirement is that predicting aircraft speed, weight and configuration 30 minutes in advance would require mandating speeds for the crews and/or a modification to procedures and systems to permit data link of each aircraft operating weight and planned approach configuration to the ATC system. This violates the proposed ground rules. Since the predictor algorithm will not have complete knowledge of aircraft initial wake conditions the predictions provided will be based on the potential range of initial wake conditions. This should not incur a severe penalty on the system, since transport aircraft generally fly similar speeds in high density operations and most operators will use a narrow range of flap settings for a particular operation.
3. The predictor is not being used to predict the actual movement of any particular wake vortex. This would require exact, and unavailable, knowledge of atmospheric state at each spatial and temporal location on the flight path. Instead the predictor will estimate the range of expected wake behavior given the uncertainties in aircraft and atmospheric parameters.
4. The prediction algorithms will operate on a matrix of individual aircraft types, rather than the current 3 or 4 element matrix of aircraft weight categories.
5. The predictor algorithm must accommodate feedback from wake vortex sensors. The sensed wake behavior will be used to ensure system safety through mechanisms such as increasing uncertainty buffers

when the wake behavior deviates from predictions, to revert to a default spacing criteria when a threshold of prediction errors is crossed, or to provide a time critical alert to ATC if a wake persists long enough in the corridor to be a hazard to the following aircraft. The anticipated system will combine weather-based predictions with wake sensor feedback to reduce the level of uncertainty.

6. The predictor algorithm must be based on wake vortex knowledge that is or will be available in the near term, while accommodating increments in this knowledge.
7. The operational domain of the AVOSS will be the approach corridor and the initial climb corridor only. The purpose of AVOSS is not to reduce the number of wake encounters that currently exist in the initial descent and terminal area regions before beginning the approach. Operational procedures alone will be used prior to glide slope intercept for wake avoidance purposes.
8. The predictor algorithms must function in a sufficiently wide range of airport and meteorological conditions to improve airport capacity, but are not required to function in all conditions. Under conditions that do not permit accurate wake vortex predictions the AVOSS may provide existing manual ATC separation criteria as the "default" spacing.
9. The predictor algorithms and AVOSS operation will be tailored to commercial turboprop commuter and turbojet aircraft. The traffic mix at busy hub airports contain very few small aircraft during peak demand, and the airport capacity will be little effected by maintaining current separation standards for those aircraft. The technical risks and development schedule for AVOSS should be greatly enhanced by tailoring sensor development, wake studies, aircraft/wake interaction investigation, and operational procedures to these larger commercial aircraft.

Given the basic predictor algorithm requirements, the structure of the predictor algorithms are suggested. Figure 2 shows the expected structure. The predictor subsystem will ingest meteorological data and projections, an aircraft specifications matrix, and airport configuration data. The meteorological data and projections will not only include the actual parameters of interest, but must also include the confidence intervals on those parameters. By combining meteorological data and airport configuration data AVOSS will establish data such as head wind and cross wind components at each corridor window.

The aircraft matrix will include that data required for each operational aircraft type to predict the initial wake characteristics. The first order wake data expected to be required includes the spacing of the wake cores and total circulation strength. First order estimates of these values can be calculated from aircraft wing span, weight, speed, and air density. Other factors, such as flap setting also affect the initial wake structure but initial examination of wake data, taken from a B727, B757, and B767 during tower flybys at Idaho Falls in 1990 (reference 5) suggest that a close approximation to the initial behavior can be estimated from span, weight, and speed alone. Initial AVOSS predictor algorithm development will proceed under the hypotheses that basic aircraft parameters are adequate for estimating the initial wake characteristics. Further research, some of which is described below, is needed to assess the need for detailed

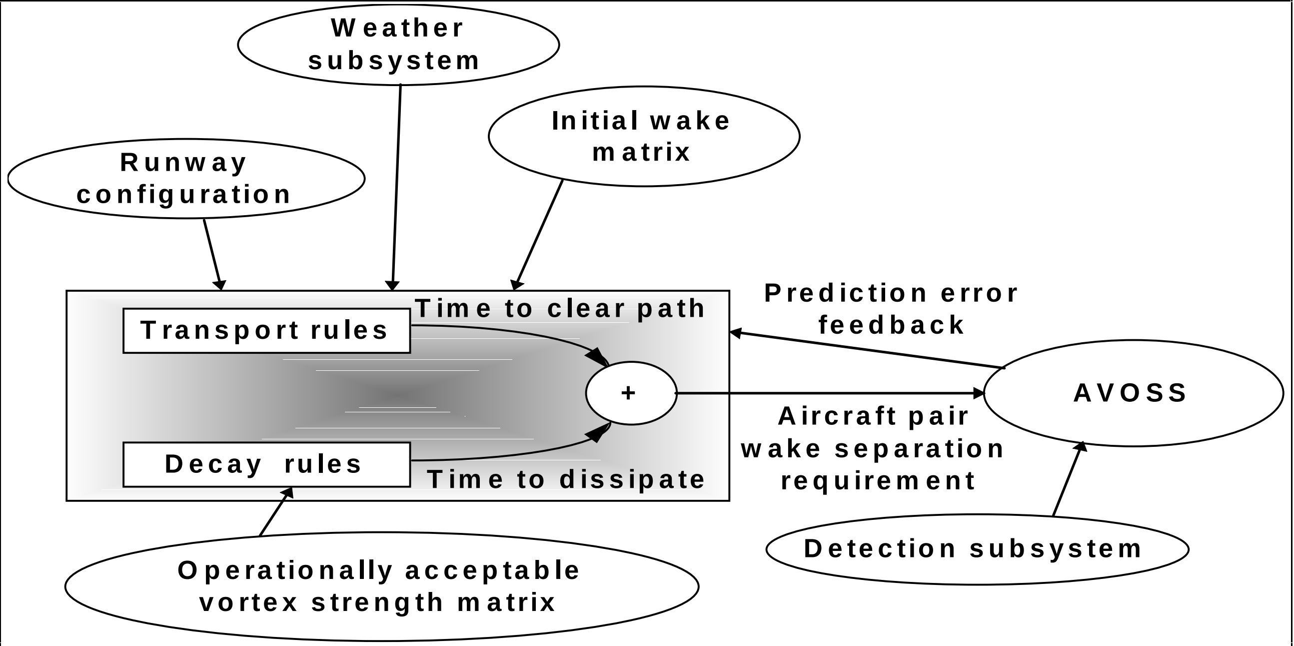

Figure 2- AVOSS Predictor Subsystem

configuration data and more refined initial wake estimates. Under this assumption the speed of the aircraft can be predicted based on a nominal approach speed for the aircraft type and the speeds actually being used on final during the high traffic period. Expected weights of the aircraft can be estimated from statistical distribution of takeoff and landing weights at a particular terminal.

After ingesting the required meteorological and aircraft data, the predictor will perform a set of computations for each window along the approach path. The first set of computations will determine, for each aircraft type, the time required for its vortices to exit the approach corridor. Consistent with the terminology of reference 2, this time is referred to as the "transport time" for the vortex in that window. Second, the predictor will determine the time required for the vortex of each aircraft to decay below a specified acceptable encounter strength for each following aircraft type. This calculation is also performed for each window along the approach and the time is referred to as the "decay time". This calculation requires, in addition to the meteorological and initial wake estimations, an acceptable vortex strength definition against which vortex strength can be compared. Next, the predictor compares the transport time and decay time for each aircraft pair at each window and takes the minimum value as an acceptable aircraft time spacing. This time is referred to as the vortex "residence time" at each window. Finally, the predictor compares each window residence time and chooses the maximum value as the predicted acceptable time spacing for the entire approach. Following application of an appropriate uncertainty buffer the aircraft time separation matrix is provided to the ATC interface.

3.1.1 Approach Corridor Dimensions

The corridor to be protected will be subject to FAA and industry consensus. The AVOSS can be designed to any specified criteria for the approach and departure corridors, and the choice will affect the capacity gains that can be realized. Candidate protected corridor dimensions for the AVOSS system are presented. The rationale for these dimensions are described in greater detail in reference 6. Consideration of previous wake vortex efforts, actual flight technical error observed in service (reference 7), FAA standards for instrument approach obstacle clearance (reference 8) and the limits of the ILS path itself were used to establish the candidate corridor dimensions. For example, reference 2 defined a corridor width of 300 feet (150 feet each side of the runway centerline) from the middle marker to the runway. This was based on statistical data showing 3-s aircraft variation from centerline at the middle marker to be about 50 feet and research showing that a vortex separated laterally from the aircraft by 100 feet "cannot significantly affect aircraft motion".

Equation 1 provides a definition of the candidate AVOSS approach corridor width between the outer and middle marker. The width is a constant 91.5 m (300 feet) from the runway touchdown zone to the middle marker. The middle marker is assumed to be located 859 m (2816 feet) from the runway threshold. In this equation, D represents the distance from the landing runway in units of feet. The width of the AVOSS corridor beyond the middle marker is roughly 6 to 7 standard deviations of the observed traffic in reference 7 and 1/2 to 1/3 the width of the localizer course.

Equation 2 provides a definition of the candidate AVOSS approach corridor floor between the outer and middle marker. The equation provides the distance from the glide slope to the corridor floor and assumes that the glide slope angle is three degrees and the glide slope altitude is 61 m (200 feet) at the middle marker. This provides a very conservative floor that does not reduce separations for vertical wake motion at all inside the middle marker, and requires the vortex to be 61 to 122 m (200 to 400 feet) below glide slope at all other locations. This distance is always greater than a full scale deviation from the glide slope guidance. Equation 3 provides a second option of the corridor floor. The floor is still at ground level from the runway to the middle marker, but rises to 21.3 m (70 feet) below glide slope at the middle marker and increases to 61 m (200 feet) below glide slope at the outer marker. Although 61 m is only ½ scale glide slope guidance deviation at the outer marker, this represents considerable aircraft altitude error at glide slope intercept. At the middle marker this option places the AVOSS floor 150 percent deviation below the glide slope guidance. These and other corridor floor options will be tested during AVOSS development and final industry acceptance will involve a safety assessment and consensus process.

$$Width = 91.4 + 0.02539(D - 859) \qquad (1)$$

$$Floor1 = 61 + 0.00725(D - 859) \qquad (2)$$

$$Floor2 = 21.3 + 0.00471(D - 859) \qquad (3)$$

Table 1 summarizes the corridor dimensions at several approach windows. The "ILS Limit" column represents full scale deviation from the localizer guidance assuming a runway length of 2439 m (8000 feet), or full scale glide slope deviation. The "AVOSS" columns are the recommended AVOSS corridor width or floor dimensions. Table 1 also gives the time required for a vortex to transport vertically and laterally outside the corridor at a sample translation speed. An initial vortex pair spacing of 30.5 m (100 feet) is assumed for computing the lateral transport time. The table is for illustration only and does not include many factors that will be modeled in AVOSS, such as changes in vortex drift rate at various altitudes and assumed flight technical error on the part of the generating aircraft.

Position	ILS Limit, Width	AVOSS Corridor Width	ILS Limit, Below Glide Slope	AVOSS Corridor Floor, Option 1	AVOSS Corridor Floor, Option 2	Lateral Transport Time at 5.1 m/s (10 knot) drift rate	Vertical Transport Time at 1 m/s (200 foot/min) sink rate, Floor Option 2
Runway Threshold	213m (700 ft)	91.5 m (300 ft)	3.7 m (12 ft)	15.9 m (52 ft)	15.9 m	12 sec	16 sec
Middle Marker	283 m (929 ft)	91.5 m	14.3 m (47 ft)	61 m (200 ft)	21.3 m (70 ft)	12	21
3.7 km (2 nm) from runway	515 m (1689 ft)	164 m (537 ft)	49.1 m (161 ft)	81.6 m (267 ft)	34.7 m (114 ft)	19	35
9.27 km (5 nm) from runway	967.7m (3174 ft)	304.9 m (1000 ft)	117 m (385 ft)	122 m 400 ft	61 m (200 ft)	33	61

Table 1 - AVOSS Corridor Dimensions and Example Transport Times

The takeoff case presents additional challenges for the corridor concept in that the altitude profile of departing aircraft vary widely, as opposed to the precise altitude profile of an aircraft during an instrument landing system (ILS) approach. This factor may be accommodated in several ways. One is to establish a takeoff corridor to accommodate expected variations in aircraft liftoff point, climb gradient, and departure vectors. This would make the takeoff spacing criteria aircraft pair specific since a range of expected climb gradients can be predicted for each aircraft type. Another approach is to ignore the sinking motion of the vortices and depend on lateral transport only. Yet a third method is to ignore vortex transport and depend only on the decay predictions. Evaluation of these techniques will be made during AVOSS design.

3.2 Weather Subsystem Requirements

While the core of the AVOSS system is the predictor subsystem, the predictions and system effectiveness will only be as good as the nowcast, or near-term weather prediction, provided by the meteorological subsystem. Initial requirements for this subsystem can be derived from the AVOSS system concept and previous wake studies. Separation criteria predictions are required as aircraft are metered into the terminal area, requiring 20 to 50 minute weather state predictions. The meteorological subsystem information will have a statistical element. There will be no attempt to predict the actual wind that any single vortex would experience at a later time. Instead the mean and standard deviation of the winds over a suitable interval will be used by the predictor algorithm to estimate the range of expected wake transport and decay intervals. The weather system will also be required to advise AVOSS when weather phenomena exists that make accurate wind predictions impractical, such as convective cell activity, or that a discrete event that will affect the weather state, such as cold fronts or gust fronts, will arrive. Finally, predictable changes in the planetary boundary layer occur in the morning and evening hours which affect stratification and the low altitude wind structure. Due to the need to adjust traffic flow in advance of the weather change, some prediction capability for this effect must be included. This is particularly critical in the evening when the formation of a temperature inversion may reduce surface winds and tend to increase wake separation requirements.

Some of the required weather capabilities can be provided by the Integrated Terminal Weather System (ITWS) program (reference 9) under development by the FAA and Massachusetts Institute of Technology (MIT) Lincoln Laboratory. Coordination with that program has begun to provide weather information to AVOSS. Additional products, such as nowcast wind and lapse rate products will be developed.

3.3 Wake Vortex Sensor Subsystem Requirements

Although various capability levels of AVOSS may be implemented, some of which would not require a wake vortex sensing subsystem, the AVOSS concept includes a wake sensor. As is the case for the weather subsystem, only general sensor requirements will be stated at this time. Detailed sensor requirements will be defined during the course of the research and development.

To be operationally useful to the AVOSS system the sensor must be capable of detecting, tracking, and quantifying the strength of wakes. Operation must be highly reliable and automated. The tracking domain should cover at least the protected corridor. Atmospheric stratification could potentially lead to accurate predictions at one altitude and large prediction errors at nearby altitudes. The volumetric domain of a wake sensor will be defined based on the criticality of prediction errors at each location and the confidence of predictions. Operational evidence (reference 10) and vortex sink characteristics suggest that the most critical domain for protection will be at relatively low altitudes close to the airport environment, perhaps from the runway to a distance of about 3.7 km (2 nm) from the runway.

Figure 3 shows a concept for the use of position and strength feedback. As time of day progresses the predictor algorithm will produce an estimate of transport time and decay time, and the confidence intervals for these values, at various windows on the approach path. The sensor system will provide actual transport and decay times to the predictor so that the buffer and values provided to ATC can be adjusted whenever the actual data deviates from the predicted. With appropriate buffer size choices this adjustment will occur before any aircraft are exposed to a potential hazard. In the sudden event of a vortex persisting much longer than expected a message can be provided to ATC to command a go-around procedure for the following aircraft. Other uses of the sensor data would be to allow AVOSS to default to standard separation criteria when specified prediction errors or variations in successive vortices develop.

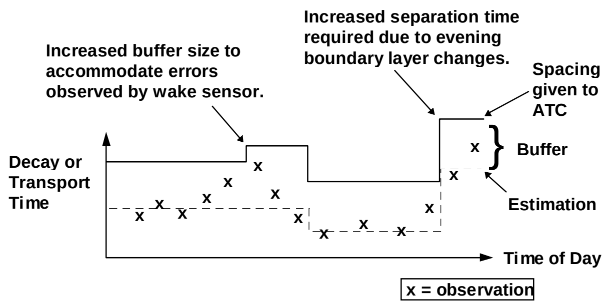

Figure 3 - Wake Vortex Sensor Feedback.

The wake vortex sensor subsystem will be required to operate both in visual and in instrument meteorological conditions appropriate to the approach minima at a particular airport. The sensor or sensors will not be required to operate in conditions where accurate wake predictions are not likely to be achieved or where the wake is not likely to be the primary constraint in airport operations. Examples of these conditions include convective storm activity, extremely strong winds, heavy snow or freezing rain. The default vortex spacing criteria may be applied during these periods.

3.4 AVOSS Operational Integration

The AVOSS concept described above will be validated for operational readiness and integrated into automated and manual ATC systems. This will require interfaces beyond the minimum required for experimental testing. The interfaces will include those required for matching the AVOSS output to the ATC system expectations and for operational safety and redundancy. The rate at which separation criteria updates are provided to ATC (i.e. once ever 30 minutes or once every 3 hours), the maximum changes permitted between updates (i.e. 10 seconds, 30 seconds, or no limit), the resolution provided (i.e., 5, 10, or 15 seconds) can all be refined for controller and ATC automation acceptance. Due to the statistical nature of the wake predictions and increasing uncertainty in atmospheric state as forecast time increases, frequent updates could increase the maximum potential acceptance rate of the runway. Too frequent updates would also have negative impact on controller workload and possibly create system problems as the traffic flow adjustments ripple back into the TRACON and center airspace.

The size of the separation matrix and translation into separation distance will also be adjusted for the ATC system in use. Internally the AVOSS will operate with individual aircraft pair types, such as B-727 or DC-10, perhaps with grouping of the small aircraft category. A highly automated ATC system may be capable of directly using this matrix for highly efficient aircraft scheduling and sequencing. A less capable system, or a manual ATC environment, may require that the aircraft be grouped into three or four major groups for actual use. The AVOSS could provide output in this grouped format. All AVOSS provided wake constraints will be time based and indicate the minimum separation time between airplane pairs anywhere on the approach or initial departure path. Planned ATC automation tools can directly use this time matrix for separation, although controller interface issues would need to be addressed. A manual system would require output in a distance format for direct application by the controllers. Operational procedures and aircraft speed at various positions along the approach path must be considered in this translation of time into distance.

3.5 AVOSS System Tradeoffs

The general AVOSS concepts outlined above cover a wide range of possible system implementations, ranging from a simple system that advises a manual ATC system when a specific reduced separation matrix can be used to a multiple sensor system interfaced to an automated ATC system to optimize spacing between individual aircraft pairs. Figure 4 suggests four possible wake system implementations that vary in cost and capability. At one extreme (upper row of figure 4) a static separation matrix determined from a large matrix of aircraft, potentially with one matrix element per aircraft type, can be collapsed into a 3 to 5 category system for manual ATC use. NASA Langley has taken this approach in response to a FAA request for a scientific basis for revised separation standards and aircraft classifications. No dedicated weather or wake sensors would be required for this system, and this is considered to be the "default" AVOSS spacing when weather conditions are changing too rapidly for accurate dynamical wake predictions. A fully automated ATC system could use the full separation matrix for more efficient operations. The lower row in figure 4 represents dynamical spacing interfaced to either a manual or an automated ATC system. The manual ATC system would employ a relatively simple procedure that provides for

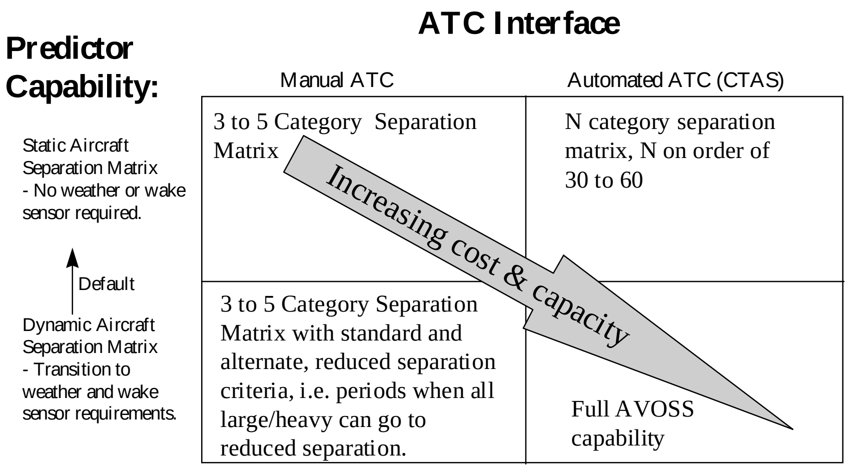

Figure 4 - Wake Vortex System and ATC Interface Capability Levels

a fixed, reduced separation matrix under certain weather conditions. An example of this procedure would be to allow less than current standard spacing between all large and heavy aircraft pairs when the atmospheric conditions permit. Dynamical separation standards require a dedicated weather subsystem and, for maximum capacity, a dedicated wake sensor subsystem. The level of AVOSS complexity to be applied at a given airport will be a function of the capability of the ATC system at that facility and tradeoff studies that show the capacity gain expected with various AVOSS levels.

4. Current Research Activities

The NASA is addressing the development and demonstration of a prototype AVOSS through a combination of analytical, wind tunnel, field and flight tests. Critical activities underway include the following.

4.1 Numeric Wake Vortex Modeling

The Terminal Area Simulation System (TASS) large-eddy simulation code of reference 11, proven highly effective in the successfully completed NASA/FAA wind shear program, is being modified to model the effect of various atmospheric conditions on the behavior of aircraft vortices. Modifications include the required wake initialization routines, regridding and grid nesting, and post-processing software to diagnose vortex core location and strength. A related effort is developing the ability to model the evolution of the planetary boundary layer (PBL) with changes in sun angle, cloud cover, and terrain (reference 12). Both 2-dimensional and full 3-dimensional modeling of wake behavior are being conducted. Emphasis will be placed on validation of the model behavior against observed wake data prior to using TASS for AVOSS predictor algorithm development. Following validation of TASS, parametric studies will be performed to quantify the effects of stratification, wind speed and vertical shear, and various turbulent scale lengths on the transport and decay of the vortices from various sized aircraft. Once TASS is validated within a given envelope of weather and terrain conditions, these parametric studies should provide more information than could be feasibly gathered from field experiments where multiple factors are usually changing with each observed wake and a limited subset of possible atmospheric conditions can be expected to occur. TASS results will be useful not only for predictor algorithm development, but also as numeric simulation data for developers of wake vortex sensors.

4.2 Field Measurements of Aircraft Wake Vortices

Crucial to the validation of TASS, prediction algorithm development, and full system testing and demonstration is a field effort sponsored by NASA Langley and conducted by the MIT Lincoln Laboratory (reference 13 & 14). This field effort serves multiple purposes:

1. Provide a comprehensive data collection suite to gather meteorological, aircraft, and wake data at a major airport.
2. Provide the above data for validation of wake models and direct use by predictor algorithm developers.
3. Establish the required field facilities and system interfaces for predictor algorithm and AVOSS prototype testing and demonstration.

The Lincoln effort has established a facility at the Memphis International Airport that provides the most complete wake vortex data facility established to date in an operational setting. Aircraft wake vortex data was collected with a 10.6 micron continuous wave laser mounted in a mobile van. The van could be driven to various airport locations as runway operations changed or to collect data at different airplane crossing altitudes. The lidar was implemented with real-time wake vortex identification and tracking algorithms to optimize data quality (reference 15).

A 150 foot tower measured wind direction, temperature, and humidity at five elevations. Solar flux, soil temperature, and soil moisture are measured for correlation with the atmospheric boundary layer characteristics and validation of PBL models. A radar profiler with a radio acoustic sounding system (RASS) provided winds aloft from approximately 100 meters above ground level (AGL) to about 2500 meters AGL with a vertical resolution of 100 meters and a 25 minute averaging period. The RASS provided temperature up to about 1000 meters AGL at a 5 minute averaging period. Also employed was an acoustic sodar that provided 10-minute average winds with a vertical resolution of 20 meters from an altitude of 20 meters up to about 300 meters AGL. Dedicated rawinsonde balloon launches were made from the airport during the tests. Lincoln was responsible for total system integration but the National Atmospheric and Oceanic Administration and the Volpe National Transportation Systems Center assisted with radar profiler and sodar installations. NASA Langley deployed an OV-10A aircraft to Memphis during measurement periods to collect meteorological data over spatially diverse regions to augment the fixed meteorological site measurements. Wind, turbulence, pressure, temperature, and dew point measures were taken by the OV-10.

Lincoln also collected extensive aircraft data for most aircraft being observed through agreements with the major aircraft operators at Memphis. The operators provided the actual approach weight of each aircraft observed and information on flight procedures required to estimate flap setting from airspeed and weight. Air Traffic Control beacon data provided the altitude, aircraft type, and ground speed of each aircraft crossing the laser facility. Lincoln uses this data and the meteorological data to estimate the aircraft airspeed and correlate individual arrivals to the operator-provided weight data. This processing provides detailed information on the aircraft generating each observed wake.

The initial Memphis deployment occurred between November 15 and December 14, 1994. During this deployment all systems were operated together for the first time and the lidar wake tracking software was refined and brought to an operational status by Lincoln. Approximately 600 aircraft wakes were observed, with about 100 observed with the lidar tracking algorithms functioning. A second deployment was conducted in August of 1995 (reference 14). High quality wake vortex data was taken in a wide domain of initial wake altitudes and atmospheric conditions required for TASS validation efforts and AVOSS development. Three altitude bands were selected, out-of-ground (OGE) effect to validate previous models of vortex behavior in that domain (reference 16) and well as the TASS model, near-ground-effect (NGE) to capture vortices generated out of ground effect and quickly descending into surface interaction, and in-ground-effect (IGE) to capture vortices generated at altitudes less than ½ wing span above ground. These altitude bands were chosen due to the requirement to validate vortex models at all altitude regimes for an operational system, limitations in previous vortex transport models in ground effect, and a relative lack of quality wake and meteorological data collected at low altitudes. During the 1995 deployment over 600 wakes were observed by the Lincoln lidar, with about 400 cases surviving data quality checks. Data was collected at varied hours of the day from early morning to midnight, in stable and unstable atmospheric conditions, and in both calm and light to moderate ambient wind shear conditions. Numerous high interest wake tracks were collected in conditions that caused the wakes to either sink vertically through the corridor with little drift, or to stall near or on the runway centerline at low altitudes. Stalled vortices lasting over a minute at the runway threshold were observed, as were vortices that were formed in ground effect then gained in altitude. These are critical environments in which to validate the Langley numeric models and in which to understand and

Local Time	Cloudy, Windy	Cloudy, Calm	Clear, Windy	Clear, Calm
6:00 AM - 8:30 AM			10 OGE	17 OGE 17 NGE 11 IGE
11:00 AM - 5:00 PM		35 NGE	8 IGE	38 OGE 22 NGE 8 IGE
5:00 PM - 7:30 PM		7 OGE 36 NGE	14 OGE	33 OGE 12 NGE
10:30 PM - 12:00 AM			16 OGE 1 NGE	56 OGE 24 IGE
12:00 AM - 1:00 AM			19 OGE	71 OGE 6 IGE

TABLE 2 - Approximate List of 1995 Memphis Wake Vortex Measurements
Cloudy indicates more than 5/10 sky cover. Windy indicates more than 5 m/s (10 knots) surface wind or significant vertical shear. OGE = Out-of-Ground Effect, NGE = Near-Ground-Effect, IGE = In-Ground-Effect.

quantitatively predict vortex behavior. Table 2 represents a list of wake cases collected by time of day, wind condition, and initial wake altitude region. This table represents field notes collected by Langley personnel in August and may have slightly different numbers than the final data set, which has been delivered but not fully analyzed at this time. Analysis and TASS validation is continuing at this time and future deployments will be conducted as required to develop and test AVOSS subsystems and the integrated AVOSS system.

4.3 Operationally Acceptable Vortex Strength Definition Requirements

The transport rule component of the AVOSS system is not dependent on knowledge about wake vortex interaction with the following aircraft. The decay rule component of the predictor, however, must predict when the wake of any given aircraft has decayed to an operationally acceptable strength for an encounter by any given following aircraft. Work is currently ongoing at NASA Langley and Ames Research centers, using combinations of analytical, wind tunnel, and flight test techniques to develop and validate tools that predict the dynamics of aircraft wake encounters (reference 17). Industry and FAA Flight Standards involvement will also be required to provide the appropriate consensus on the results. The output of this activity will be a sensor-observable wake vortex “strength definition” and acceptable encounter values for various aircraft types in the commercial fleet.

4.4 Wake Vortex Sensors

Efforts are in progress at Langley to develop and demonstrate ground based sensor technologies to support the AVOSS concept. Both radar and laser technologies are being examined for operational feasibility. A technology selection is scheduled to take place in 1996. The selected technology will be further developed and fielded as early as 1997 for field tests and initial AVOSS integration. The goal of the sensor development effort is to provide the wake sensor subsystem requirement for an AVOSS prototype demonstration in the 1999/2000 time frame.

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