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Airport Capacity Improvement**

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DESIGN OF AN AIRCRAFT VORTEX SPACING SYSTEM FOR AIRPORT CAPACITY IMPROVEMENT

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Abstract

The National Aeronautics and Space Administration (NASA) is addressing airport capacity enhancements through the Terminal Area Productivity (TAP) program. Within TAP, the Reduced Spacing Operations element at the NASA Langley Research Center is developing an Aircraft VORtex Spacing System (AVOSS). AVOSS will integrate the output of several systems to produce weather dependent, dynamic wake vortex spacing criteria. These systems provide current and predicted weather conditions, models of wake vortex transport and decay in these weather conditions, and real-time feedback of wake vortex behavior from sensors. The goal of the NASA program is to provide the research and development to demonstrate an engineering model AVOSS, in real-time operation, at a major airport. A wake vortex system test facility was established at the Dallas-Fort Worth International Airport (DFW) in 1997 and tested in 1998. Results from operation of the initial AVOSS system, plus advances in wake vortex prediction and near-term weather forecast models, "nowcast", have been integrated into a second-generation system. This AVOSS version is undergoing final checkout in preparation for a system demonstration in 2000. This paper describes the revised AVOSS system architecture, subsystem enhancements, and initial results with AVOSS version 2 from a deployment at DFW in the fall of 1999.

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Abbreviations

ATC	Air Traffic Control
AVOSS	Aircraft VORtex Spacing System
CTAS	Center Tracon Automation System
CW	Continuous Wave
DFW	Dallas-Fort Worth International Airport
EDR	Eddy Dissipation Rate
FAA	Federal Aviation Administration
ITWS	Integrated Terminal Weather System
MIA	Miami International Airport
MIT	Massachusetts Institute of Technology
NCEP	National Center for Environmental Prediction
NCSU	North Carolina State University
RASS	Radio Acoustic Sounding System
SEA	Seattle International Airport
SFO	San Francisco International Airport
SODAR	SOund Detection and Ranging
TAP	Terminal Area Productivity
TAPPS	Terminal Area Planetary boundary layer Prediction System
TDWR	Terminal Doppler Weather Radar
TKE	Turbulent Kinetic Energy

AVOSS Overview

The present NASA development effort is funded by the Terminal Area Productivity (TAP) program. The goal of the TAP program is to develop technologies required to allow air traffic levels during instrument operations to approach or equal levels presently achievable only during visual operations. A number of factors lead to a reduction in airport capacity in those weather conditions that preclude the use of visual approach procedures. These factors include a reduction in the number of available runways and the longitudinal wake turbulence separation constraints used by Air Traffic Control (ATC). These wake constraints (table 1) evolved over time to prevent wake encounters in weather conditions most conducive to long-lived wakes, and are unnecessarily large in weather domains that lead

to rapid wake decay or drift away from the flight path. In table 1, small aircraft are those with maximum takeoff weights less than 18,598 kg (41,000 pounds), large are those aircraft between 18,598 and 115,668 kg (41,000 and 255,000 pounds) and heavy are over 115,668 kg (255,000 pounds). During visual conditions the separation responsibility is passed to the pilots, who use their knowledge of weather conditions, lead aircraft type, and lead aircraft flight path to effectively self-separate from wake encounters. In many situations the resulting spacing is less than would be required in instrument operations. The AVOSS is designed to structure this process and minimize the difference in aircraft spacing between visual and instrument operations.

Following Aircraft	Leading (Generating) Aircraft			
	Small	Large	B757	Heavy
Small	3*	4	5	6
Large	3*	3*	4	5
Heavy	3*	3*	4	4

* 2.5 NM for < 50 second runway occupancy time
Table 1 – FAA spacing criteria at runway threshold (NM).

The basic AVOSS architecture is unchanged from previous descriptions^{1,2,3,4} and shown in figure 1. This architecture supports the basic functional requirement of calculating the separation required to prevent aircraft encounters with wake vortices, given the current and expected meteorological parameters. The meteorological subsystem uses sensors and modeling techniques to describe the vertical profiles of the wind, turbulence, and temperature from the surface to the glide slope intercept altitude. A statistical description of relevant variables is provided to minimize spatial variations and permit prediction of the worst-case wake behavior that may occur during an operational time period. The wake predictor uses this weather profile and descriptions of the aircraft fleet at the airport to predict wake drift rate, sink rate, and decay rate for each modeled aircraft type. The wake behavior is compared to pre-defined safety corridor dimensions and a wake demise definition to derive required aircraft separation intervals. Wake vortex sensors are used to verify that the wakes are behaving within the range of predicted values.

The AVOSS development is focused on a year 2000 demonstration, in a relevant airport environment, of a real-time wake vortex spacing system. The system demonstration will include all systems shown in figure 1, up to but not including

the ATC interface. The system integration element will link all subsystems for automated system operation. Actual aircraft spacing reductions will not be made as an element of the demonstration. The objective of the development effort and demonstration is to bring the maturity levels of all systems to the point that the concept can be proven in an operational environment, with all variables present, and that the system is ready for handoff to the FAA and industry for operational test bed development. The system to be demonstrated will emphasize the scientific validity of the weather profile measurements and wake predictions, and not the final engineering required for prototype operational equipment. As such, certain features such as system self-test and ATC interfaces may be absent or implemented only to the degree required for demonstration of the system concept.

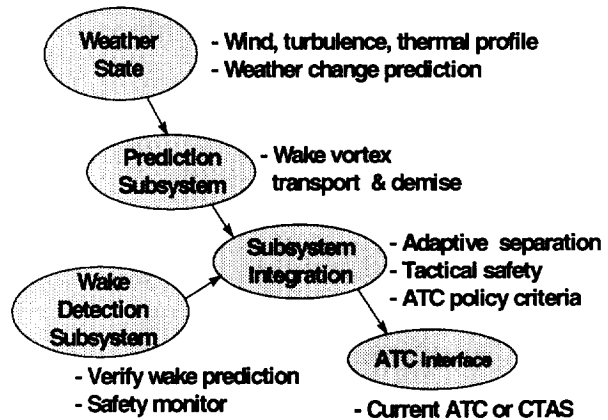


Figure 1 - AVOSS Architecture

A detailed description of AVOSS Version 1 and preliminary performance data for that system was provided by reference 4 and is summarized below. Following this summary an update to Version 1 performance is presented and the enhancements made to produce Version 2 AVOSS are described.

AVOSS Version 1 Review and Performance Update

The TAP program activities are currently focused on the application of AVOSS to approaches to a single runway. The criteria for single runway in-trail spacing are based on the time required for the wakes from each aircraft to sink or drift out of a safety corridor, or decay to demise. The safety corridor consists of lateral limits, centered on the localizer, and a floor below the glide slope. Once a

wake has drifted beyond these lateral limits or descended below the floor, it is no longer considered a potential hazard to following aircraft. Wake behavior is calculated at a set of locations along the approach, referred to as "windows", from the glide slope intercept altitude to the runway threshold. Each window models the wake at a different location and altitude on the approach. Reference 4 describes the default window locations on the approach, as well as the equations for determining the safety corridor width and floor altitude at each window. The effect of changing spacing on final due to different aircraft speeds is considered and a top-of-approach spacing value, referred to as the "approach spacing" is provided. The approach spacing value will meet all wake constraints as well as runway occupancy time requirements if applied at the glide slope intercept location. Currently the output is in nautical miles for aircraft weight category pairs (i.e., small aircraft following a heavy aircraft), although time-based separation behind each aircraft type (i.e., Boeing 727) is used internally and can be provided to appropriate ATC systems.

The safety corridor floor is at ground level from the runway to a transition point, where the glide slope is about 61 meters (200 ft) above ground. In this region no spacing reduction will be provided due to wake sinking motion. The floor then makes a step increase in height to 21.3 meters (70 feet) below glide slope at the transition point and increases to 70 meters (230 feet) below flight path at the glide slope intercept. The lateral width of the corridor is 91.5 meters (300 feet) between the runway and the transition point, widening to 352 meters (1155 feet) at the glide slope intercept point.

The actual wake spacing calculations begin by computing the wake trajectory and decay time history for each aircraft in the data base at each approach window. A weather profile is read which describes the needed meteorological statistics. The cross wind variable is described in terms of the mean component and the turbulent component (variance) for a 30-minute period. The cross-wind variance determines the uncertainty in wake drift rate for the specified time period. Hence, the potential range of wake residence times for a useful time period is computed. Conceptually, if the cross wind is being influenced by thermals or other phenomena that create gusts and lulls in the wind, the separation provided will be safe even during one of the lulls in the wind.

Two significant assumptions are made in the current implementation, regarding the process of using weather statistics to generate wake predictions. One, that the region about the airport is reasonably homogeneous geographically, that is, no nearby mountains or other features exist to abruptly change the weather across distance. This homogeneity allows the wind statistics from the vertical column estimate of wind to be used to represent the wind along the approach. At a distance from the runway of 4 km, where the altitude of the aircraft is about 220 meters, the wind statistics are extracted from the 220-meter level of the column estimate. Second, that the wind statistics do not change dramatically from one 30-minute period to the next. Rapid but short-duration changes of wind, as occur in thermal passages, will result in high variability over small averaging periods but relatively stable statistics at 30 to 60 minute periods. While it is not reasonable to expect the instantaneous wind at 200 meters above the airport to reflect the instantaneous wind 4 km away, the long-period statistics taken at these two locations can be expected to be similar⁵. A 30-minute period was chosen as an initial compromise between the long-period statistics needed for spatial extrapolation of the data and for system stability, and the desire to operate at a short period to better compare wake predictions with observations and extract optimal spacing reduction performance. The system includes detection of discrete events, such as gust fronts, that invalidate this assumption, and provides an automated means of disabling spacing reduction in those cases.

The wake predictor provides a time history of the wake motion and decay, which is passed to an algorithm that compares the trajectory to the safety corridor limits to provide wake residence time values. Three residence time components are calculated, a lateral residence time, a vertical residence time, and a demise time. These describe the time required for the wake to exit the lateral corridor limit, the vertical corridor limit, or to decay below the demise value, respectively. The three times are independently computed for the port and starboard wake of each aircraft, producing six values. Values that cannot be determined are filled with the value "9999", which is used throughout the system to indicate invalid sensor data or wake residence time. This value will always be provided for vertical transport time near the threshold, since the wakes can never sink below ground level. The value 9999 is also used if the predictor algorithm does not return a valid

wake time history, the time history terminates while the wake is still in the corridor above the demise strength, or uncertainties in meteorological parameters do not allow reliable wake prediction. The six residence time components (lateral, vertical, and demise of two wakes) are combined as follows to produce a single residence time for the aircraft.

$$\tau = \text{Max}(\text{Min}(\text{LatPort}, \text{VertPort}, \text{DemisePort}), \text{Min}(\text{LatStar}, \text{VertStar}, \text{DemiseStar})) \quad (1)$$

Where Lat, Vert, and Demise refer to lateral and vertical residence time and demise time, respectively and Port and Star refer to the port and starboard wake, respectively. For example, using a lateral residence time of 65 seconds, a vertical residence time of 9999, and a demise time of 70 seconds will produce a wake residence time of 65 seconds. A port vortex residence time of 65 seconds combined with a starboard residence time of 9999 would produce a time of 9999 for that aircraft, which would prevent spacing reduction.

These calculations are repeated for each aircraft type at each window. The time-based spacing for each aircraft pair at each window is combined with the expected groundspeed of each aircraft and the distance from the window to the top-of-approach to determine the time-based separation required at the glide slope intercept. The worst-case time spacing at glide slope intercept, considering all approach window requirements, is then converted to a distance-based approach spacing for each aircraft weight category pair. Greater detail of this process, as well as methods of handling special cases, are provided in reference 4. The reason for computing an approach spacing that considers all approach windows is two-fold. First, it provides a system-level method to assess the sensitivity of real-world spacing changes to advancements in the state of the art in weather profiling or wake modeling. Changes in wake behavior at one altitude may or may not have a significant effect on approach spacing, depending on whether that window was limiting spacing. Second, the approach spacing output can provide guidance to ATC on the actual spacing required as aircraft intercept the localizer on approach.

Update Version 1 Performance

A preliminary investigation⁴ of AVOSS performance was presented in 1999. That investigation made use of meteorological data collected by the wake vortex systems at the

Dallas-Fort Worth International Airport (DFW) from January 23 to May 31 of 1998. Only the data between the hours of 8:00 AM to 10:00 PM local time and for weather conditions conducive to instrument approach procedures were included. The airport was considered to be using instrument procedures anytime the ceiling was below 1524 meters (5000 feet) or the visibility was below 8 km (5 miles). That study found the spacing behind heavy generator aircraft to be reduced, on the average, by 2.6 km (1.4 NM) and reduced behind B-757 generators by 2.2 km (1.2 NM). Little reduction behind large generators is possible since current criteria only apply wake constraints to small aircraft following the large aircraft. A first-order approximation to the maximum runway arrival rate showed a 9 percent average increase possible with AVOSS-provided spacing criteria.

That analysis has been extended to include a year of data at the DFW airport. The resulting data set extends from January 23, 1998 to January 31, 1999, with the exception of the month of August. August data was not available due to weather sensor failures. Data considered unreliable by a project meteorologist was removed. The remaining data represented 283 days of the 374-day period, or 76 percent availability. Time periods were selected from this set that represented 8:00 AM to 10:00 PM local time and the same ceiling and visibility criteria noted above. In addition to a traffic mix representative of DFW, a mix representing Miami (MIA) and Seattle (SEA) were used to compute average spacing reductions and throughput changes. The DFW mix was 25/60/10/5 percent small/large/B757/heavy aircraft, respectively. The MIA mix was 7/66/12/15 and the SEA mix was 10/75/7/8 for the same categories.

The one-year analysis was consistent with the partial-year results, but with somewhat reduced performance. The throughput increase dropped from 9% with partial year results to 5.4% with the full year. This performance loss was mostly due to an increase in average spacing for small aircraft following large aircraft from 6.58 km (3.55 NM) in the initial study to 7.37 km (3.98 NM) in the full year study. With large fractions of large and small aircraft in the assumed traffic mix on a given runway, this single pair has a strong influence on the overall results. Table 2 shows the average spacing reduction behind B757 and heavy aircraft at each traffic mix, and the resulting throughput increase. Spacing reductions behind large aircraft are negligible and are not shown.

The increase in potential landing rate is moderate at SEA (6.4%) due to a high fraction of large aircraft. The MIA throughput increase (12.4%) is greatest due to a high fraction of heavy and B757 aircraft. A more detailed description of this study, as well as comparisons of data from a wake vortex detection wind line to AVOSS predictions for the same period will be the subject of future reporting.

AVOSS Version 2 System Design

Lessons learned from the operation of AVOSS Version 1, as well as advances in wake prediction and weather modeling, were integrated in a Version 2 system. Particular needs that were identified and the resulting system changes included the following.

Weather Data Quality

A number of factors can affect the quality of the estimates of the vertical profiles of wind, turbulence, and temperature. The wind profile statistics are developed^{6,7,8} through the fusion of data from several sounding sensors, nearby Terminal Doppler Weather Radars (TDWR), and a meteorological tower. The sounding sensors, a radar profiler and two acoustic Sounding and Ranging (SODAR) sensors can be contaminated at times by high ambient noise environments or by poor return signals due to unusually dry, clean air. The resulting poor signal to noise ratio can produce erroneous or missing measurements. Likewise the TDWR radar derives a wind profile using a 360-degree scan, which encompasses a large geographic area. Frontal boundaries in that region can contaminate airport wind estimates, and a lack of atmospheric scatterers can reduce the availability of data. In general, data was usually available in the lower 200 to 300 meters but sometimes unreliable above 300 meters. Since the AVOSS wake predictor cannot be run without weather inputs, the Version 1 system used all available data and interpolated or extrapolated as required to produce spacing estimates. Analysis of results then required a labor-intensive manual quality screening of the raw sensor data and resulting profile for each day. A second problem with the Version 1 weather algorithms was a lack of accurate thermal profiling above the ground and the use of turbulence data near the top of the meteorological tower (40 meters) at all altitudes for estimating wake demise.

Version 2 includes several advancements to the weather subsystem. A process was developed for

fusing the temperature measurements along the 45-meter meteorological tower with the temperature aloft data provided by a Radio Acoustic Sounding System (RASS). The result is a vertical profile of temperature. Another process makes use of eddy-dissipation rate (EDR) data provided at the 5 and 40 meter levels of the meteorological tower, along with wind and thermal data at the 5 and 10 meter levels, to estimate the planetary boundary layer stability type and degree of mixing, and provide an estimated vertical profile of EDR. The wind profile process, developed by MIT Lincoln Laboratory, has been improved to better screen the quality of arriving data and to minimize the impact of sensor errors on the wind variance calculations. The result of the weather processes is a set of three files for each 30-minute period. Each file describes the vertical profile of wind, turbulence, or thermal stratification from the surface to at least 600 meters above ground. The altitude value of 600 meters is significant since this is the approximate glide slope intercept altitude of a typical instrument landing system.

All three weather processes now include an automated quality screening of data. The quality process determines the number of raw sensor data points failing basic screening criteria or missing within separate altitude regions. A set of quality flags is then provided within the weather profile to indicate the health of individual sensors and the confidence of the resulting profile. AVOSS uses this quality data internally to prevent spacing reduction using low-confidence profiles. For example, the wind profile is considered useful only if more than 50 percent of the altitudes levels between the surface and 600 meters are based on actual sensor data (not interpolated across missing data), at least 40 percent of both SODAR's and the radar profiler data points are valid in that altitude range, and no gust front or convective storms are within 6 NM of the airport. The DFW Integrated Terminal Weather System (ITWS) test bed provides the latter product. When the wind profile is not useful the AVOSS will not use lateral wake drift to reduce spacing, but may still use decay or wake sinking motion to reduce spacing. These criteria are considered a first step at applying automated weather quality processes and will require refinement and verification during test bed operation.

Nowcast

Version 2 is the first wake vortex system to integrate short-term forecast, or nowcast, of

weather conditions. A numerical weather model, referred to as the Terminal Area Planetary boundary layer Prediction System⁹ (TAPPS), is run twice daily at the North Carolina State University Mesoscale Modeling and Dynamics Lab. Inputs to the model consist entirely of operational products available from the National Center for Environmental Prediction (NCEP) and are totally independent of the sensors deployed at DFW. Initialization of the TAPPS model is performed twice daily using NCEP products taken at 00Z and 12Z. The model requires 2 to 3 hours to run and simulates the evolution of the planetary boundary layer over the eastern Texas region for a 24-hour period. Post-processing of gridded TAPPS products is performed to extract the same 30-minute statistics of wind, turbulence, and temperature as are produced by the observational weather system at DFW. These products are placed in a file format identical to the observational weather files, combined into a single archive file, and transmitted to AVOSS. AVOSS then extracts the time period of interest from the archive file while running in real-time throughout the day.

The nowcast products are being integrated for several purposes. First, to determine the utility of this modeling technique to predict airport meteorological conditions hours in advance. With sufficient skill in forecasting the potential may exist to replace some of the dedicated on-airport sensors with TAPPS products. Second, to provide information required to predict changes in aircraft spacing several hours in advance. This information could then be used by ATC for planning purposes. The nowcast capability is not being used to prescribe the actual arrival spacing required. In actual operation, AVOSS is being run with both the observational weather products and the nowcast products. The observational products provide the spacing that should be used and against which the wake vortex sensor data is compared. The nowcast products are used to compute and display expected runway throughput for several hours in the future. Displays of aircraft pair spacing computed from both product sets are shown for diagnostic purposes only.

Improved Wake Vortex Predictor

Several changes have been made to the wake vortex predictor used by AVOSS. First, the parameter used for decay predictions has been changed from Turbulent Kinetic Energy (TKE) to Eddy Dissipation Rate (EDR). While either TKE or EDR may be used to predict wake decay, TKE

presents unique operational difficulties. The value of TKE measured is highly sensitive to the time scale specified. Short time scales describe the energy content of small scale eddies while larger time scales include the energy content of large scale phenomena, such as convective thermals, that may have more influence on wake drift than on wake decay. Furthermore, the time scale required to capture a given spatial scale varies with the ambient wind speed, and TKE can be expected to vary significantly with changes in altitude above the ground. The optimal spatial and time scale required for wake decay mechanisms are not fully understood. The EDR parameter is much less sensitive to the time scale chosen and is more easily extrapolated to altitudes above the measurement sensor. Second, the numerical stability of the original predictor code has been significantly improved. The methods used by AVOSS to reduced spacing will prevent any spacing reduction behind a given category aircraft if the predictor fails to execute properly for any aircraft in that category at any of the prediction windows. The original predictor would sometimes fail to produce useful tracks or would terminate prematurely, prior to the wake exiting the corridor, in certain combinations of aircraft altitude and wind. Third, analysis of prior field tests and wake numeric modeling results have led to minor refinements of wake decay estimation in ground effect.

Operational Flexibility

The AVOSS system makes extensive use of parameter files to specify the run mode of the system. The aircraft used can be rapidly changed by editing a file listing the type, radar beacon identification, weight, wingspan, and expected speed of each generating aircraft. The minimum and maximum spacing to be applied for runway occupancy and for default spacing criteria are specified in a second file. A third parameter file is used to specify whether the weather quality flags will be used in computing spacing, whether wake lateral drift and vertical drift will be ignored when computing spacing, the location of any special approach windows required to provide wake predictions at wake sensor locations, the value of wake strength used to compute demise, and inputs required to compute runway throughput. In operation AVOSS always provides two spacing values, one based on all wake factors (drift, sink, demise) and one that relies only on the wake motion factors. By setting flags to also disable wake drift and sink in the latter spacing values, no

wake factors are considered and the default approach spacing with current FAA criteria is provided. AVOSS is normally run in a mode such that default spacing and throughput, as well as the spacing and throughput with all wake factors enabled, are computed.

Throughput Calculation

The prior AVOSS system provided aircraft spacing criteria, and post-processing was employed to estimate the effect on runway throughput. The throughput results from Version 1 were achieved with a simple first-order calculation of the number of aircraft per hour that could arrive using the spacing provided by AVOSS. No provision was made for variances in the delivery accuracy of the aircraft or for the possible need to round off AVOSS spacing values to 1/2 mile or integer mile values.

Version 2 computes the resultant potential runway arrival rate when computing the spacing at each 1/2-hour interval. The throughput calculation¹⁰ includes the specified spacing values, the expected ratio of each weight category, rounding of spacing values to specified intervals (1/2 or 1 NM), and variance in delivery of aircraft to the prescribed rounded spacing value. The use of rounded spacing values and delivery variance is intended as a first-order simulation of system performance with an ATC interface.

The time variance is a quantification of the spacing buffer that controllers use to insure spacing regulations are not violated. To calculate throughput, a probability matrix p is defined:

$$p_{ij} = \text{probability}_i \times \text{probability}_j \quad (2)$$

where p_{ij} is the probability of aircraft category i following aircraft category j .

A product matrix is defined:

$$prod_{ij} = p_{ij} \left(\frac{\text{separation}_{ij}}{\text{velocity}_i} + \text{buffer} \right) \quad (3)$$

where the separation is the AVOSS-calculated spacing rounded to a specified interval and (from reference 10):

$$\text{buffer} = 1.65(\text{ATC variance}) \quad (4)$$

The quantity in brackets in equation 3 is expected time spacing for category pair i,j (seconds).

Throughput, in units of aircraft per hour, is calculated by summing of the product matrix across all aircraft pairs:

$$\text{throughput} = \frac{3600}{\sum_{ij} prod_{ij}} \quad (5)$$

The default parameters for calculation of runway throughput at DFW are the DFW traffic mix defined above, spacing rounded to the nearest 1/2 NM, and an ATC variance of 10 seconds.

Improved Wake Sensor Logic

During operation of Version 1 the wake sensors were tasked to detect and quantify the location and strength of the wake vortex pair from each aircraft. The results were provided to AVOSS in the form of a file containing a series of records describing the wakes at each scan. Each record contained seven fields: a time stamp followed by the lateral and vertical position and strength of each wake. The AVOSS system then parsed the wake records to determine the residence time of each wake.

Operational difficulties arose in this process. Each sensor in use (pulsed lidar, continuous wave (CW) lidar, and ground wind line) have individual limitations that effect wake measurements. For example the CW lidar may have difficulty tracking both wakes when they are at widely different ranges from the lidar, and the pulsed lidar may introduce significant noise in position measurements due to the current pulse length of 60 meters. In addition, each sensor crew must decide when to begin and terminate wake tracks when aircraft are close in trail, and can optimize system settings to accommodate ambient turbulence levels. Many wake files terminated prior to the wake exiting the corridor or reaching demise, and hence were useless by the current validation method. In other cases the confidence in reported position was low due to large changes in position between scan records or missing data within records. With the residence time parsing being done at the AVOSS workstation, remotely located from the sensors, there was little feedback to the sensor crews describing the utility of the wake files being received. The need to couple the sensor to AVOSS prevented stand-alone sensors tests to optimize residence time processing. Due

to these factors, and the fact that the sensor system has more data available to it than is passed to AVOSS (signal-to-noise and other data) the task of extracting wake residence time was transferred to the wake sensor subsystem. The file formats were modified to include the lateral and vertical residence times and the demise time of each wake.

The revised architecture provided several benefits; (1) the ability to conduct stand-alone tests with the sensor, (2) immediate feedback to the lidar operators of the utility of the files being produced, (3) better coordination and configuration control between AVOSS integration and sensor subsystem teams, and (4) innovations at the sensor level for estimating residence time with the available data. An example innovation is an alternate demise values suggested by the pulsed lidar team, defined as the last time that the wake is detectable against the background atmospheric turbulence, regardless of strength.

Automated wake sensor comparisons and data logging

The output of the Version 1 AVOSS system only consisted of the predicted wake behavior behind each aircraft, the residence time of the wake behind each aircraft at each window, and the resulting aircraft spacing criteria. Estimation of average system performance or comparisons of wake predictions with wake sensor data was a time-consuming post-processing task.

Version 2 contains a wake compare utility that runs immediately after each wake sensor file is received. Two files are passed to the compare code, a file listing predicted residence times behind each airplane and the wake sensor file. The compare code first examines the time stamps of the two files to ensure that the wake file was taken within 30 minutes of the last wake predictions. Then the location of the wake sensor scan plane and the aircraft identification in the file are compared to the AVOSS aircraft data base to ensure that the sensor data can be matched to a prediction. Lastly the residence time data in the wake sensor file is examined to ensure it contains useful data. Premature termination of a wake track or failure to detect one of the wakes can result in a "bad-value" indicator in the residence time fields.

Frequently data is available only for the slower-moving upwind wake, as the downwind wake may

be more difficult to track or may move away too quickly for detection. When residence time is available for only one of the two wakes the wake drift rate is examined to determine if the "critical" wake was quantified. A wake is considered critical if it drifts in a direction opposite the expected no-wind drift direction at a rate of more than 0.5 m/s. For example, the port wake would normally be expected to sink vertically or drift to the left, as viewed from behind the aircraft, as it encounters ground effect. If the port wake is seen to be drifting to the right by more than 0.5 m/s then it is assumed to be the most critical wake. In this case the starboard wake can be expected to drift in the same direction at a faster rate and the wake file can be used even if the starboard wake was never detected. A least-squares fit to the lateral position data is used to estimate drift rate. If all tests are passed then the wake residence time in the sensor file is compared to the predicted wake residence time, using the same formulation for residence time that AVOSS applies to predictions (equation 1). A safety buffer time is calculated from the difference between the predicted and actual residence time. The buffer is positive if the predicted time is greater than actual and negative if the actual residence time exceeds the predicted time. A negative buffer is considered an "exceedance".

The compare code produces a statistics file each day that describes the number of AVOSS runs made, average spacing reductions, the number of wake files received from each sensor, the number of files useful for calculating buffer times, and the number of positive and negative buffers. A separate exceedance file is produced that provides one record per detected exceedance. Each record lists a time stamp, aircraft type, approach window location, the sensor reporting the wake data, and the length of the exceedance in seconds. The statistics file and the exceedance file provide a means to rapidly assess system performance and to quickly identify specific cases requiring study.

In addition to the outputs of the compare code, a log file is produced each day. Each log file record provides the approach spacing value for each aircraft pair, the default approach spacing, possible runway throughput with both the default and reduced spacing, basic airport ceiling and visibility data from surface observations, the status of certain parameter file flags, and the quality flags from all input weather files. All fields are written at run-time, except the surface weather observation data that is added at the end of the day. The log

files provide a rapid means to examine spacing and throughput performance as a function of time of day, weather conditions, weather data quality, or other factors.

System Architecture and Operation

The system architecture for AVOSS Version 2 is shown in figures 2 and 3. The system is distributed between systems operated by MIT Lincoln Laboratory, Volpe National Transportation Systems Center, North Carolina State University, and NASA. The focal point for data distribution is a wake vortex network within the ITWS office at the DFW airport. The wake vortex network is operated by Lincoln Laboratory and has access to TDWR products, ATC radar beacon data, and data feeds from all wake sensors and dedicated meteorological sensors. The meteorological sensors⁴ include a radar profiler, two acoustic SODARs and an instrumented 45-meter tower. Once inside the ITWS office the weather data is processed into a consensus vertical wind profile.

An event correlation function is also performed within the wake systems inside the ITWS office. The event correlation accepts radar beacon data and flight plan data from ATC and processes these to detect aircraft passages at the wake sensor measurement locations. Each detection includes the aircraft type and the time of passage. This data is then used to process all incoming wake vortex data files to insert the aircraft type into the file. The estimated aircraft passage time, as written by the sensor, is compared to the beacon time. If a status flag in the wake file indicates that the sensor-estimated time has high confidence then no action is taken with the time difference. If the confidence flag is not set then the difference in time between sensor estimate and the radar beacon passage time is used to adjust all wake time history data and residence times in the file. Operationally, the confidence is high when an operator at the lidars inserts a manual marker in the data via push button at aircraft passage, or a directional acoustic trigger at the wind line detects the aircraft fly over. The event correlation function is essential to automated real-time application of the wake files.

The NCSU TAPPS nowcast model is initialized twice daily with NCEP products. The resulting nowcast prediction file is transferred to Lincoln Laboratory in Lexington, MA. From there it is placed on the wake vortex network at DFW for access by AVOSS. All data, meteorological and

wake vortex, is then placed onto a common disk space which is shared by the AVOSS processor. A dedicated data line from the ITWS office to Langley Research Center allows AVOSS to operate remotely from Langley.

The system software (figure 3) consists of a set of core functions, which can be executed either in real-time or as part of batch processes for system sensitivity studies or other testing, and a real-time shell that is unique to the field systems at the Dallas-Fort Worth Airport. The core system accepts the three weather file types (vertical profiles of wind, turbulence, and temperature) along with the system files describing the aircraft data set and run parameters. The output of the core is the predicted wake behavior for each aircraft and window combination, predicted residence times, and the spacing requirements at each individual window and at the top-of-approach. Default approach spacing, default runway throughput and reduced-spacing throughput are also provided.

The real-time shell performs the duties specific to the field sensors. These functions include integration of multiple-sensor data to estimate turbulence and thermal vertical profiles, comparison of predicted and observed wake behavior, derivation of error statistics, and system displays. External to the AVOSS real-time shell processes are other processes spread among numerous teams and organizations. These organizations include MIT Lincoln Laboratory for all meteorological sensor interfaces, vertical wind profile, and event correlation; North Carolina State University for the operational nowcast model; and individual sensor teams for wake vortex track and strength diagnosis.

Real-time operation occurs on a 30-minute cycle. The dedicated weather sensors report data shortly before the hour or half-hour. On the hour and half-hour the weather data is processed into the three vertical profile types. The wake vortex predictor is invoked and spacing criteria and potential runway throughput are calculated. The results are stored in log files and displayed for real-time observation. The spacing matrix is frozen for the next 30-minute period and represents the suggested spacing for that time. As aircraft pass the wake vortex sensors, the wakes are observed and measured residence times are provided to AVOSS. As each wake data file is received, AVOSS matches the aircraft type and scanned window location to stored wake predictions, displays the predicted

and observed wake trajectory, and compares predicted and observed wake residence times. The safety buffer is computed and any negative buffers (exceedance) are logged and displayed. This wake comparison process continues until the next 30-minute spacing update is calculated. This comparison process provides a challenging test of the wake vortex prediction algorithms and the design assumption that weather statistics data collected in one period can be used to space aircraft in the next period. In total, the AVOSS system provides a powerful tool for evaluating, in an integrated system manner, the performance and utility of weather fusion processes, nowcasting models, wake prediction algorithms, and system parameter changes.

Dallas-Fort Worth Deployment of 1999

The Version 2 AVOSS system was initially tested in the fall of 1999. The core AVOSS processors remained at NASA Langley and operated via the dedicated data line. Daily deployment logistics were coordinated from Langley. The real-time tests involved linked processes at DFW, Langley, Lincoln Laboratory, and NCSU. Although coordination at multiple sites was required, the actual AVOSS operation was largely automated. The most labor intensive aspects were operation of the two lidar systems, to begin and end wake tracking, monitor general system health, optimize system settings for the ambient conditions, and other housekeeping duties. The actual process of converting lidar wake observations to data files was totally automated. The wind line required no personnel to operate except for maintenance. The nowcast system operated and transferred data twice a day without manual intervention. AVOSS operated automatically except for selection of preferred display options, entering lidar scan plane locations when they changed, data offloading, and software corrections when needed. After the first several days of operation, the system was set up to make wake predictions at all potential lidar scan locations, which eliminated the need to modify parameter files as the scan location was altered.

The data collection began on November 11, 1999 and continued through November 19. Operations resumed on November 30 and ceased on December 3. A good variety of weather conditions was experienced, including calm wind, strong along-runway wind with light cross-wind component, and moderate cross wind conditions. Both high and low turbulence conditions were experienced and both short-lived and long-lived

wake conditions were seen. No wake data was taken when the wind favored landing to the north. The first few days of system operation provided a shake-out of processes that could not be tested until all systems were in the field.

Only runway 17C was instrumented for wake data collection. The pulsed lidar was located 856 meters to the right (west) of the extended runway centerline and 1706 meters north of the threshold. From this location three approach windows were scanned, one each at 1080 meters, 1702 meters, and 2262 meters from threshold. Most data was taken at the 1702 meter location, which provided a laser azimuth angle nearly perpendicular to the flight path. The continuous wave lidar was located near the runway threshold, 190 meters west of centerline and only 84 meters north of threshold. Only one approach window was scanned, at 84 meters from threshold. The wind line is located on the approach path 983 meters from threshold. Table 3 provides a brief summary of conditions and data collected.

Deployment Results

All results presented are preliminary. As noted in table 3, some post-processing is required to recover data lost to temporary problems. In-depth analysis or review of results has not yet occurred due to the time available since the deployment.

AVOSS Performance

The system log files for all days were merged into a single log file to examine average spacing reductions, runway throughput potential, and weather system performance. Table 4 shows the number of AVOSS predictive runs made each day, the number of input weather files passing all quality criteria, calculated (reduced spacing) and default arrival rate, and throughput increase. At most, 48 predictive runs can be made each day, one each 30-minutes. The table shows that AVOSS logged 48 runs on most days, with fewer on a few days due to system hardware or software problems. The atmospheric wind profile (Agood) passed quality checks in 86% of the cases, the EDR turbulence profile (Egood) passed in 71%, and the thermal profile (Tgood) passed in 62% of the runs. One entire day was run with no turbulence files passing quality checks. This loss was due to timing issues preventing the needed data from reaching the profile code until just after the code has begun executing on its 30-minute schedule. The wake predictions are considered

reliable only when both the wind and turbulence file pass quality checks. Both passed checks in 61% of the runs. The thermal data is considered less critical to AVOSS based on sensitivity experiments¹¹ conducted with the Version 1 system. System reliability improved after a few days in the field, as would be expected during an initial deployment, but also suffered slightly after a one-week downtime. The latter situation is partially due to software changes and upgrades made during that week.

The weather quality process was successful in detecting system problems, both with respect to weather sensors and system implementation. The AVOSS sensors and system interfaces are not hardened at this time.

The spacing and runway throughput data is examined only for those cases where both the wind and turbulence data met the quality criteria. Note that the throughput provided in table 4 was calculated with equations (2) through (5), using the default ATC parameters for rounding the calculated spacing and variance in spacing delivery precision. The throughput values provided earlier, using the Version 1 AVOSS with a one-year data set, employed a simple throughput calculation that did not simulate the rounding or variance effects. As such the throughput in table 4 can be expected to be less than the earlier values.

The results show that the potential runway arrival rate increased on the average by 1.9 aircraft per hour, or 6% from the no-AVOSS value. The performance varied greatly by day. On the first day, during which the wind was light and the lidars observed wakes lasting for significant period of time, the throughput increase was less than 3%. On the best day the arrival rate could have been increased by 3.56 aircraft per hour on average, for an 11% throughput increase. Three of the 13 days produced an throughput increase of more than 8%. These results are consistent with the expected performance of such a system. When long-lived wakes were observed the AVOSS was correctly providing standard spacing. When short-lived wakes were observed the system was reducing the spacing. The overall 6% throughput increase, with a simulated ATC interface, is consistent with the previously-estimated 9% increase without the simulated interface.

Comparison of Wake Predictions and Observations

The statistics file and exceedance log file produced by AVOSS were examined to determine the degree to which wake predictions and observations matched. Table 5 provides a summary of key data from these files. The table lists the number of files from each wake sensor that were logged by the comparison process, the number that produced a safety buffer calculation and the number of positive buffers, negative buffers (exceedances), and the average of all buffers. Safety buffers were only calculated when a wake file could be matched to a wake prediction from a specific aircraft type, when either the critical wake or both wakes were tracked, and when both the wind profile and turbulence profile passed quality checks.

A number of serious limitations are present in the data provided. Due to initial system integration and timing issues, the statistics file did not always process wake files and some statistics files were not useable or only covered a portion of the day. A date rollover issue caused the comparison code to log two wind line wake files at the beginning of each day. The wind line counts have been decremented by two in table 5. Most significantly, experience with real data revealed logic errors in the compare code, to be discussed, that frequently led to large exceedance values being calculated when in fact the wake prediction and observation agreed.

The purpose of the statistics and exceedance file is to both diagnose overall agreement between predictions and observations, and to identify specific cases requiring further study. Only through this study and iterative system refinement will an operational wake system be produced. A number of factors may lead to residence time exceedance detections. These include: (1) errors in the meteorological profile provided to the wake predictor, (2) deficiencies in the wake predictor, (3) inadequate system logic for estimating and calculating residence time confidence intervals, (4) errors in the diagnosed wake position or strength by the wake sensor, (5) the integrity of the comparison logic, and (6) other system logic issues. Each exceedance requires examination to determine which AVOSS element led to the error and to determine corrective actions.

The data shows that, in general, only a small number of the wake files received were useful for

validation of the wake predictions. December 3 provided the best performance with 31 of 71 files, or 43%, producing a buffer value. Overall for the entire deployment, only 19% of the wake files processed resulted in a safety buffer calculation. Reasons for the low fraction of comparisons include the factors listed above required to compare files, and the fact that in many cases the wake tracks terminated prior to verifying wake exit from the safety corridor or only one of the two wakes was tracked. If the drift rate did not indicate the only wake tracked was the upwind wake, then the file was not useable.

At first examination the wake files appear to compare poorly with predictions. Of the 423 buffer time calculations logged, only 174 (41%) resulted in positive buffers while 249 (59%) produced negative buffer values. On nearly all days, the mean calculated buffer was negative, indicating wakes persisting on average longer than predicted. Closer examination revealed that the comparison logic was too simplistic to handle the variety of situations experienced and produced false exceedance detections in many cases. The primary flaw was the use of the same residence time calculation (equation 1) for the wake sensor data as was used for the AVOSS predictor processing.

An example of a false exceedance detection was produced using a wake file from the wind line at 19:27 on November 14. The aircraft was an MD-80 and the wind line file and the AVOSS wake prediction produced the time values for lateral residence, vertical residence, and demise shown in table 6. The wind line only provides lateral residence time values and always provides the bad-value for vertical residence and demise times. In this case, AVOSS predicted that lateral drift was too slow for separation reduction, but that the wake would sink below the corridor floor in 15 seconds and decay in 51 seconds. The wind line data is consistent with this prediction. The wake file neither confirmed or refuted the wake vertical motion or decay, but indicated faster than predicted lateral motion. The comparison logic compared the 15-second predicted vertical residence time to the 34-second measured lateral residence time and produced a 19-second exceedance detection. This compare logic error was responsible for many exceedance values when using the wind line data, which biased the overall statistics. On November 30, when the wind line provided no data to AVOSS (table 5), the mean buffer calculated from all wake files was a

positive 18 seconds. This was the only day with a positive mean buffer value. This example also shows that the comparison logic should account for the fact that not all exceedance cases are hazardous. When both the predicted and measured wake residence time are well below the minimum aircraft spacing required for runway occupancy considerations, as is the case here, then the exceedance value is of scientific interest but does not represent a hazard for practical aircraft operations.

A second example of a wake exceedance is from the pulsed lidar for an MD-80 at 15:25 on December 1, 1999. The comparison logic produced a 20-second exceedance detection by comparing the predicted vertical residence time of 17 seconds to the measured demise time of 37 seconds (table 7). The wake file contained no data for the starboard wake, so all measured values are based on the port wake only. In this case the exceedance appears valid. The predicted and observed wake behavior were in agreement, with the exception of the sink rate of the wakes. Both data sources indicated that the lateral drift was not useful for spacing reduction and the wake actually decayed somewhat faster than predicted. The lidar data indicate that the wake initially sank almost as quickly as predicted. At the 17-second predicted vertical residence time the wake was within 7 meters of the corridor floor, then stalled at the corridor floor altitude for another 20 seconds before finally sinking farther. This case provides another example of an exceedance detection when the actual wake behavior provided a residence time well below runway occupancy time. This case, along with other similar events, suggests the need to better quantify the uncertainty in the wake sink rate in certain atmospheric conditions. The weather on this day was very windy, with 7 to 10 m/s (15 to 20 knot) winds from the south.

A final case study is taken from a DC-8 at 17:23 on the same day, December 1. This case produced a very large exceedance value of 105 seconds yet, in general, the wake measurements agreed with the wake prediction. Both sources indicated that the lateral drift was not adequate to allow spacing reduction (table 8). The predicted vertical residence time of 17 seconds compared favorably with the measured value of 11 seconds for the port wake. The predicted demise time of 72 seconds also compared favorably with a 77-second measurement for the port wake. The starboard wake, however, produced a demise time of 122

seconds and a vertical residence value of 9999, indicating that the wake was in the corridor at track termination. Examination of the measured wake track shows that the starboard wake did sink as predicted and was below the corridor floor at 11 seconds and was only 19 meters above the ground at 50 seconds. In the final 20 seconds of the file the wake suddenly rose and was at an altitude of 114 meters at the final time, with little decay taking place. For reference, the flight path altitude is about 105 meters and the corridor floor is at 80 meters at this approach location. This long wake lifetime is not consistent with the ambient winds of about 10 m/s (20 knots), nor with the fact that the measured wake trajectory involved close proximity to the ground and then a rise. The lidar was operating in a mode that tracked the wake until the circulation was not distinguishable from background turbulence, regardless of strength. With the strong winds present it is possible that the lidar was actually tracking background turbulent eddies at late times. Further examination of the lidar data will be required to determine the accuracy of the starboard wake position and strength.

These cases illustrate several key points related to overall AVOSS performance:

1. For most cases examined to date, the predicted and measured wake behavior agreed well, both in terms of wake motion and decay.
2. Simple comparison of total wake residence time, using equation 1, is too simplistic for real-world wake measurements with sensors of varying capability.
3. Wake comparisons and safety monitoring logic must recognize the minimum runway occupancy time applied by AVOSS when the predicted and observed wake residence times are below that time.
4. The wake exceedance cases examined to date, that appear valid, are generally related to uncertainty in the wake sink rate. Several measured wake tracks show wakes that sink more slowly than expected or even rise. This sink rate uncertainty may require disabling the vertical motion prediction in a subset of atmospheric conditions or increasing the vertical dimension of the safety corridor.
5. Distinguishing weak wake vortices from background atmospheric turbulence is a challenging sensor requirement and may lead to unrealistic measured wake lifetimes in turbulent conditions.
6. The use of a single value (9999) for both bad-values and for wakes that are predicted or observed to remain in the corridor for long periods creates a loss of information in the comparison process. This value can imply either a lack of data or a valid track that remained in the corridor for a time that exceeds the standard FAA spacing criteria.
7. Continued system operation and monitoring will be required to optimize system components and interfaces, and ensure that the system logic handles unusual cases that might not be envisioned prior to deployment.

Future Activities

Near-term AVOSS activities will focus on system refinement in preparation for the final project demonstration. The refinements will include enhancement of the logic that compares wake predictions with measurements, additional predictor algorithm development in an attempt to better characterize sink rate uncertainty, and analysis of lidar data to improve tracking performance and reject turbulence if required.

Longer-term activities include support of industry activities to apply wake vortex technologies to various operational problems, including closely-spaced parallel approaches and departures. An immediate issue is the availability of the closely-spaced parallel approaches at the San Francisco International Airport (SFO). Two parallel runways spaced 229 meters (750 feet) apart are used simultaneously when visual approach procedures are in effect. When instrument procedures must be used only one of these runways is available, seriously degrading airport capacity and increasing delays. During visual approaches, aircraft fly nearly side-by-side, effectively eliminating wake vortex concerns for the paired aircraft. Side-by-side operation at close range in cloud is not feasible, and various proposals to enable simultaneous runway use during some instrument conditions lead to wake vortex concerns. Application of AVOSS weather profiling and wake prediction and measurement to the parallel runway scenario may provide capacity increases well in excess of the roughly 12% possible in the single-runway scenario. A combined single-runway and parallel runway system may provide optimal gains, as wind conditions that are not favorable to one application will tend to favor the other. For example, light winds that produce little wake drift may provide small single-runway capacity gains

but be very favorable to allowing simultaneous parallel runway operations.

Summary

A second-generation wake vortex spacing system has been developed and operated at the Dallas-Fort Worth International Airport. This system includes numerous significant improvements over the initial system, including real-time weather products quality checks, improved wake sensor tracking algorithms and wake residence time derivation, operational nowcast, real-time comparison of wake predictions with measurements, and automated performance and wake prediction error logging. During operation in the fall of 1999, this AVOSS system demonstrated the ability to detect weather sensor errors, perform quality wake predictions, and recommend appropriate reduced aircraft spacing criteria. The potential single-runway capacity increase varied from 2.7% to 11.4%, depending on ambient weather conditions, with an average gain of 6% during the deployment period.

While the automated comparisons of wake prediction and measurements indicated numerous exceedance cases, where the wake persisted longer than predicted, examination of these cases to date reveal overly-simplistic comparison logic and good agreement between predicted and observed wake behavior in most cases. The system data logging allowed rapid identification of these cases for analysis as well as rapid assessment of sensor data availability and quality.

The remaining program activity will focus on refinements to the wake prediction comparison logic, wake tracking algorithms, and estimation of the uncertainty in the wake sink rate predictions. The final project field deployment and demonstration is currently planned for mid-calendar year 2000.

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Traffic Mix	B757 Generator	Heavy Generator	Throughput Increase
DFW	1.9 km (1 NM)	1.9 km (1 NM)	5.4 %
MIA	2.2 km (1.2 NM)	2.4 km (1.3 NM)	12.4 %
SEA	2.1 km (1.15 NM)	2.1 km (1.15 NM)	6.4 %

Table 2 - Average Spacing Reduction and Runway Arrival Rate Increase for Three Traffic Mixes using AVOSS Version 1 with One-Year of DFW Weather.

<u>Date</u> (1999)	<u>General Conditions</u> (aircraft landing to the south unless noted)	<u>System Health</u>
Nov. 11	Light south wind, long-lived wakes	First operations of the pulsed lidar - debugging code for event correlation with pulsed lidar files and for wake comparison code
Nov. 12	Light wind	Network issues prevented lidar data flow part of the day. Weather file timing issues created some turbulence consensus files with failed quality tests.
Nov. 13	Moderate wind from south	First continuous wave lidar operations but communication issues transferring files. No pulsed lidar operations.
Nov. 14	Light north wind, landing to north	No wake data due to aircraft landing towards the north.
Nov. 15	North wind shifting to east then from south, landing to north early, changed to south flow at noon	Good data collection and operations day
Nov. 16	Calm early, then increasing from south	Good data collection and operations day
Nov. 17	Moderate wind (about 5 m/s, or 10 knots) from south	Good data collection and operations day
Nov. 18	Strong south wind (about 8 m/s or 15 knots), rapid wake decay	Good data collection, some system timing issues affecting quality
Nov. 19	Wind west early shifting to north. Began landing to north at 14:45Z (8:45 AM local)	Little wake data due to early shift to north landing. Lidars secured for one-week downtime.
Nov. 30	Wind light from east then southeast, seeing good wake drift rates	Problems with event correlation prevent aircraft type assignments for pulsed lidar, wind line does not provide data, AVOSS processor shut down part of day for software upgrade. Must reprocess this day for wake comparisons.
Dec 1	Strong south wind	Good data collection and operations day
Dec 2	Strong south wind (over 10 m/s, or 20 knots), rapid wake decay	Good data collection and operations day
Dec 3	Strong south wind	Good data collection but early shutdown for lidar shipping

Table 3 - DFW 1999 Deployment Dates and Summary

<u>Date</u>	<u>Total AVOSS runs</u>	<u>Number Runs with both Agood and Egood</u>	<u>Number Runs with Agood</u>	<u>Number Runs with Egood</u>	<u>Number Runs with Tgood</u>	<u>Calculated Arrival Rate, aircraft/hour</u>	<u>Default Arrival Rate</u>	<u>Arrival Rate increase, aircraft/hour per runway</u>	<u>Arrival Rate increase, percent</u>
Nov. 11	47	6	43	7	14	31.19	30.36	0.83	2.77%
Nov. 12	48	20	46	21	9	32.00	30.58	1.42	4.68%
Nov. 13	48	0	39	0	10	N/A	N/A	N/A	N/A
Nov. 14	48	14	45	14	34	31.86	29.95	1.91	6.38%
Nov. 15	48	46	47	47	13	32.03	30.67	1.36	4.39%
Nov. 16	48	45	46	46	44	32.32	31.10	1.22	3.99%
Nov. 17	48	41	43	45	41	32.66	31.12	1.54	4.93%
Nov. 18	48	31	32	46	42	34.11	32.37	1.74	5.35%
Nov. 19	48	40	40	47	25	34.40	31.83	2.57	8.07%
Nov. 30	41	39	41	39	40	34.78	31.22	3.56	11.40%
Dec. 1	23	17	17	23	17	33.37	31.67	1.71	5.37%
Dec. 2	48	31	31	42	48	34.34	32.24	2.09	6.48%
Dec. 3	39	30	31	38	25	34.57	31.81	2.76	8.65%
Total:	582	360	501	415	362				
Percent:		61.86%	86.08%	71.31%	62.20%				
Mean:						33.14	31.24	1.89	6.04%

Table 4 - Summary of AVOSS Weather Input Reliability and Throughput Performance During Deployment.

Note: Quality criteria is met for the Atmospheric wind profile, the Eddy Dissipation Rate Turbulence file, and the Thermal file if Agood, Egood, or Tgood are true, respectively.

<u>Date</u>	<u>Number of Pulsed Lidar files</u>	<u>Number of Continuous Wave Lidar files</u>	<u>Number of Wind Line files</u>	<u>Number of Buffers calculated</u>	<u>Number of Positive Buffer times</u>	<u>Number of Negative Buffer times</u>	<u>Mean Buffer time (sec)</u>
Nov. 11	Not useable						
Nov. 12	2	0	8	0			
Nov. 13	0	0	0	0			
Nov. 14	0	0	14	1	0	1	-19
Nov. 15	35	24	49	35	10	25	-13
Nov. 16	78	147	100	99	47	52	-5
Nov. 17	30	89	202	54	20	34	-14
Nov. 18	77	86	178	31	4	27	-24
Nov. 19	2	11	128	2	0	2	-90
Nov. 30	87	54	0	13	12	1	18
Dec. 1	109	140	75	101	47	54	-6
Dec. 2	103	137	198	56	15	41	-27
Dec. 3	39	5	27	31	19	12	-1
Total:	562	693	979	423	174	249	

Table 5 - Preliminary Wake Comparison Data (see text for data interpretation cautions).

Source	Lateral Residence Time	Vertical Residence Time	Demise Time
Predictor algorithm	9999	15	51
Wake sensor	34	9999	9999

Table 6 - Comparison at 19:27 on 11/14/1999 for MD-80 from wind line, times in seconds. Value of 9999 indicates invalid or undetermined status (i.e., wake did not leave corridor during wake prediction or sensor track, wake not detected, other)

Source	Lateral Residence Time	Vertical Residence Time	Demise Time
Predictor algorithm	9999	17	55
Wake sensor	9999	9999	37

Table 7 - Comparison at 15:25 on 12/01/1999 for MD-80 from pulsed lidar, times in seconds.

Source	Lateral Residence Time	Vertical Residence Time	Demise Time
Predictor algorithm	9999	17	72
Wake sensor	9999	11 port, 9999 starboard	77 port, 122 starboard

Table 8 - Comparison at 17:23 on 12/01/1999 for DC-8 from pulsed lidar, times in seconds.

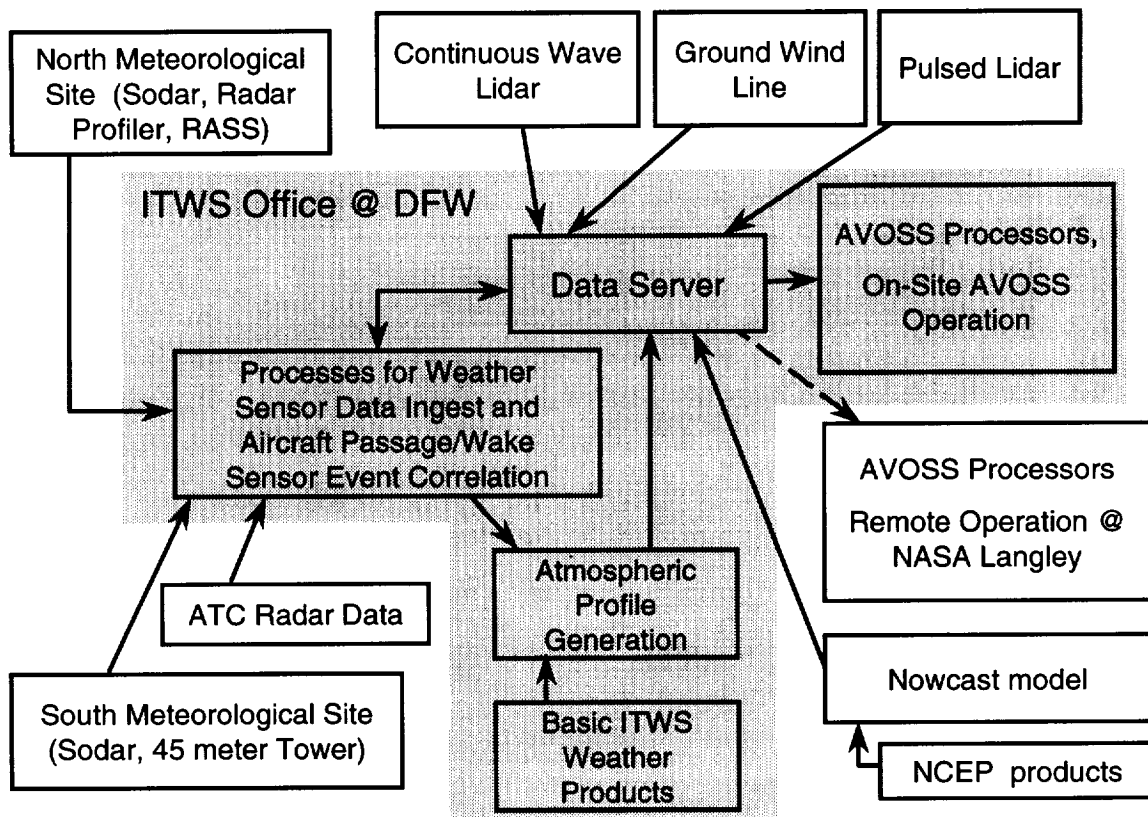


Figure 2 - AVOSS network architecture

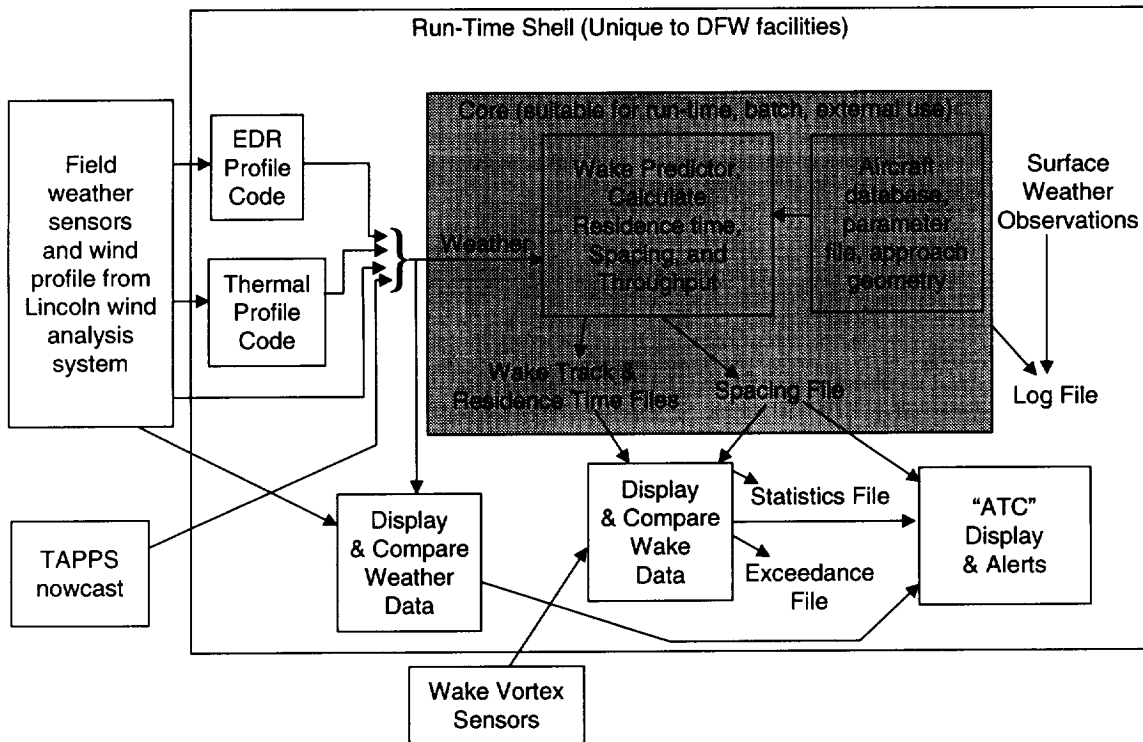


Figure 3 - AVOSS Software Components