NASA/TM-2001-211052

Enhanced Airport Capacity Through Safe, Dynamic Reductions in Aircraft Separation: NASA's Aircraft VOrtex Spacing System (AVOSS)

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August 2001

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Acknowledgments

The authors would like to acknowledge the assistance of those individuals who aided in the preparation of this document. In particular, we acknowledge Mr. David Hinton and the members of the AVOSS team whose prior work laid the foundation for this paper. In addition, informal conversations with members of the WakeVAS team as well as representatives of numerous airport authorities contributed to the ideas presented herein.

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Abstract

An aspect of airport terminal operations that holds potential for efficiency improvements is the separation criteria applied to aircraft for wake vortex avoidance. These criteria evolved to represent safe spacing under weather conditions conducive to the longest wake hazards, and are consequently overly conservative during a significant portion of operations. Under many ambient conditions, such as moderate crosswinds or turbulence, wake hazard durations are substantially reduced. To realize this reduction NASA has developed a proof-of-concept Aircraft VOrtex Spacing System (AVOSS). Successfully operated in a real-time field demonstration during July 2000 at the Dallas Ft. Worth International Airport, AVOSS is a novel integration of weather sensors, wake sensors, and analytical wake prediction algorithms. Gains in airport throughput using AVOSS spacing as compared to the current criteria averaged 6%, with peak values approaching the theoretical maximum of 16%. The average throughput gain translates to 15-40% reductions in delay when applied to realistic capacity ratios at major airports.

Introduction

Since the late 1990s the national airspace system has been recognized as approaching a capacity crisis. In light of this condition, industry, government, user organizations, and educational institutions have been working on procedural and technological solutions to the problem. One aspect of system operations that holds potential for improvement is the separation criteria applied to aircraft for wake vortex avoidance. Wake vortices are generated during all phases of flight, as a by-product of a wing that is generating lift. Wake vortex encounters have caused injuries as well as loss-of-control accidents, particularly for smaller aircraft following larger aircraft, and must be avoided. The problem is most critical in terminal areas due to a combination of low altitude and high-density operations. Decades of research on wingtip vortices have shown that although the initial position and strength of a wake is dependent on physical parameters of the generating aircraft (weight, speed, wingspan, etc.), the wake position, movement, and strength persistence over time depend on local meteorological parameters (winds, turbulence, and temperature).

The Federal Aviation Administration (FAA) aircraft separation criteria for wake vortex avoidance are summarized in Table 1. These criteria were empirically developed and provide adequate spacing in worst-case weather conditions. There is no provision to reduce spacing when the weather conditions are conducive to early wake dissipation or advection from the approach corridor. To realize this potential spacing reduction, the AVOSS provides dynamic spacing criteria based on the current weather conditions to maximize runway acceptance rates. AVOSS was developed for the problem of aircraft on approach to a single runway, but the concept extends to other terminal area scenarios. Wake prediction models provide estimates of the wake position and strength based on terminal area weather conditions. These estimates are used to optimize the spacing between pairs of aircraft on the approach. As a safety check, field wake sensors confirm the predicted behavior. An AVOSS proof-of-concept was successfully demonstrated in July of 2000 at Dallas Fort-Worth International Airport (DFW). Data collected during the demonstration showed that the reductions in aircraft spacing enabled by AVOSS would result in significant delay reductions at capacity constrained airports. This paper describes the AVOSS architecture and theory of operation, as well as the latest performance results. A description of the field deployments is provided, and plans for system evolution from its current state as a proof-of-concept to one suitable for operational use are discussed.

Table 1. FAA Wake Avoidance Separation Criteria

Following Aircraft, (nm)	Lead Aircraft			
	Small	Large	B757	Heavy
Small	2.5	4	5	6
Large	2.5	2.5	4	5
Heavy	2.5	2.5	4	4

Notes:
Small ≤ 41,000 Maximum Gross Takeoff Weight (MGW)
41,001 lb < Large ≤ 255,000 lb MGW
Heavy > 255,000 lb MGW
2.5 nm separation increased to 3 nm when airport has >50 sec Runway occupancy time

System Design

The AVOSS architecture is shown in Figure 1. The weather subsystem was developed in cooperation with the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, North Carolina State University, and the National Oceanographic and Atmospheric Administration (NOAA). The system consisted of two instrumented towers, Doppler radar and sodar profilers for measuring winds aloft, and a radio acoustic sounding system (RASS) to measure temperatures aloft. At 30-minute intervals, data from these sensors as well as two Terminal Doppler weather radars were integrated into vertical profiles of winds, temperature, and turbulence using a fusing algorithm developed at MIT Lincoln Labs [1]. This data is used as a short-term forecast of the weather that is input to a state-of-the-art wake-prediction model [2]. This model provides estimates of wake transport (lateral and vertical) and strength. The 30-minute interval was considered to be an acceptable amount of time for a persistence-based forecast of the weather while providing realistic lead time for anticipated enroute controller planning. Northwest Research Associates developed the prediction subsystem, with participation from NASA and the Naval Postgraduate School.

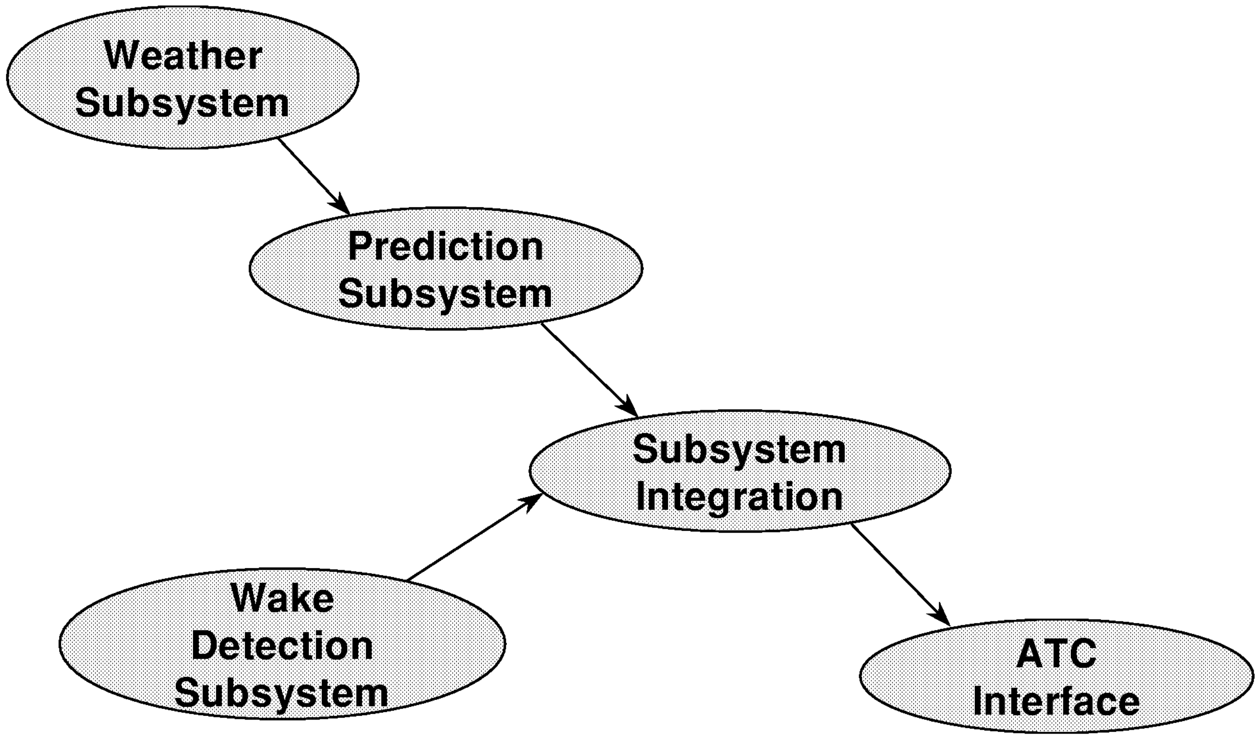


Figure 1. AVOSS architecture

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

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

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

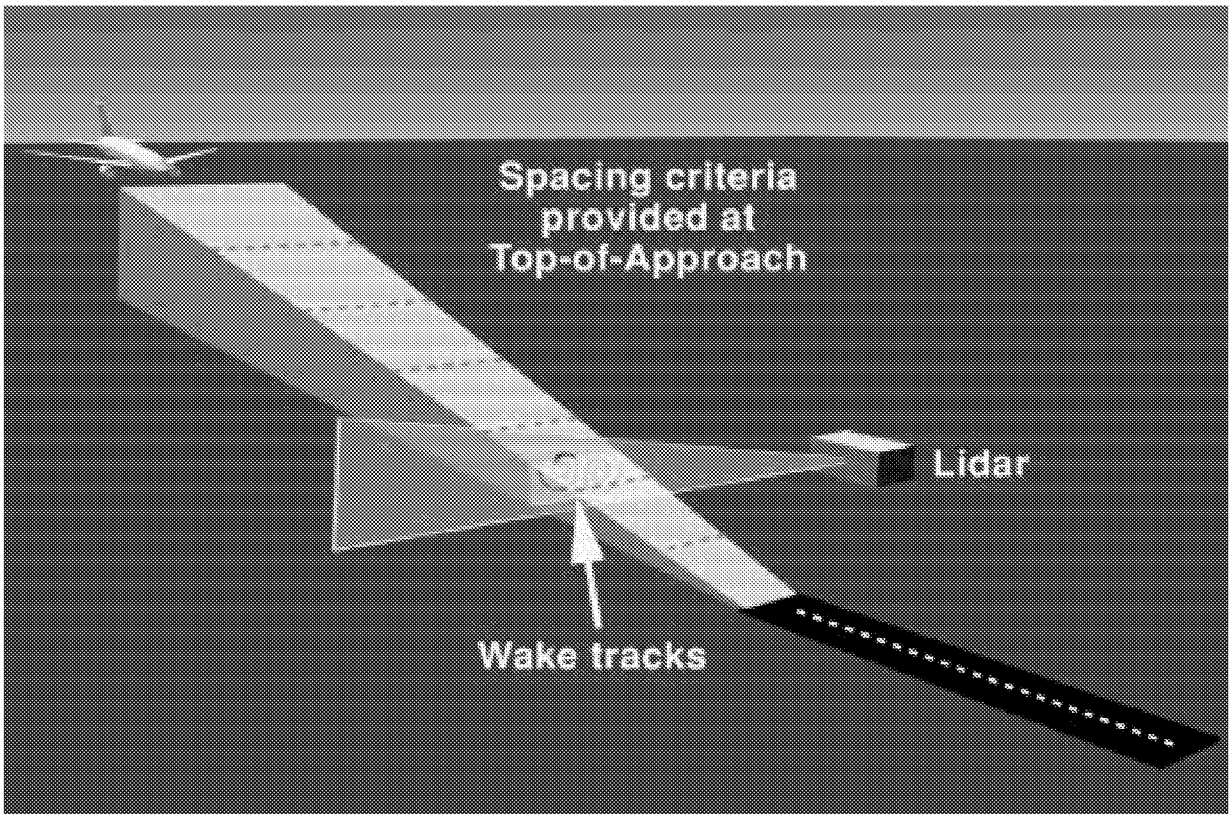
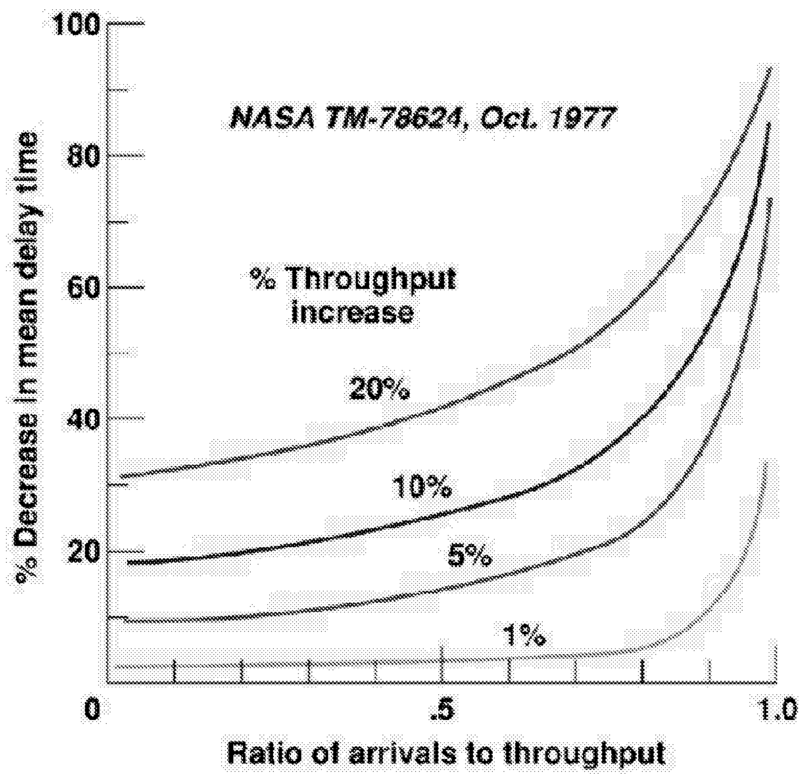


Figure 2. Safety corridor and sensor placement concept

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

AVOSS Performance

Analysis of the field data from the 1999 and 2000 DFW deployments reveals the maximum Instrument Flight Rules (IFR) throughput gain averaged 6%, while ranging from 0% to 16%. The gain is computed by comparing the throughput using the AVOSS spacing recommendation to that achieved with the default FAA spacing. The 0% gain indicates that on some days the AVOSS did not recommend reducing the default spacing. The 16% gain in throughput is approximately equal to the maximum gain possible when comparing the default spacing to the minimum runway occupancy time (ROT) limited spacing. Figure 3 illustrates the importance of these results [4]. The plot shows the relationship between increases in throughput and delay, as a function of capacity. As the demand for a runway approaches maximum capacity (a/t=1), delays increase exponentially, providing the potential for large decreases in delays with relatively small increases in throughput. Many capacity-constrained airports operate near 100% capacity. As the chart shows, for a runway at 90% capacity, a 6% increase in throughput can offer a nearly 40% reduction in delay.



A 6% throughput increase at DFW places 7 aircraft on the ground in an hour that would otherwise be in the air

Figure 3. Impact of throughput increase and delay as a function of capacity

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

Future plans/roadmap to operation

Potential applications

A future AVOSS development notionally referred to as a Wake Vortex Advisory System (WakeVAS) may embrace one of the following concepts: single in-trail or closely-spaced parallel approaches, departures, or intersecting runway operations, depicted in figure 4. Each of these concepts would also require customization to a particular airport. Subsystems for weather and wake sensing, as well as initial procedure development will be site-specific, while weather forecasting and pilot and controller interfaces will be more generic.

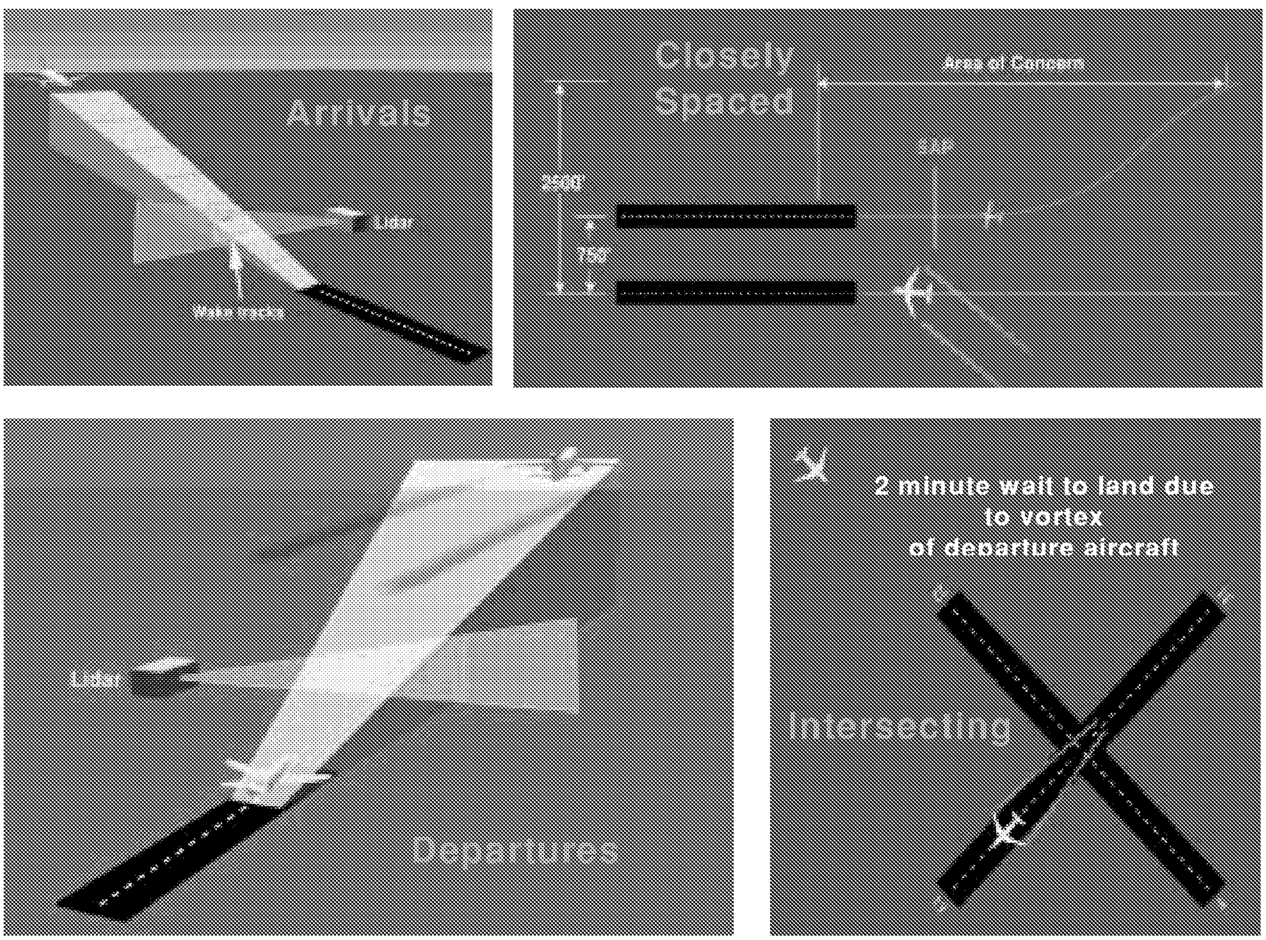


Figure 4. Potential WakeVAS terminal configurations

Single in-trail approaches

The earliest operational deployment of a WakeVAS will likely be for single in-trail approaches, building directly on the results of the AVOSS development, as described earlier. Operational deployment of single in-trail WakeVAS systems would benefit nearly every capacity-constrained airport in the United States. The potential for delay reductions is significant: the impact of the increased spacing for aircraft following the 757 instituted in 1996 resulted in an immediate 12% increase in delays at Los Angeles International Airport [5]. On average, the AVOSS recommended spacing reductions of nearly one mile for large category aircraft following 757s.

Closely-spaced parallel approaches

A closely spaced parallel approach WakeVAS system may offer the greatest potential for delay reduction. Based on AVOSS and similar windline-derived data, wake transport from one runway to an adjacent runway appears to be a rare event. Utilization of appropriate procedures can prevent a problem in Visual Flight Rules (VFR) conditions. During reduced-visibility conditions, however, the inability to use these procedures results in as much as a 50% reduction in arrival capacity, given the loss of the second runway's capacity. A WakeVAS combined with an offset ILS, RNAV, or Simultaneous Offset Instrument Approach (SOIA) arrival procedure may restore the usability of the second runway under most reduced-visibility conditions, since these procedures are designed to lower the operational ceilings at which pilots may accept VFR arrival clearances. Such a combined system could significantly reduce a parallel runway's downtime.

Departures

Separation reductions for single runway departures represent another solution with high potential benefit. Wake vortex spacing requirements are included in both VFR and IFR departure clearances, so a wake-avoidance solution would provide departure capacity improvements during both VMC and IMC. Wake turbulence monitoring and prediction would have to cover both the near-ground area off the runway and any common departure path used by sequential departures. The complexity of a departure WakeVAS would be dependent on the airport and local airspace. Additional impacts, such as interaction with noise abatement and fan-out procedures, may arise.

Intersecting runway operations

An intersecting runway system may also offer an opportunity for early implementation. When arriving and departing aircraft cross each other's paths while airborne, there is a potential for encountering a wake at nearly right angles. A good example is New York's La Guardia (LGA) airport. At LGA, when aircraft are arriving on Runway 22 and departing on Runway 31, controllers frequently need to apply additional separation between aircraft. This situation requires controllers to apply 2 minutes of separation between subsequent Runway 22 arrivals and Runway 31 departures, almost double the separation if wake turbulence were not a factor. Although this airport configuration only occurs about 20% of the time, studies have shown that it accounts for roughly half the delays at LGA. An intersecting runway WakeVAS would likely require less procedural development than would other WakeVAS applications. The system would set the time interval for consecutive operations, to be followed by the controllers, with no other procedural changes required. Since the critical area for potential wake encounters is largely within ground effect, current wake sensors are adequate for detection (no issues of sensor coverage). An intersecting runway system, however, has less nationwide applicability because the number of capacity-constrained airports with an intersecting runway problem is limited.

Initial steps

A NASA-led government/industry team is currently laying the groundwork for a WakeVAS. Participants include: the FAA, MIT/Lincoln Labs, MITRE, NASA, and the Volpe Center. The group is researching subsystem issues such as evaluating existing technologies (including sensors, wake vortex prediction, and other factors) with regard to maturity for deployment of wake-vortex-related systems and procedures.

Work is also focused on identification of candidate airports for the development and deployment of a prototype WakeVAS. Airport selection criteria is based on several factors, including a cost and benefit analysis, the projected impact of the various WakeVAS concepts on airport delay and capacity, and the willingness and ability of the airport authority to participate in advocating and funding a WakeVAS.
Specific definition of user needs at those airports deemed promising will follow. An initial system architecture concept along with an analysis of the technical and operational risks of each type of system will also be developed. An exploration of the proposed architecture will lead to the development of candidate procedures.

The successful development of an ambitious system such as a WakeVAS would not be possible without the participation of all affected users. The formation of working groups is anticipated to focus the entire operational development. These groups would include, at a minimum, professional controller and pilot organizations, airport authorities, airlines, industry, and government agencies. This article represents one element of the initial informational phase.

Phased implementation approach

It is envisioned that the initial deployment of a WakeVAS would be a limited system, likely based on subsystem confidence levels. For example, wake behavior must initially be measured from the runway to the glide-slope intercept height to verify that the wake predictions are reliable. To date, only low altitude (below 600 feet) wake behavior has been measured. Phased testing can be done with ceilings above the glide slope height to establish the zone over which an operational WakeVAS would need to sense wake behavior. Research to date indicates that wake behavior at altitudes above ground effect (approximately twice the wingspan of the generating aircraft) is more accurately predicted and may not require sensor verification in an operational system. If this were determined to be the case, then ceilings would only need to be above 300 to 600 feet to use lidars for wake sensing. Historical data (see figure 5) shows that with a ceiling limit of 300 feet (approximately the final mile of a standard approach), and a wake sensor limited

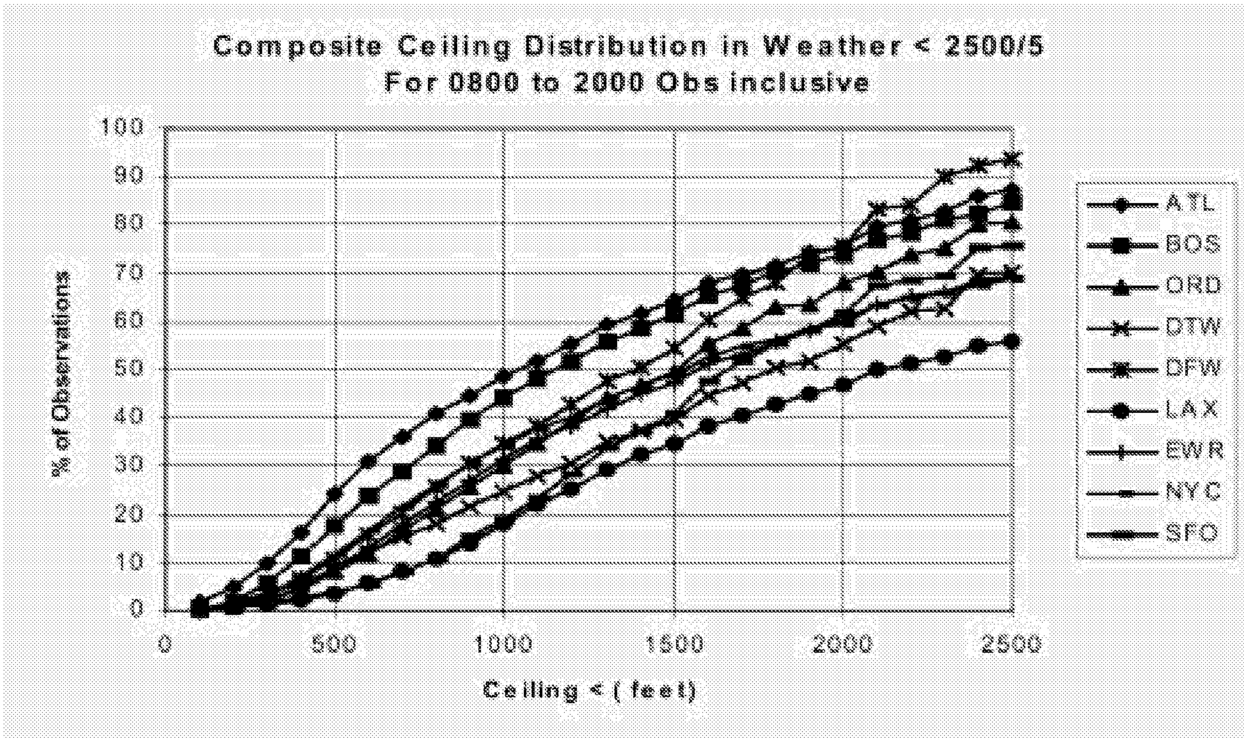


Figure 5. Hourly ceiling and visibility data collected from 1961-1990 at various airports

by ceiling (i.e. lidar) a WakeVAS would still have about 90% availability in instrument approach conditions [6]. All-weather wake sensors are therefore not required for a usable WakeVAS.

Conclusion

NASA has developed a proof-of-concept Aircraft VOrtex Spacing System (AVOSS). Successfully demonstrated in a real-time field demonstration during July 2000 at the Dallas Ft. Worth International Airport, AVOSS is a novel integration of state-of-the-art weather sensors, wake sensors, and analytical wake prediction algorithms. Gains in airport throughput if AVOSS spacing were used as compared to the current criteria averaged 6%, with peak values approaching the theoretical maximum of 16%. The average throughput gain translates to 15-40% reductions in delay when applied to realistic capacity ratios at major airports. A low percentage (1%) of validation measurements indicated variances in the system that need to be eliminated as the system is developed for operational use.

A NASA-led government/ industry team is working to define the requirements for an operational system. High-level concepts for single and parallel approaches, departures, and intersecting runways are being studied. AVOSS subsystem maturity levels are being assessed and cost benefit analyses are being conducted to target potential WakeVAS locations and configurations offering the lowest risk/highest payoff for a phased introduction. Stakeholder support is being generated through team communication, leading to the eventual formation of working groups to guide development and implementation.

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2001	Technical Memorandum

4. TITLE AND SUBTITLE
Enhanced Airport Capacity Through Safe, Dynamic Reductions in Aircraft Separation: NASA's Aircraft VOrtex Spacing System (AVOSS)

5. FUNDING NUMBERS
WU 727-01-26-02

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18112

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2001-211052

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 03 Distribution: Nonstandard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
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14. SUBJECT TERMS
Air Traffic Control; Airport capacity; Wake vortex

15. NUMBER OF PAGES
15

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL