

Measurements of Aircraft Wake Vortex Separation at High Arrival Rates and a Proposed new Wake Vortex Separation Philosophy

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Abstract

This paper presents data and a proposed new aircraft wake vortex separation standard that argues for a fundamental re-thinking of international practice. The current static standard, under certain atmospheric conditions, presents an unnecessary restriction on system capacity. A new approach, that decreases aircraft separation when atmospheric conditions dictate, is proposed based upon the availability of new instrumentation and a better understanding of wake physics.

Background

In the United States, current safe wake vortex separations are achieved with a set of rules for air traffic control and procedures for pilots. The pilot procedures apply any time aircraft are conducting visual approaches and departures. The procedures are based on a general understanding of wake behavior. They include taking off prior to the liftoff point of a preceding heavier aircraft; landing beyond the touchdown point of a heavier aircraft; and remaining above the flight path of a heavier aircraft. The rules are based on the general observation that wakes sink

when out of ground effect, and tend to separate laterally when in ground effect. Ultimately, the responsibility for wake avoidance lies with the pilot during visual operations.

In Instrument Meteorological Conditions (IMC), pilots cannot necessarily see other aircraft so the controller has the responsibility to provide separation of aircraft for wake avoidance. The separation is achieved with a set of rules found in the Air Traffic Controller's Handbook [1]. These rules depend on the airport configuration and type of operation (arrival or departure). The rules for the airport terminal area are summarized in Table 1. Note that the departure rules are an exception applied both in Visual Meteorological Conditions (VMC) and IMC.

Also note that for non-radar, timed instrument approaches, the nominal separation is 120 seconds, but it is increased to 180 seconds for small aircraft behind heavy aircraft due to wake concerns. The controller has the responsibility of spacing aircraft such that the separations in Table 1 are maintained. The FAA has the responsibility to ensure that the separations in Table 1 are adequate for wake hazard avoidance.

Table 1 Summary of FAA Wake Vortex Separation Rules

Type of Terminal Operation	Single Runway or Parallel Runways Less than 2500' Apart	Intersecting Runways
Departures	<p>Behind B757 or heavy- 120 second hold; 180 seconds if intersection or opposite direction same runway</p> <p>OR</p> <p>Radar separation minima</p> <ol style="list-style-type: none"> 1. Heavy behind heavy- 4mi 2. Large/Heavy behind B757 –4mi 3. Small behind B757 – 5mi 4. Large behind heavy – 5mi 5. Small behind heavy – 5mi <p>For pairs not listed the separation is 3 miles</p>	<p>120 seconds behind B757 or heavy departure or landing if projected flight paths will cross; includes parallel runways more than 2500' in separation if will fly through the airborne path of other aircraft</p>
Arrivals	<p>Radar separation minima (at threshold):</p> <ol style="list-style-type: none"> 1. Heavy behind heavy- 4mi 2. Large/Heavy behind B757 –4mi 3. Small behind B757 – 5mi 4. Large behind heavy – 5mi 5. Small behind large – 4mi 6. Small behind heavy – 6mi <p>For pairs not listed the separation is 3 miles, except 2.5 miles in cases when 50 second runway occupancy time is documented</p> <p>Non-radar minima: 120 seconds for aircraft landing behind an arriving Heavy/B757, except if follower is small then 180 seconds</p>	<p>120 seconds for aircraft arriving after a departing or arriving B757 or heavy if arrival will fly through the airborne path of other aircraft</p>

Table 1 are maintained. The rules for wake avoidance were determined empirically with experiments such as tower flybys with wingtip smoke generators, and represent the *worst-case estimation of wake behavior*, which is necessary for any *static criteria* where safety is of utmost importance. Over the 30+ years of wake vortex research much progress has been made in quantifying the wake behavior as influenced by atmospheric factors such as winds, turbulence and thermal stratification. Wake vortex avoidance rules that are sensitive to the environmental influences on wake behavior could provide much more efficient spacing criteria than the worst-case criteria currently

used. This is an increasingly important consideration as we approach airport capacity limitations.

Research to date indicates substantial capacity improvements can be achieved by reducing wake constraints. In [2] the average 6% potential throughput increase achieved in the Dallas Aircraft Vortex Spacing System (AVOSS) demonstration would result in as much as a 40% delay reduction at airports operating near capacity limits, such as Atlanta International Airport. The Massachusetts Institute of Technology's Lincoln Labs completed a benefit study [3] in which a simulation of departure

operations at Dallas/Ft. Worth projected a yearly savings of five to ten million dollars from reduced delays resulting from reducing wake separations.

The potential savings at many closely spaced parallel runway airports, that must reduce operations from two to one runway under IMC, may be even greater. It is clear in these projections that not every factor has been addressed or analyzed in a system as complex as the National Airspace System (NAS). The potential benefits may be reduced because of these factors. Therefore, a wake concept of operations that addresses capacity limitations must be adaptable and able to improve wake-constrained efficiency in a variety of operations.

Previous Work

The AVOSS project provided an impetus to advance the state-of-the-art in wake modeling and sensing technology, as well as weather sensing to support predictions of wake behavior. These technologies were integrated to address the single runway arrival radar separation rules. Current weather conditions relevant to wake behavior were sensed and used as a persistence-based forecast to provide inputs to real-time wake prediction algorithms that were considered valid for a specified time interval. The predicted wake behavior was applied to a region of monitored airspace called the safety corridor, which was a rectangular region centered on the Instrument Landing System (ILS) localizer and glideslope. Wake hazard or residence times in the corridor were used to compute required spacing for wake avoidance. Wakes could cease to be a hazard by 1) sinking below the floor of the safety corridor, 2) being advected laterally from the corridor by crosswinds, or 3) decaying to a specified value. Real-time wake sensing systems such as pulsed and continuous-wave (CW) lidar, and wind-lines were used to check the results of the prediction system. A prediction of wake behavior is required in addition to the sensors since spacing recommendations need to have some practical amount of lead-time and be stable for a certain time interval. For detailed descriptions of the AVOSS see refs [4,5].

Concept Design

NASA Langley has generalized the system configuration demonstrated in AVOSS to a concept for minimizing the impact of aircraft

wakes on operations by applying the AVOSS technologies at potentially any airport with any operational configuration. The core enabling components of AVOSS do not depend directly on the operational application to which they are applied, but the overall system configuration must be modified for the airport runway configuration and procedures. The AVOSS technologies produced substantially improved knowledge of wake position and strength as compared to that implied by current wake separation procedures, and this knowledge can be used to maximize efficiency in all airport operations. This can be understood further by considering the common requirements for a Wake Vortex Avoidance System (WakeVAS). Figure 1 shows a functional diagram of such a system.

As the flowchart in Figure 1 shows, a region of airspace that will be monitored and assessed for wake hazard must first be defined. This region is a rectangular region centered on the ILS localizer and glideslope for single-runway approaches in AVOSS, but it could be a wider “fan” for departures, a cross around the intersection of intersecting runways, or a rectangle around a parallel runway complex. The dimensions of the region imply requirements on the range and resolution of all the sensors used in a WakeVAS. Once the region is defined, it can be monitored with active wake sensors and prediction algorithms. When the monitoring shows or predicts the region to be free of wake hazard with a certain level of confidence, reduced spacing procedures can be applied. In the upper branch of Figure 1, a technology-independent solution is suggested where current wake knowledge implies a permanent, static change to separation criteria in a limited number of specific operations. An example is the 2500-foot rule, where parallel runways separated by less than 2500’ must be considered a single runway for wake avoidance procedures. It may be possible to relax this requirement to a number less than 2500’ for specific airports because of local predominate meteorological conditions. The majority of locations and operations are likely to require some kind of active monitoring and dynamic procedure for an overall significant benefit to the NAS. The lower branch of Figure 1 shows this type of system, which requires a safety monitor due to the predictive element of ensuring the protected region is free of wake hazard. The safety monitor “catches” instances of actual conditions diverging from the predicted

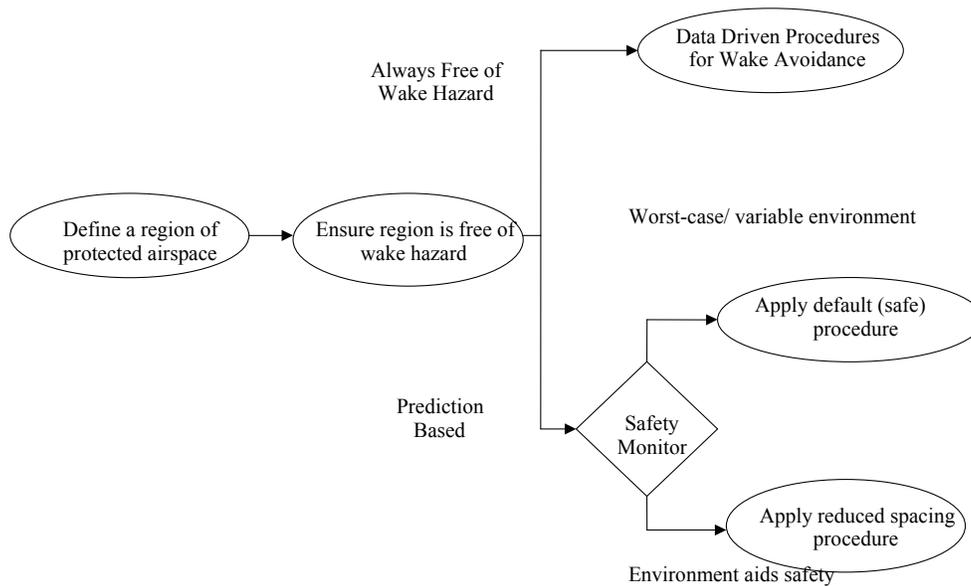


Figure 1 WakeVAS functional block diagram.

conditions, and a default or fallback procedure is applied.

The current discussion has used examples of a ground-based network of sensors and systems to protect a region of airspace by issuing a wake vortex advisory to a controller. Another potential integration of the concept into the NAS is as a flight deck system. Wake predictions and/or observations could be presented to pilots through a Synthetic Vision System (SVS) [6] or a Cockpit Display of Traffic Information (CDTI) display, using on board sensors and computation or a data-link to a ground based system. This concept, studied in [7], would place the responsibility of wake avoidance back on the pilots in all meteorological conditions. This is not a large paradigm shift in terms of wake avoidance procedures, since currently under VMC pilots remain clear of a preceding aircraft's wake by adjusting the flight path based on a crude understanding (and mental prediction) of wake behavior and assessment of the current weather conditions. The large paradigm shift lies in whether synthetic vision systems allow for the introduction of "Electronic Flight Rules" where pilots see and avoid other aircraft and terrain under IMC using a virtual visual representation of the flight environment. It is reasonable to project that this technology will be

utilized in at least a subset of NAS operations in the future.

A time-based inter-arrival spacing tool described in [8] could be used to accurately achieve WakeVAS spacing recommendations. The spacing tool is a flight deck resource that allows pilots to accept precise time intervals as a spacing clearance from a leading aircraft. The tool would reduce variances in spacing produced by current speed-based clearances and improve the benefits realized by the WakeVAS.

For a synthetic vision wake display, the output of the WakeVAS is sent to airborne displays and used for situational awareness by the flight crew. For application as a controller tool, the interface may be integrated into a final approach spacing tool or as an advisory from the Integrated Terminal Weather System (ITWS) [9]. Air traffic controllers use the system output to guide clearances given to the flight crew. It is important to note that for the controller tool implementation of the WakeVAS, dynamic separation rules will be required. If pilots use new tools to see and avoid other aircraft and the associated wakes, the current procedures used in VMC may apply. Finally, knowledge of reduced wake spacing procedures in effect at certain locations where the weather permits may need to be available to the local and national traffic

management components of the NAS, since airport acceptance rates will be affected.

The WakeVAS concept is consistent with the FAA’s Operational Evolution Plan (OEP) for the NAS [10]. Under the objective “Keep Terminal Throughput Closer to Visual Levels in all Weather Conditions” there are two solutions that depend on wake vortex spacing limitations. These are “Maintain Runway Use in Reduced Visibility”, and “Space Closer to Visual Standards”. Changing the wake vortex separation rules concerning parallel arrivals and departures in Table 1 enables allowing some parallel runways to remain independent under reduced weather minimums. Similarly, reduced separation on approach and departure for all runway configurations requires reduced wake spacing rules to support spacing closer to visual standards. WakeVAS concepts are also consistent with the RTCA 2000 NAS Concept of Operations [11]. In Chapter 5, “Arrivals and Departures”, the RTCA document describes

automatic exchanges of information between service providers and aircraft to include weather and hazard alerts such as wind shear, microburst, and wake vortex. Specifically, the RTCA document calls for increased pilot situational awareness through the use of CDTI, to be expanded to include wake vortex separation with other traffic. Increased use of Flight Management System (FMS) approaches is also considered, and real-time weather data links mentioned in the document will enable these approaches to use weather-dependent wake vortex separation criteria. Finally, the RTCA recommends using enhancements in real-time wake turbulence detection and prediction to enable VMC traffic rates in IMC. These may be realized, in part, by information provided to the service provider to enable dynamic wake separation rules.

A preliminary list of candidate airports to use for testing a dynamic wake vortex separation system in the US is shown in Table 2 [12].

Table 2 Preliminary List of Candidate WakeVAS Airports

Airport	ATL	BOS	DFW	EWR	LAX	LGA	ORD	SFO	JFK
Type of runway configuration	2 pair Closely-Spaced Parallel Runways (CSPRs)	CSPR & Intersecting	2 pair CSPRs	CSPR & Int.	2 pair CSPRs	Int.	Int.	2 pair CSPRs	2 pair indep.
Operation tested	Single-rwy Arr. & Dep.	CSPR & Int. Arr. & Dep.	Single-rwy Arr. & Dep.	CSPR & Int. Arr. & Dep.	CSPR Arr. & Dep.	Int. Arr. & Dep.	Single-rwy & Int. Arr. & Dep.	CSPR Arr. & Dep.	Single-rwy Arr. & Dep.
% B757 & Heavy	22	12.9	11.3	12.2	20.8	9.1	10.3	24.9	31.1
% hours below VMC for CY2000	35	34	31	22	55	25	39	49	28

Wake Vortex Separation Data under VMC and IMC at High Arrival Rates

Recent data was taken at two high operation rate airports to determine actual separation probability density functions for use in both capacity and safety simulation models. Atlanta Hartsfield (ATL) and New York La Guardia (LGA) airports were chosen for specific study

due to their extremely high operational arrival rates as published in the Department Of Transportation Capacity Benchmark Study [13]. Several days of data were recorded to approximately 1 second accuracy, recording inter-arrival separation time at runway threshold,

aircraft type, weight category, and runway occupancy time. The full details of the data collection and analysis are described in [14].

Adequate data was collected in both IMC and VMC at LGA, but only VMC data was collected at ATL. Arrival rates at both airports ranged between 32 to 39 arrivals per runway per hour. A histogram of four data sets is shown in Figure 2. It is striking how similar these inter-arrival time distributions are to each other and suggest that they are a manifestation of the stochastic

system characteristics, FAA procedures and operational technology. Analysis indicates that all of these distributions can be represented with 95% confidence by a suitably selected sum of Gaussian distributions. It is also noteworthy that both the LGA VMC and IMC distributions are almost identical. Since very short inter-arrival times were observed at both airports, the data was normalized based upon official wake vortex separation standards and is plotted for ATL (under VMC) Figure 3.

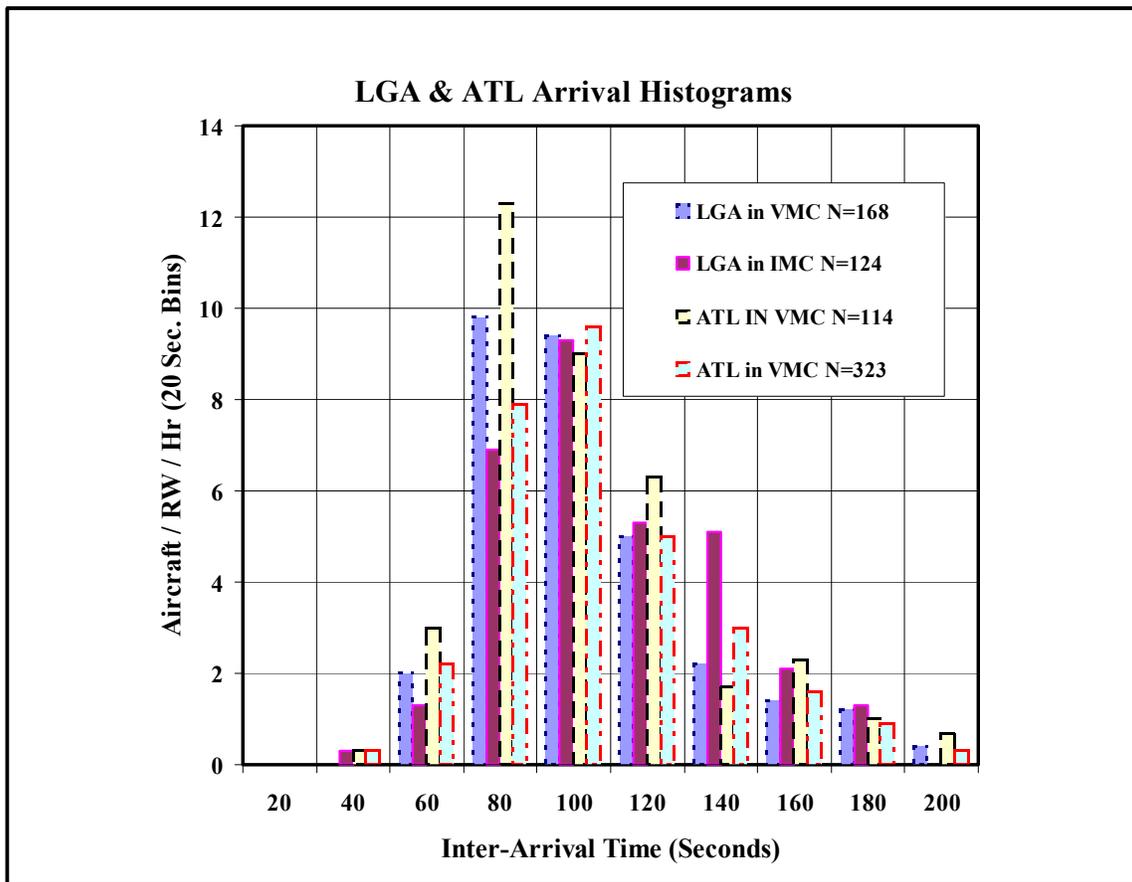


Figure 2 Histograms of inter-arrival times at LGA and ATL. These distributions are well represented by a combination of Gaussian distributions. Note the significant number of aircraft landing less than 90 seconds apart.

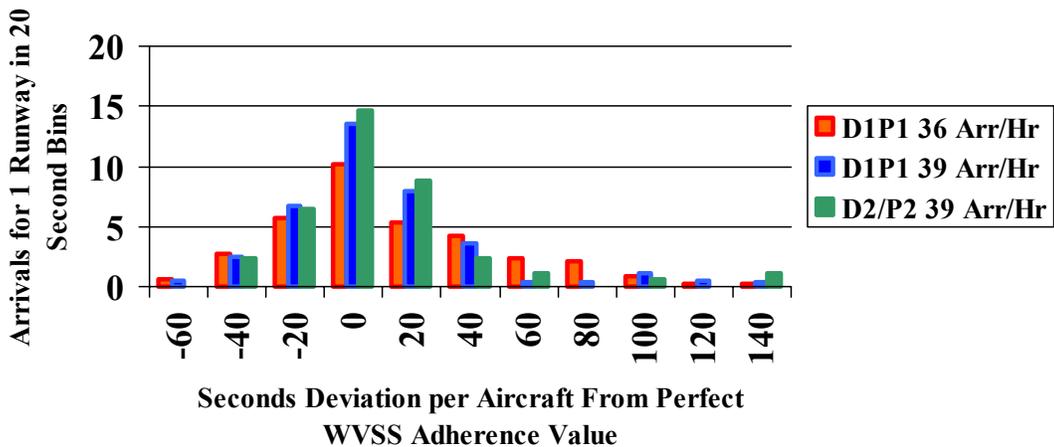


Figure 3. ATL inter-arrival times normalized by Wake Vortex Separation Standard (WVSS) times. The largest deviations are frequently large aircraft following small.

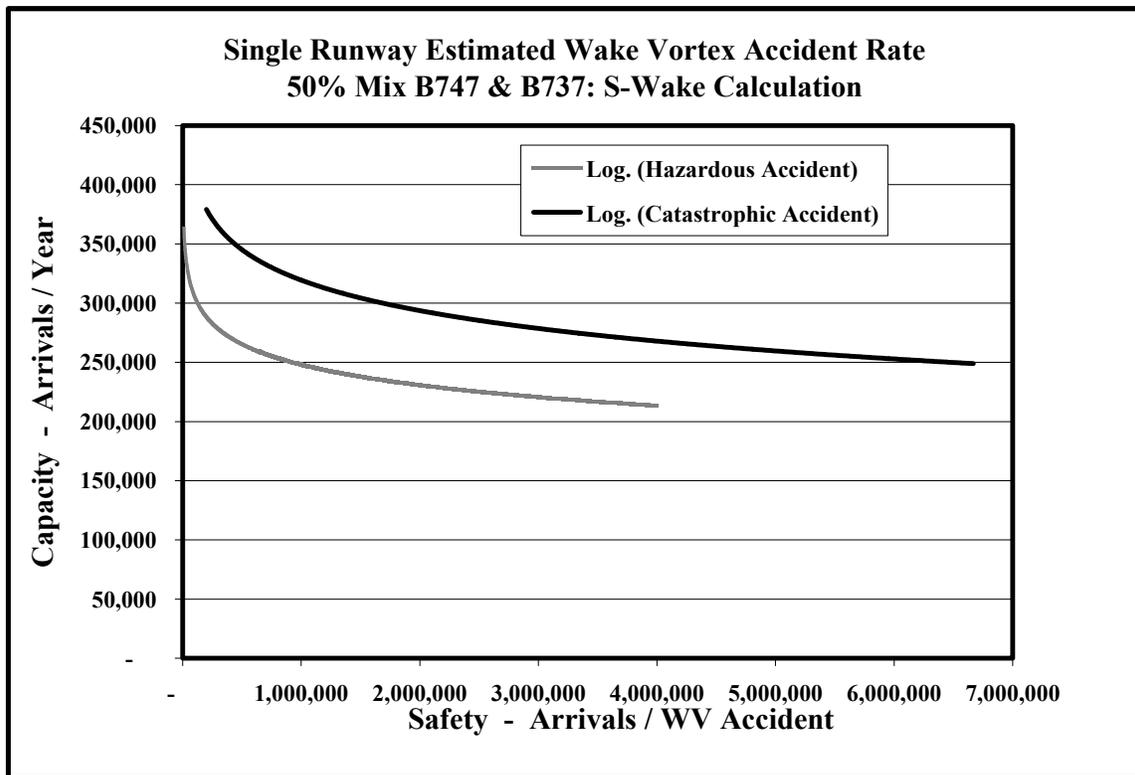


Figure 4. Simulated Hazard Probability estimates for a hypothetical aircraft mixture using the NRL IWAKE models. These calculations assume a Heavy-Large aircraft mixture and uniform spacing as a function of arrival rate. Note that for 250,000 arrivals/rw/year (approx. 75 sec separation), this calculation predicts 26 years between catastrophic accidents.

Approximately 30% of all of these arrivals were observed to be short of FAA wake vortex separation standards. These arrival rates are routinely observed at LGA and ATL under both instrument and visual flight rules. Since no hazardous wake vortex incidents have been reported at either of these airports in the near terminal area, one may question whether the current static wake vortex standards are unnecessarily conservative. Using unpublished data from the National Aerospace Laboratory of the Netherlands (NLR) wake vortex hazard analysis and current levels of safety, one can predict that for a pure mix of 50/50 Heavy/Large aircraft there would be 26 years between catastrophic accidents at a 75 second separation arrival rate. An acceptable time interval between catastrophic events is a policy decision and subject to debate. The relationship is logarithmic and shown in Figure 4.

Conclusions

Both the US and Europe are using static wake vortex aircraft separation criteria. This separation criteria was set at a time when airport capacity and delay was not an issue. Today, this separation criteria establishes the capacity limits of our air transportation system and is one of the safety frontiers that limits future growth in operations. The increasing movement to a mixture of heavy and small aircraft exacerbates this problem. It is time to apply our considerable knowledge of wake vortex and atmospheric physics behavior and modern instrumentation to a more dynamic wake vortex separation standard. The standard recognizes safe runway occupancy time as the fundamental separation criteria, with wake vortex separation added only when a wake vortex hazard exists. NLR has pioneered methodology for estimating hazard levels and this methodology should be expanded as the basis for future international standards discussions.

Acknowledgements

This work was conducted under a combination of funding from both NASA and the US Army. NASA supports WakeVAS work at LaRC through the Virtual Airspace Modeling and Simulation Project and cooperative efforts with the FAA. The measurements of wake vortex spacing at ATL and LGA were funded by the US Army in support of R. C. Haynie's Ph. D. dissertation at George Mason University.

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David is a research engineer at NASA Langley Research Center. He is the technical lead for WakeVAS development. He has a BSEE from the University of Dayton and a MSEE from University of Arizona, and is currently undertaking study at Virginia Tech for his Ph. D. in Electrical and Computer Engineering. David holds commercial and instrument fixed-wing pilot ratings.

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