WAKE VORTEX AVOIDANCE SYSTEM

W. Bryant, S. Lang, J. Tittsworth, Federal Aviation Administration, 800 Independence Avenue SW, Washington, DC USA
S. Darr, Dynamic Aerospace Inc., Sharon, MA

ABSTRACT

There is an urgent need to increase airport capacity without building new runways. Aircraft separation based on wake vortex (WV) mitigation significantly affects airport capacity. While the ICAO WV standards established in the 1970's are effective for safety, they are more conservative than necessary to preserve safety; and thus unduly reduce airport capacity. The FAA and NASA have developed an integrated, time-phased approach to meet the needs of the aviation community in lessening the impact of wake turbulence on airport operations. The U.S. National Airspace System (NAS) is developing transition plans to evolve from today's operations to a future system called Next Generation Air Transportation System, or NextGen. NextGen goals include a capacity improvement of 2 to 3 times today's system capacity. To achieve this goal, improvements in communications, navigation, surveillance, and weather technologies must be integrated with wake avoidance solutions and ATC and flight deck procedures and tools. In addition, the safety of the total solution must be demonstrable to the stakeholders and regulatory authorities.

This paper presents the elements of a Wake Vortex Avoidance System (WakeVAS) and describes the progress made to date in maturing some of its elements and implementing them as evolutionary steps towards NextGen. Key system performance requirements and the process for defining them are presented for some of the matured elements. Less mature elements of a WakeVAS are also described in terms of observed performance characteristics when used in research mode (e.g., LIDARs) as well as fundamental research issues that need to be addressed before these elements can be considered for inclusion in a WakeVAS. Some of this work is being accomplished in cooperation with the European research community. Lessons learned from safety case development for Simultaneous Offset Instrument Approaches and Lambert – St. Louis International Airport (STL) dependent approach procedures are highlighted with insight into their extensibility to more complex solutions such as Wake Turbulence Mitigations for Departures (WTMD).

1. INTRODUCTION

In the United States, the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) have worked the science of wake turbulence. In the early part of the current century, FAA and NASA formed a partnership to capitalize on the strengths of both organizations. One outcome of this was a concept of WakeVAS (Wake Vortex Avoidance System). This was to be the end-state system of systems that would provide the best technology and knowledge-based solutions for dealing with the hazard of aircraft created wakes. While WakeVAS was identified as a system solution, it was more an integration of all wake solutions to enable increased airspace capacity while maintaining or improving NAS safety.

As previously stated, NextGen was to be the integration of all solutions affecting components of the air traffic system and WakeVAS was to be the integration of all wake solutions developed for NextGen. This portrayal indicates an evolutionary path to NextGen. The FAA and NASA, through their partnership, had identified the need for solutions to build on each other. It was through this incremental path of development that significant changes to wake separations could be made. This allows us to gain interim capacity increases generated by each sub-element rather than waiting for the full WakeVas capacity increase some 10-15 years in the future

1.1. NextGen

NextGen is the term used for the future state of the air transportation system in the United States. This can be compared to Sesar within Europe. While this is a fairly generic term, it signifies significant changes in how air traffic will be handled in the future, from trajectory based operations (TBO), to changes in both Surveillance and Wake Turbulence separation standards. NextGen is viewed as the required changes to meet the demands placed on the air transportation system by the projected increases in the number of aircraft operations in the future. This paper focuses on one aspect of NextGen, that of Wake Turbulence separation changes, needed to allow for future increased demand. Whilst the changes to Wake separation is envisaged being possible through better understanding of wake phenomenology and technology, these changes can only occur through their connection to the other facets of an air traffic system, Surveillance, Navigation, Communication and Procedures.

1.2. WakeVAS ConOps

In the United States, FAA and NASA have worked the science of wake turbulence. In the early part of the current century, FAA and NASA formed a partnership to capitalize on the strengths of both organizations. One out come of this was a concept of WakeVAS (wake vortex avoidance system). This was to be the end-state system of systems that would provide the best technology and knowledge based solutions for dealing with the hazard of aircraft created wakes. While WakeVAS was identified as system, it was more an integration of all wake solutions that could be developed to enable increased airspace capacity and while maintaining or improving NAS safety.

NextGen is to be the integration of all solutions affecting all components of the air transportation system and WakeVAS is to be the integration of all wake solutions developed by NextGen. This portrayal indicates an evolutionary path to NextGen. The FAA and NASA through their partnership had identified the need for solutions to build on each other. That it was through incremental development that significant changes to wake separations could be made. This evolutionary path allows us to gain incremental capacity increases generated by each sub-elements rather than wait for the full WakeVAS capacity increase some 10-15 years in the future.

1.3. Evolutionary Path of WakeVAS to meet NextGen Objectives

The NextGen Air Transportation System Integrated Plan specifically identifies the potential for increased use of wake vortex measurement and prediction systems to increase landing and departure capacity at airports. It also identifies reduced separation standards as an element of enhanced air traffic management operations. The Integrated Plan identifies the provision of wake vortex strength and location prediction as a transformation direction intended to provide more context relevant information for aircraft operators, air traffic service providers, airports, and transportation service users.

The wake vortex research conducted jointly during the period 2000 – 2006 by the FAA and NASA is segmented into evolutionary elements that support the NextGen objectives detailed above. These segments are described in greater detail in sections 2.1 through 2.3, and consist of near-term procedural changes, mid-term wind-based operational concepts, and far-term active prediction and pair-wise spacing concepts. In the continuing development of the NextGen Concept of Operations, the Integrated Work Plan, the R&D Plan, and the NextGen Enterprise Architecture, the joint FAA-NASA wake vortex research program provides information to the Joint Planning and Development Office through the JPDO working groups to ensure the JPDO products accurately reflect the research plan. Conversely, the USA wake vortex research program is coordinating with the JPDO to ensure it is supportive of the NextGen objectives.

2. WAKEVAS ELEMENTS

The FAA and NASA developed the joint Wake Turbulence Research Program to address all airport capacity constraints related to wake turbulence avoidance and mitigation procedures. This research, development, and operational implementation program is designed to produce a time-phased series of enhancements in airport arrival and departure operations, based on three expected initial implementation periods: near-term (2006 – 2008), mid-term (2008 – 2012), and far-term (2012+).

Until recently, both planning and execution of the Program were being pursued through coordinated actions of both agencies. The FAA led all of the near-term and the early parts of the mid-term Program elements, as well as the weather and wake vortex data acquisition and analysis activities to support them. NASA led the later mid-term and all of the far-term Program elements. NASA led the far-term data collection and analysis activities, including research and development on new types of wake sensors. Both agencies jointly designed the wake research analytical and visualization tools that will be used to support all the Program elements.

In 2006, NASA re-directed its wake vortex commitment to focus on the development of a probabilistic wake vortex predictor and eliminate its activities for field deployments of mid-term or far-term prototypical components. The FAA assumed as much of the former NASA-led activities as possible given the available resources. Encouragingly, the characteristics of the FAA multi-phase program remain as defined in the former FAA/NASA joint program and are described below.

2.1. Near-Term Procedural Changes

Improving airspace access and modifying separation standards to increase capacity is an essential part of the capacity objective of FAA’s Flight Plan 2007 –2011. The Flight Plan defines an initiative to “Improve safety and increase throughput using wake turbulence monitoring, operational procedures, and controller tools.” MITRE/ CAASD and Logistics Management Institute have estimated that airports with CSPRs, such as Cleveland, St. Louis, and Detroit, could obtain a 20 to 40% increase in their airport acceptance rate during some conditions requiring instrument approaches. For example, a feasibility evaluation of authorizing parallel, dependent (paired) ILS approaches at St. Louis airport (STL) showed a projected increase in the acceptance rate of approximately 50%.

Currently, parallel dependent ILS approaches may be conducted to CSPRs with runway centerline spacing of at least 2,500 feet (and up to 4300 ft) with a minimum 1.5 NM diagonal separation between aircraft on adjacent runways. For this separation to be used between all aircraft on adjacent runways, aircraft are limited to the Large (41,000 to 255,000 pounds) and Small (under 41,000 pounds) wake classes. CSPRs spaced less than 2,500 feet are treated as a single runway, with a minimum separation of 3 NM (or 2.5 NM in certain circumstances) separation diagonally to aircraft on the adjacent runway or in-trail to aircraft on the same runway. This reduces the arrival rate of the runway pair to a single-runway arrival rate. Enabling the use of the 1.5 NM separation on CSPRs less than 2,500 feet, and thus regaining the higher two-runway arrival rate, requires that wake turbulence behavior in all weather conditions be characterized with sufficient fidelity to determine that the 1.5 NM separation is safe. This CSPR enhancement has been researched for parallel runways at STL, which are spaced 1,300 feet apart, and a variance from the 2500’ rule granted.

To conduct this research, the FAA installed a comprehensive array of weather and wake vortex sensing, analysis, and recording systems at STL that covered the volume of airspace at the approach end of runways 12L and 12R, and the approach to the 12’s at approximately 1000’ AGL. A pulsed-lidar wind and wake sensor system collected data from 2003 until 2006 to capture weather and wake behavior through all four seasons and to provide a sufficient number of weather and wake observations for a statistically significant sample for safety analyses. The STL data supported a waiver at that airport; additional data may be collected at other airports to support a national rule change to the “2,500 foot rule”.

The near-term research will ultimately determine the minimum runway spacing that is needed, as a function of threshold offset, to avoid a wake encounter by the trailing aircraft in all weather conditions when the leading aircraft weight is limited to the Large and small wake categories, without requiring any new technology. To safely capture additional capacity where Heavy or B757 aircraft are leading a pair, or on runways with less runway centerline spacing than determined in the near-term research to be safe in any weather conditions, WakeVAS contains mid-term and far-term elements that utilize new technology development for weather-dependent wake mitigation systems and procedures.

2.2. Mid-Term Wind Based Changes

The research to support the mid-term objectives will develop new technologies to obtain additional capacity benefits at airports with CSPRs, and for single-runway arrivals, departures, and intersecting runway operations, in certain weather conditions that support transport of the vortices for safe follower aircraft operations. The research will focus on systems that can sense and predict weather conditions causing wake vortices to be transported away from the flight path of trailing aircraft. Once these technologies are developed, WakeVAS can safely increase airport capacity to the extent that local weather conditions, the airport’s configuration, and its traffic mix will allow. Such systems could not only increase CSPR arrival capacity in instrument conditions, making it closer to visual approach acceptance rates, but also improve CSPR and single-runway departures and intersecting runway operations, enabling quicker recovery from adverse weather events such as convection that restrict airport operations.

The mid-term WakeVAS elements include the development and evaluation of systems that sense and predict crosswinds that prevent wake transport to the trailing aircraft path in a paired approach to CSPRs, in CSPR departures, or transports leading aircraft generated wake vortices away from the flight path of the trailing aircraft in single-runway approaches or departures. These crosswind prediction systems, when coupled with flight operations and air traffic procedures changes and training, potentially allow wake-independent approaches and departures on CSPRs and single runways for all classes of aircraft (including Heavy and B-757 aircraft) when weather conditions meet wind independence criteria for trailing aircraft. These additional capacity enhancements will likely require major improvements in the sensing and forecasting of terminal winds plus a capability to monitor the system and provide a safety alert in the event that its wind predictions are not met by actual conditions. These wind persistence algorithm improvements are currently under evaluation at St. Louis and Houston Intercontinental Airports.

2.3. Far-Term Active Prediction and Pairwise Spacing

The far-term WakeVAS elements include more comprehensive monitoring of weather variables and wake vortices to provide an accurate prediction of wake position in both the horizontal and vertical dimensions, as well as a prediction of wake demise. This enables additional revisions in wake mitigation procedures based on all of the meteorological factors enabling the avoidance of wake vortex encounters – not only crosswind conditions. To take full advantage of these weather and wake prediction systems, related enhancements may also be needed in: communications; navigation capabilities enabling aircraft to precisely follow wake-independent arrival and departure routings; enhanced surveillance to detect deviations from these routings; improved automatic weather data downlink from aircraft in the terminal area; and controller decision support tools or pilot displays of leading aircraft position or other information. Many of these enhancements are already planned in other NAS modernization programs.

Far-Term systems include additional ground-based (and perhaps airborne) technologies to sense atmospheric turbulence and wake position, and to reduce aircraft positional variation as well as to improve the surveillance of aircraft position. These technologies may include: air-to-ground and potentially air-to-air weather datalink; required navigational performance area navigation (RNP RNAV) systems; automatic dependent surveillance-broadcast (ADS-B), and cockpit display of traffic information (CDTI). The far-term WakeVAS may provide additional capacity gains by enabling “wake independent conditions” to be determined to be available most often, based on the most complete information on the position of aircraft and their wakes, and all relevant weather conditions. This far-term capability also has the highest cost.

The WakeVAS research will provide the FAA and the aviation industry with enhanced wake turbulence procedures through technically feasible technology options that increase capacity while meeting safety requirements. The FAA Program’s multi-phase approach provides intermediate solutions. Periodic reviews of the benefits, risks, and costs of each Program element are designed to support Program management decisions as research results become available. The FAA and industry will then decide which WakeVAS capability enhancements should be implemented based on traffic projections and the consequent market demand for additional airport capacity, balanced against the initial and continuing cost for the ground-based (and possibly airborne) systems that are required for each WakeVAS Conops.

3. KEY PERFORMANCE REQUIREMENTS FOR NEAR-TERM AND MID-TERM WAKE SOLUTONS

Key performance requirements for any separation reduction solution are ultimately traced back to three design parameters of any separation reduction solution: Capacity gain (benefit), cost and safety. These three performance requirements are often seen in tension, and are often measured only in ratios to each other. FAA investments are often approved based on cost/benefit ratios alone, with safety a litmus test that must be passed rather than optimized against cost or benefit. While the FAA Safety Management System (SMS) is intended to provide a quantitative basis for measuring the safety sufficiency, in many cases it is difficult to directly measure hazards that may only occur once in 10^6 to 10^9 events. When the researcher is left with the need to perform a relative safety assessment, comparing the likelihood of events to today's operations, the quantitative basis is eroded and the question of "how much safer is a change than today's operations" arises. That decision is based on uncertainties in the relative comparison and will likely be in tension with the other two performance parameters.

Benefits associated with capacity improvements at an airport are sensitive to the number of hours an operational improvement can be used, specific airport operations and constraints at the airport implementing the change, demand fleet mix and the priorities of the major airlines operating at the airport. Cost factors are similarly dependent on airport and solution specific details. These key performance parameters are not addressed directly in this paper, but examples are provided as necessary to provide a more comprehensive picture of the relationships between capacity cost/benefit ratios.

3.1. Performance Requirements for Some Near-Term Solutions

Near-term solutions can be achieved through new procedures alone, or through new procedures supported by simple controller decision support tools.

3.1.1. 1.5 NM Diagonal Separation at STL

One example of a procedures-only solution is the CSPR dependent approach waiver allowing 1.5 NM diagonal separation to runways with 1300 foot runway centreline spacing, down to CAT I minimums, following Large and Small aircraft at Lambert St. Louis International Airport (STL)[1]. All key performance requirements associated with this solution must be provided by the procedure itself and though the existing navigation, communications and surveillance systems. The performance requirements for STL associated with safety are collision risk and wake encounter risk. The diagonal separation minimum of 1.5 NM between the lead and trailing aircraft ensures mitigation of collision risk as it does for dependent approaches to runways spaced greater than 2500 ft. Thus the key performance requirement of this procedure is to ensure the risk of a wake encounter for the trailing aircraft on 12L or 30L is not greater than the risk observed in today's operations for the trailing aircraft on 12R or 30R. The approach path to the left runway (12L or 30L) is higher than the approach path to the right runway and the runways are spaced 1300ft apart. The combination of the lateral separation and higher glide path for the trailing aircraft provide the necessary wake mitigation. Figures 1 and 2 present the measured wake behaviour for large and small aircraft wakes at two regions of interest, In Ground Effect and Out of Ground Effect.

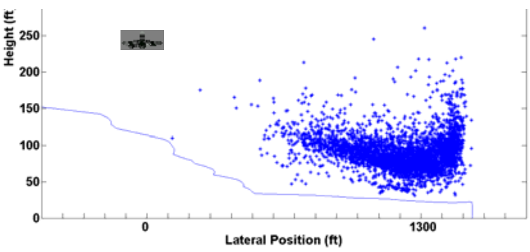

FIG 1. Wake Transport to Parallel Approach IGE

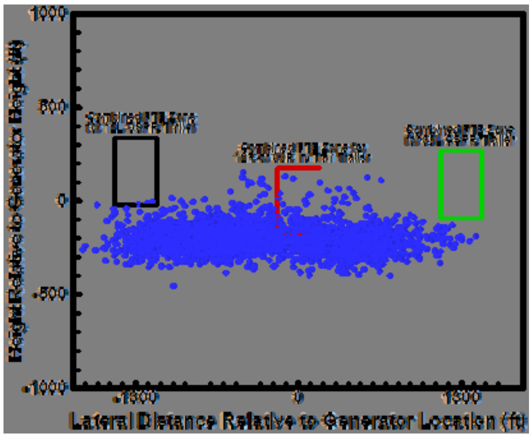

FIG 2. Wake Transport to Parallel Approach IGE

As demonstrated in Fig 1, the wake mitigation is provided IGE through the lateral separation of the left approach (12L or 30L) from the generating aircraft on the right approach (12R or 30R). Fig 2 demonstrates the wake mitigation provided by lateral separation and the higher glide path of the trailing aircraft. Table 1 presents a comparison of the likelihood of a wake encounter for the proposed procedure compared to that for single runway approaches separated by 2.5 NM. Frequency is conservatively estimated by frequency of wakes found in the approach corridor (depicted as an aircraft's Flight Technical Error (FTE) defined rectangular box) at the time corresponding to the separation distance. In the highlighted case, the frequency of potential wake encounters using 1.5 Nm diagonal separation at 45 seconds is compared to the frequency of potential wake encounters using 2.5 Nm In-trail separation at 75 seconds.

	12R and 30R In-Trails	12R Leads - 12L Trails	30R leads - 30L Trails
45 Sec	No. of Events in FTE Zone = 127 Probability = 19.7E-3 $\Gamma_{10,50,90\ Percentile}$ = 2234,2536,2741 ft^2/s	No. of Events in FTE Zone = 4 Probability = 0.6E-3 $\Gamma_{10,50,90\ Percentile}$ = 2333,2525,2538 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s
60 Sec	No. of Events in FTE Zone = 22 Probability = 3.4E-3 $\Gamma_{10,50,90\ Percentile}$ = 2106,2366,2552 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s
75 Sec	No. of Events in FTE Zone = 7 Probability = 1.1E-3 $\Gamma_{10,50,90\ Percentile}$ = 1871,2288,2368 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s
90 Sec	No. of Events in FTE Zone = 1 Probability = 0.2E-3 $\Gamma_{10,50,90\ Percentile}$ = 1985,1985,1985 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s
105 Sec	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ =0,0,0 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s	No. of Events FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s
120 Sec	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s	No. of Events in FTE Zone = 0 Probability = 0.0E-3 $\Gamma_{10,50,90\ Percentile}$ = 0,0,0 ft^2/s

TAB 1. Wake Encounter Likelihood Comparisons 2.5 NM in trail (75 secs) vs. 1.5 NM diagonal (45 secs)

This procedure change requires no infrastructure costs and provides a capacity increase of about 15 additional arrivals per hour during the periods it replaces 2.5 NM in trail (single runway operations).

3.1.2. SOIA at SFO

Simultaneous Offset Instrument Approaches (SOIA) is another example of parallel approach procedures providing reduced separation[2]. Figure 3 provides a graphic depiction of the procedure used at San Francisco International Airport (SFO). The first key safety performance requirement for this procedure is assurance from collision risk, and the second is wake encounter risk. Outside of the Missed Approach Point (MAP) collision risk is mitigated by the use of Precision Runway Monitoring (a one-second update radar) and controller monitoring of a no transgression zone for large flight path deviations. Wake mitigation in the same regime is provided by the lateral offset of the two approaches by at least 3000 ft. Inside the MAP, both aircraft are performing visual segments of an instrument approach and the pilots and controllers provide visual separation and thus collision avoidance, and the pilot provides wake avoidance through mitigations such as flying slightly higher on the glide path and landing longer than the leading aircraft on the left approach. SFO uses SOIA to ceilings as low as 2100 ft and 4 miles visibility. For operations down to 1600 ft ceilings, controller tools will be required to ensure the trailing aircraft is inside a pairing window (e.g., less than 0.7 NM behind the lead aircraft) to provide wake avoidance assurance.

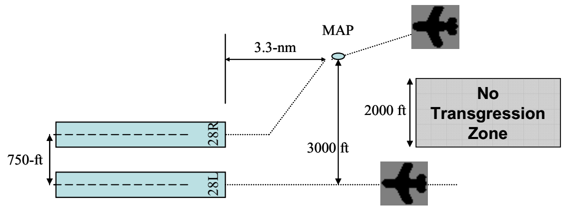

FIG 3. SOIA Operations at SFO

The key cost factors for SOIA is the PRM itself (approximately $25M for purchase and installation) and operating costs for staffing monitor positions. Arrival capacity increases of about 15 aircraft per hour can be achieved over the single runway operations it replaces.

3.2. Performance Requirements for Some Mid-Term Solutions

Mid-term solutions represent the first step in applying the weather prediction component of the notional WakeVAS system. Three solutions are envisioned in the mid-term phase of solutions. The first is a crosswind based solution for departures from CSPRs called Wake Turbulence Mitigation for Departures and is described further in this paper. The second solution is a crosswind based solution for arrivals to CSPRs, called Wake Turbulence Mitigation for Arrivals (WTMA) and will be described in future papers. The third solution is a Crosswind-Reduced Departure Operations (CREDOS) and is described, in part, in other papers presented at the 1st European Air and Space Conference (CEAS).

3.2.1. Wake Turbulence Mitigation for Departures (WTMD)

Departure operations from CSPRs are capacity constrained in the United States when a Heavy or B757 aircraft departs from one runway and a wait time of 2 minutes must be applied to the subsequent departure from the parallel runway. When a crosswind of sufficient strength is present, as depicted in Figure 4, the two minute wait is not necessary. WTMD is based on the ability to predict persistent crosswinds and to present to air traffic controllers a simple indication that the two minute wait is not required.

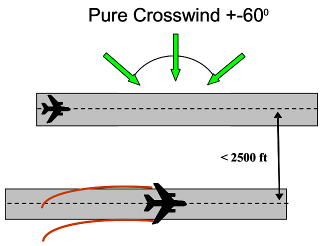

FIG 4. WTMD Operational Depiction.

WTMD is comprised of automation and procedures. The automation is further decomposed into a wind forecast algorithm that predicts the wake free status of each of the four runway ends of the CSPRs, a source of crosswind measurement at the surface and aloft, supervisor tools to permit enabling and disabling of the WTMD procedure, and controller tools indicating when WTMD operations are enabled and disabled. Procedures include ATC departure operations and separation services with and without reduced separation as well as Supervisor decisions and actions to enable and disable WTMD operations. Together, these components form the WTMD system and their combined performance requirements dictate the overall performance of WTMD. Key performance requirements include benefit as well as safety (collision and wake encounter avoidance). Benefit is considered in these discussions because one automation component, the wind forecast algorithm, drives opportunity as well as safety of the WTMD. Figure 5 presents the WTMD system safety performance functional flow diagram.

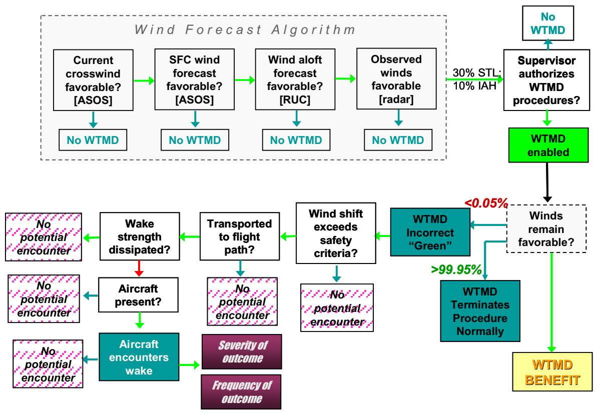

FIG 5. WTMD System Safety Performance Functional Flow Diagram

WTMD is in the requirements definition phase of research and performance requirements are not yet completed. However it is possible to assess the current balance between conservativeness of the wind forecast algorithm and the opportunity (benefits) it provides. This can be done through the evaluation of the nominal case of WTMD operations in the context of the risk of a wake encounter and the opportunity for reduced separation.

3.2.1.1. Key Performance Requirements for Automation

Display devices and host automation platforms must have robust interfaces to exchange data and system status. This is true for interfaces to data sensors supporting the automation algorithms as well. Such performance requirements are common to existing ATC systems and are not technically difficult to meet. As mentioned in the discussion of performance requirements, the predictors do not have to accurately predict wake behaviour but just be conservative. The level of conservativeness necessary will depend on the performance of the sensors used for real time validation ad well as the procedures used.

A wind forecast algorithm has been developed to predict the strength and persistence of crosswinds, and has been applied to two airports (IAH and STL). The algorithm is based on historical variability in ASOS winds over a range of time periods as described in a related paper presented at this conference. The algorithm was tuned to similar conservative criteria for both STL and IAH and provided a similar false green rate of .05% or 5 x 10^{-4}. This represents the frequency with which the wind forecast algorithm does not accurately predict wind change from the direction shown in Figure 4 to one which is outside of the criteria set for enabling WTMD operations. It can be seen from Figure 5 that a false green prediction must occur coincidently with several other factors. Specifically, the unforecast wind causing the false green prediction must exceed the safety criterion (currently set at 2 kts towards the wake free runway), there must be an aircraft present to generate a wake and that wake must survive long enough to transport over to the adjacent runway, and finally, there must be an aircraft in the proximity of the wake. The crosswind safety criterion (i.e., 2 kts towards the wake free runway) was developed based on preliminary analysis of departure wake and coincident crosswind data at STL and Frankfurt (FRA) airports. Based on preliminary analysis, when crosswinds of 2kts or more are observed, wakes transport 1000 ft or farther 5% of the time. In addition, analysis of the false green predictions resulted in 50% of them occurring with a crosswind that exceeded the safety criteria of 2 kts. Therefore, an early indication of the performance of the automation can be made by multiplying the factors:

(1) Rate of false green predictions x rate of false prediction resulting from exceeded crosswind safety criteria x rate of observed wakes transporting 1000 ft under 2 kts or greater crosswind = 0.05% x 50% x 5% = 1.25 x 10^{-5}. This does not account for the likelihood that a generator aircraft will be present, or that an encounter aircraft will be present.

The algorithm provides an opportunity for reduced separation operations at STL about 30% of the operational day; at IAH about 10% of the operational day has wake independent procedure opportunity. Before assessing the overall system performance of WTMD, the impact of procedures must be considered.

3.2.1.2. Key Performance Requirements for Procedures

Based on today's operations, collision risk is mitigated to an acceptable level using runway headings and visual separation during independent departure operations of Large and Small aircraft at CSPRs. The same acceptable risk can be achieved for Heavy and B757 aircraft.

Wake encounter risk for WTMD operations will be further mitigated beyond that provided by the normal operation of the wind forecast algorithm through usage authorization procedures. When the wind forecast algorithm indicates WTMD opportunities, the Supervisor will review existing wind products within the normal responsibilities associated with anticipation of weather events that will affect safety and operational configurations of the airport. Many of the same weather events that trigger airport configuration and operations changes are also associated with the false green predictions of the wind forecast algorithm. Research is underway to determine the safety and capacity benefits that can be realized from automated identification of these weather events. Current estimates of supervisor authorization of WTMD during the weather events associated with false green predictions and normal estimates of human failure rates – is ~ 20%.

The frequency of supervisor intervention to terminate WTMD procedures in anticipation of a sudden wind shift event is anticipated to be low based on the rate of false green predictions and therefore the supervisor intervention procedure is not anticipated to negatively affect the benefits associated with WTMD.

3.2.1.3. Total system performance requirements

Total system performance will be assessed by combining the contributions of automation and procedures. Based on estimates for automation and procedures contributions to the risk of a wake encounter, a surrogate for the combined risk of a wake encounter from the WTMD system is:

(2) The automation contribution to the rate of wake encounters x the procedure contribution to the rate of wake encounters = 1.25x10^{-5} x .20 = 2.5 x 10^{-6}.

This surrogate risk compares very favorably to the risk of a wake encounter for a departure from one runway 1000 ft away and 2 minutes after a Heavy or B757 departure from the parallel runway. Based on wake data collected and analyzed at STL and FRA, today's risk is 1 x 10^{-3}. This comparison of the safety performance of WTMD indicates that there is room to expand the benefits performance of WTMD. While these performance metrics are not yet mature enough for full requirements definition of WTMD, they are sufficiently mature to direct research to find a better balance between safety and benefits.

3.2.2. Extensions to WTMA and CREDOS

The WTMA crosswind based solution for arrivals to CSPRs will require additional wind profile measurements beyond those required for WTMD because of the significantly larger region of reduced separation enabled by the crosswinds (e.g., from the ground to perhaps 6000 ft AGL). The CREDOS solution may also require additional wind measurements. The requirements for CREDOS and its subsystem elements are currently under development.

4. STATE OF THE ART ASSESSMENT OF CRITICAL ELEMENTS FOR FAR-TERM SOLUTIONS

There are no active prediction wake hazard avoidance "systems" in operational use today. Instead, wake hazard avoidance in the NAS is assured in one of two ways: via (a) a set of procedures for pilots, and (b) a set of rules for air traffic control. Pilot procedures apply whenever the aircraft is engaged in a visual approach or departure and consist of safe operational practices based on a general understanding of wake behavior. Under visual meteorological conditions (VMC), the pilot assumes responsibility for maintaining wake-safe distances from other aircraft. Under instrument meteorological conditions (IMC), controllers apply wake vortex separation standards to maintain wake-safe spacing between aircraft.

Eliminating the application of wake vortex separation standards when they are not needed could expand NAS capacity to accommodate a portion of the ever-increasing demand levels and even delay the need for additional runways. To do so, pilots and controllers need a dynamic, wake-safe system for reducing spacing between arriving and departing aircraft in all weather conditions. The status of key components of such a wake vortex solution is discussed in the following sections.

4.1. ConOps

The U.S. wake program is committed to effectively supporting the capacity and safety objectives of the FAA by leading the Wake Research Program to maximize the probability of ultimate approval of new WakeVAS systems and procedures. Even if studies, simulations and demonstrations show a potential capacity benefit from WakeVAS implementation, these enhancements will not, and should not, be implemented unless the regulatory decision makers and those representing key stakeholders (pilots, controllers, airlines and airports) conclude that the enhancements will provide an acceptable level of safety.

To achieve these objectives, the U.S. commissioned the WakeVAS Conops Evaluation Team (CET) to assist in its planning for the WakeVAS research activities. The CET's task was to identify the safety-related research issues of the safety regulators and stakeholder representative decision makers that are associated with the mid-term and far-term WakeVAS elements of the Program. The members of the CET were selected for their expertise in air traffic control, flight operations, national airspace system (NAS) systems integration, regulation and certification, and safety analysis. The CET included representatives of decision makers in FAA's Flight Standards, Aircraft Certification, Air Traffic and Airports Divisions, and its System Safety office. CET members also included airline and airport associations, airlines and pilot and controller union representatives. These regulators and stakeholders were supported by CET expert members in wake science, technology, and safety analysis from MITRE, MIT/LL, NASA, FAA and the NTSB, as well as FAA's principal systems integrators.

The principal objectives of the CET were to provide the U.S. wake program leaders with a series of reports containing the information needed to guide the WakeVAS research program. The CET reports have been published and are comprised of the following documents:

1) A Baseline Report containing all current wake-related systems, services, and procedures. This includes details of all relevant: FAA policies and requirements; NAS services and systems; airport operational configurations; ATC and flight operations procedures (in both normal and non-normal operations); planned NAS changes over the time periods of the near, mid, and far-term Program objective; and constraints and assumptions on changes.
2) A Safety Management Report that allocates safety-related responsibilities between the CET and the Safety Analysis Team which was commissioned to recommend improvements in wake safety analysis methods for WakeVAS.
3) For each WakeVAS Operational Enhancement (such as CSPR arrivals, single-runway departures, etc.), a Report that provides, for each concept of operation (ConOps) evaluated by the CET, the following information:
    - A comprehensive description of the ConOps, including the approach or departure procedures design, the ATC and flight operations procedures, and the functional level requirements of the necessary WakeVAS subsystems.
    - Any required changes in FAA policies, current or planned NAS systems, airport requirements or operational configurations, or air traffic and flight operations procedures.
    - A detailed analysis of normal and non-normal operations, changes in risk mitigation methods, and a list of all assumptions and means for validating them
    - Preliminary hazard identification, with a cause and effect analysis to support the qualitative and quantitative safety analysis conducted by the Safety Analysis Team, and to identify research questions.
    - A list of the safety research questions of all of the decision makers, including their data acquisition and analysis requirements, as well as the preliminary issues that can be answered without data collection in advance of the main research program.

The CET analyzed and provided a ranking of each proposed capability enhancement and their Conops, based on their effectiveness and feasibility. The full set of CET documentation is available on the USA WakeNet-USA website[1] and the Eurocontrol CREDOS website.[2]

4.2. Wake Predictors

Wake Prediction Algorithms – The real-time wake

[1] WakeNet USA FAA KSN Website, accessed July 19 2007, https://ksn.faa.gov/km/ATO/coo/opsplan/Research/planning/wakenet

[2] The CREDOS Website, accessed July 10 2007, www.eurocontrol.int/eec/credos/public/subsite_homepage/homepage.html

behavior prediction algorithm used in the Aircraft Vortex Spacing System (AVOSS) represents the state-of-the-art in a real-time wake modeling. Despite its sophistication it will not be adequate for an operational system because it does not specify the wake behavior in a probabilistic manner. A mean and variance of the wake position and strength is required along with a confidence measure of those values to perform a formal safety analysis of the system. The wake prediction algorithm should also be integrated with the weather predictions, observations, and wake observations in a closed-loop system that adjusts for predictions diverging from observations. This configuration has not previously been tested.

4.3. Deterministic Real-Time Wake Prediction Models

These semi-empirical models draw upon inputs from a generating aircraft and the atmospheric environment to predict wake vortex position and strength as a function of time or distance behind the generating aircraft. They do not predict a wake velocity field or a radial distribution of vorticity within the wake vortex. Output can be used to determine the separation needed for an in-trail aircraft to avoid an encounter with a wake vortex. Deterministic real-time wake prediction models may also be used to predict error bounds. Since they are semi-empirical, key constants must be adjusted according to theoretical studies and field or laboratory measurements.

4.3.1.1. Assumptions and Limitations

Deterministic real-time wake prediction models must execute rapidly and are based on a number of assumptions, which limit their usefulness and accuracy. Additional uncertainty in the environmental state (i.e., weather) and in the parameters of the generating aircraft can also impact prediction accuracy. Limitations and assumptions include the following:

- Both port and starboard vortices will sink and decay at the same rate.
- Vortex circulation will decay uniformly with radius.
- The model will not account for vortex transport (i.e. meandering) due to large scale turbulence eddies.
- The port and starboard vortices will remain parallel, will not allow for sinusoidal displacement, vortex pair linking, or the formation of vortex rings that occur due to Crow instability.
- Ambient wind shear does not effect sink rate or circulation decay.
- There will be an empirical treatment for ground effect (that is not physics-based).
- The solution will not be a function of aircraft-dependent parameters other than weight, airspeed, and wingspan.

4.3.1.2. Applications

- Essential element of a wake vortex *spacing* system.
- Essential element of a wake vortex *tracking* system
- Used as the basis for development of *probabilistic* real-time wake prediction models.
- Can be used by the FAA and aircraft manufactures to determine safe separation standards
- Used in aircraft accident investigations

4.3.1.3. State of The Art

The AVOSS Prediction Algorithm (APA) 3.2 represents the current state of the art for deterministic real-time models. APA 3.2 predicts the position and strength of two parallel counter-rotating vortices, based on environmental inputs of atmospheric crosswind, thermal stratification, and turbulence. Key parameters needed for input include the generating aircraft's wingspan, weight, airspeed, lateral position and altitude. Treatment for ground interaction is empirical, not physics-based.

4.3.2. Probabilistic Real-Time Wake Prediction Models

These predictors have applications and limitations similar to the deterministic predictor, but they predict the probability that a wake will be a particular distance from the flight path and the probability that the wake strength has weakened below a particular strength. The development of these models requires training with large amounts of field data. These models take into consideration the uncertainties and variability of the input conditions, as well as inaccuracies of the model formulation. A probabilistic real-time wake prediction model can be entirely data driven, or can use either one or and ensemble of deterministic real-time wake prediction models as its basis.

4.3.2.1. Applications

- Needed in a wake vortex spacing system
- Useful in a wake vortex tracking system,
- Needed for safety and capacity gains studies,
- May be used by the FAA and aircraft manufactures to determine safe separation standards,
- Used in aircraft accident investigations.

4.3.2.2. State of The Art

While the process for developing a real-time probabilistic wake predictor is well understood and some activities have been undertaken, the U.S. APA model does not yet have the required probabilistic capabilities. The APA has been extended to provide bounds on the wake position and circulation estimates, but these bounds represent in some sense worst case (3 standard deviations or more) estimates and thus result in overly conservative wake vortex separation recommendations. Given adequate funding and rich, high quality data sets, the U.S. can develop a probabilistic estimator by 2010.

4.4. Large Eddy Simulation Models

Large Eddy Simulation (LES) models are too computationally expensive to use in a real time operational setting. Their purpose is to guide the development of real time models, as well as conduct parametric studies to access wake vortex sensitivity to environmental parameters, vortex ground interaction, and aircraft dependent parameters. These models employ integration of the equations of momentum and thermodynamics, with a turbulence closure that models the sub grid scales. Scales of turbulence larger than the grid scale are predicted deterministically. Well formulated LES models are robust and can be used in many other applications other than wake. For an LES model to be useful in wake vortex studies, it must i) have non-diffusive yet computationally-efficient numerical schemes, ii) represent high-Reynolds number flow, iii) have a meteorological framework (wakes interact with atmospheric turbulence, stratification, and wind shear), iv) have a realistic formulation for the ground plane and ground stresses, v) have a three-dimensional domain that is large enough to capture the evolution of the wake, yet with a grid size fine enough to resolve the circulation around the vortex core, and, vi) must have a realistic representation of the wake vortex soon after it rolls up from the generating aircraft. Wake vortex LES codes require many trillions of calculations, and require state-of-the-art supercomputers on which to run. Since one run can take several hours of 'wall time' for a 2 min wake simulation, LES models cannot be used in real time. However, they can provide a wealth of information for developing simpler and faster semi-empirical models. Also, they can provide databases for sensor testing, simulator studies, and development of a hazard definition for wake encounters.

4.4. Mesoscale Weather Prediction Models

These models provide short term weather predictions over a region that ranges in scale from the size of several counties to the size of North America. These models also use the equations of momentum and thermodynamics, but require special treatment for gravity waves, and include parameterizations for the atmospheric boundary layer, turbulence, and cumulus convection. Mesoscale models also include terrain, land-water interactions, near real time updates to ocean and sea temperatures, as well as formulations for ground moisture, vegetation, and land-use. The models typically employ a terrain following, vertical grid structure. Their accuracy is limited by the scarcity of observations used for initialization, although recent advances have improved initialization of these models. Particularly, three-dimensional variational data assimilation (3DVAR) techniques allow for the development of initial fields that utilize observed weather data bases (e.g. Doppler radar, satellite data, etc) and forecast from previous model runs. This technique has been shown to improve the model's skill in short term prediction. Mesoscale weather prediction models can execute in real time on workstations thus eliminating the requirement for supercomputers.

4.4.1 Applications

Applications of Mesoscale models include research and operational numerical weather prediction (NWP), environmental pollution, data assimilation and parameterized-physics research, atmosphere-ocean coupling, and idealized simulations (e.g. boundary-layer eddies, convection). Mesoscale weather prediction models have the potential to be useful in NextGen since they predict changes in environmental conditions, including those that affect the transport and decay of wake vortices. For instance, mesoscale models can be useful for obtaining outlooks of expected wake separations at various airports. For wake prediction, model grids can be tailored to airport regions to predict vertical profiles of atmospheric wind speed and direction, temperature lapse rate, and turbulence in order to initialize wake vortex behavior prediction models several hours in advance for traffic planning purposes.

4.4.2 State of the Art

Publicly available operational mesoscale weather prediction models, such as Weather Research and Forecast model (WRF)' and its predecessor, Penn State's 5th generation Mesoscale Model (MM5), are easy to set up and run for the airport environment and may provide reliable forecast data that is tailored for the input needs of wake spacing predictions. The WRF model is currently the state of the art in mesoscale numerical weather prediction and is designed to serve both operational forecasting and atmospheric research needs. It features a 3-dimensional variational data assimilation system and a software architecture allowing for computational parallelism and system extensibility. Furthermore, advances in computing have allowed for computationally expensive modules: 1) resolvable scale precipitation and microphysical calculations 2) boundary layer parameterizations that utilize RANS type turbulence closure methods, 3) parameterizations for ground-level momentum, heat and moisture fluxes, and 4) atmospheric radiation schemes.

4.4.3 Future Needs and Modifications

Mesoscale models are capable of providing a platform for predicting the variables for wake prediction. However, there is currently no evidence in the literature that these models have been validated for predicting the atmosphere on a scale important for predicting wake vortex behavior variables. This is because these models are typically executed with grid resolutions too coarse to resolve wake vortices and atmospheric turbulence. Attempts have been made to diagnose turbulence profiles to predict wake vortex decay but these techniques have yet to be validated and should be investigated further. Although the models can predict vertical profiles of atmospheric wind speed and direction, temperature lapse rate, and turbulence, the prediction skill is dependent on the degree of accuracy of the boundary layer parameterizations. Therefore, revolutionary data regression techniques must be developed and validated to diagnose the vertical profiles of turbulence dissipation, the horizontal wind, and temperature lapse rate within the planetary boundary layer (PBL). Previous field studies have provided observed data sets to test and validate revolutionary data regression techniques for predicting these profiles.

Utilizing high resolution observed weather data bases of turbulence, winds, and lapse rates obtained in previous field experiments, the model can be initialized using the 3DVAR approach. Statistical analyses can be performed by regressing predicted variables to the observed variables. Derived regression formulas will be validated by predicting the necessary wake variables at other Airportal regions where high resolution observed data bases are available. Turbulence dissipation may be diagnosed from direct model simulation of turbulence kinetic energy and other boundary layer parameterization variables. Wind profiles and temperature lapse rates can also be a function of the boundary layer parameterization.

Revolutionary research that can enable the prediction of weather variables at this scale may be reliable enough to replace particular airport sensor needs, and provide input for the assessment of the stability of the real-time wake spacing predictor. Validated techniques can also provide detailed climatologies, i.e. cumulative distributions in time and space, for vertical profiles of winds, temperature, and turbulence for selected airports that would be otherwise unavailable for conducting safety studies and other un-proposed applications within NextGen.

4.5 SENSORS (WAKE/WEATHER/AIRCRAFT TYPE & CONFIGURATION)

There are no wake vortex sensors in operational use, or approved for operational use, in the NAS today. However, wake vortex sensors have been used in research applications for decades, although current research-grade wake sensors have limitations that may make them unsuitable for operational implementation into the NAS. The WakeVAS concept relies on a number of enabling technologies, some of which were demonstrated during the AVOSS project. They are listed as follows, with notes on their maturity level Research Questions (from CET) (ref: CET Document):

1. *Wake Sensors* –AVOSS utilized pulsed and continuous wave Laser Detection and Ranging (LIDAR) for measurements of vortex location and strength. A wind line was also used for measurements of vortex lateral position. Each sensor system used in AVOSS could be classified as a research sensor, but commercial pulsed LIDARs with wake-measuring capabilities can now be purchased. Detailed performance specifications of even the commercial LIDAR have yet to be determined. In addition, none of the AVOSS sensors could measure both wake position and strength in all weather conditions. Due to this and other limitations research continues on other candidate wake sensors.

2. *Weather Sensors* – AVOSS used a variety of commercial weather sensors to characterize the wake-relevant terminal area ambient conditions. A down-select of the weather sensors used in AVOSS is required to determine the minimum necessary WakeVAS sensor suite. Candidates include an instrumented tower (for low-level wind, temperature, and turbulence measurements), an ultra high frequency (UHF) profiler with a Radio Acoustic Sounding System (RASS) (low to middle level winds and temperature), a pulsed LIDAR (serving the dual task of wake and wind measurement), and aircraft measurements. Aircraft have the potential of measuring all the parameters of interest at a high resolution, under all weather conditions, over the entire region of interest, and thus represent the primary means of collecting weather information. Some corroboration with ground sensors is likely to still be required.

3. *Terminal Weather Predictor* – A WakeVAS will cause dynamic changes to airport departure and arrival rates. In order for affected parts of the NAS to react and take advantage of the changes, sufficient advance knowledge of the changes will be required. This can be achieved with an accurate terminal-area-scale prediction of the relevant environmental parameters that affect wake behavior. A technology for accomplishing this was demonstrated in the AVOSS project, called the Terminal Area Planetary Boundary Layer Prediction System (TAPPS). Emerging technologies (e.g. ensemble forecasts) are also under consideration for improving terminal-area-scale numerical weather prediction.

4. *Sensor Fusing Algorithms* – Data from a variety of sensors with different resolutions/effective ranges, and operational constraints will have to be integrated into single profiles of winds, temperature, and turbulence. Algorithms for fusing these sensor inputs (the sensor data often disagrees, as discovered during AVOSS) must be developed. These algorithms must include quality control measures so the confidence in the reported parameters can be determined. The AVOSS included a prototype for this function.

5. *Aircraft Meteorological Data* – As mentioned in the discussion on weather sensors, aircraft may be the only way to get all the required environmental data over the region of interest. Aircraft already measure and report meteorological parameters, but the resolution of the data is not adequate for a WakeVAS. The feasibility of obtaining the required resolution data from the aircraft systems has been demonstrated, but not in real-time.

4.6 COLLABORATIVE USA/EUROPEAN/ RUSSIAN RESEARCH

The USA and Europe have been exploring opportunities to collaborate in the wake vortex research and development arena since 2000. The commitment made by both sides of the Atlantic has been to focus wake vortex research to address questions that arise from the practical application of new wake vortex mitigation strategies. The successful utilization of wake vortex networks to engage the full spectrum of interested partners has facilitated the collaboration, and the WakeNet's have led to the development of a joint US/European wake vortex project for single runway cross wind based departures called CREDOS. The success of WakeNet-USA and WakeNet2-Europe has been observed by other countries and the Russian Federation formed WakeNet-Russia in 2005 to pursue opportunities to collaborate with Europe and the USA.

The Russian Federation is sponsoring the development and demonstration of an integrated ground/airborne real-time wake prediction system. The proposed system provides both strategic wake vortex separation from the ground based components and tactical wake vortex advisories from the airborne components based on information from participating aircraft and relevant weather information. The sponsors and developers of this system have indicated a strong interest in collaborating with the USA, Europe, and China to ensure that the developed system is compliant with the air traffic systems of those countries.

The developing collaboration will merge most of the major US, European and Russian actors in the domain of Wake Vortex research. The presence of the FAA brings considerable experience and expertise acquired in the USA. This mutual collaboration will reflects the importance with which the subject is viewed on both sides of the Atlantic as well as the effectiveness of EU-US communication in the domain of reduced separations. This collaboration is a direct consequence of many years of information exchange through the thematic networks of WakeNet-Europe and WakeNet-USA.

The alliance between the US, the EU and Russia is a very powerful way to collaborate and is receiving more attention than ever before mostly due to the globalization and integration process currently taking place in European Economies. Some Eastern European and Russian markets offer an abundant supply of highly educated, skilled, and inexpensive (in relation to its qualification) labor force with an access to new technologies.

5. SAFETY CASE DEVELOPMENT

5.1. Approach

Safety case development is performed within the framework of the Safety Management System (SMS) implemented by the FAA in 2007[3]. This process requires that the proposed change be clearly defined as a system, that hazards be defined for that system, and the risks for the hazards be analyzed in terms of frequency and severity. Those risks are then assessed against criteria for ranking them as low, medium, or high. Finally, high risks are identified and mitigation strategies are developed and implemented to reduce the risk to an acceptable level.

Absolute safety assessments refer to the direct measurement of the risks of each of the hazards associated with a proposed change to the ATC system, in the case of the U.S. the National Airspace System (NAS). This type of assessment is highly desirable for both the operator and the safety oversight authority. The proposed change can be designed to more exacting specifications and optimize the benefits for the operator. In addition, the safety oversight authority will have an absolute risk evaluation to review and is likely to accept the risk evaluation without recommending additional mitigations or risk monitoring requirements to manage uncertainties in the evaluation. This approach also permits the safety oversight authority, over time, to obtain a fuller evaluation of the safety of the existing NAS.

Relative safety assessments refer to the comparison of the risk associated with a proposed change to the risk of today's operations. With the introduction of SMS to the FAA's management of the NAS, all existing operations and systems were grandfathered into the process with an approach that today's operations are safe until proven otherwise. Relative safety assessments do not build up the library of safety knowledge about the NAS over time, but they do provide an indication of the direction of change of the safety of the overall NAS. These relative safety assessments are desirable when it is too costly, time consuming, or simply not possible to collect sufficient data or analyze sufficient cases to determine events that occur only once in 10^7 or 10^9 operations.

Wake turbulence solutions are especially difficult to assess in terms of absolute risk because the community of researchers and stakeholders have not found common ground on the hazard severity definition of a wake encounter. In fact it is understood from operational experience that wake encounters do exist in today's operations. In the development of a safety argument for the approval of a reduced diagonal separation minimum at Frankfurt International Airport, the potential for a wake encounter for single runway operations was modelled and compared to that for diagonal separation for parallel runway operations[4]. Figure 6, from that safety assessment report, presents the risk of a wake encounter as a function of wake strength for both the in trail and parallel approach case. Two models of Flight Technical Error (FTE) are shown, ICAO and a tighter model based on measured FTE at FRA. For both cases of FTE, the plots show that regardless of what wake encounter severity definition is used (based on wake strength), the frequency of that risk is lower for the parallel approach procedure than for the in trail case.

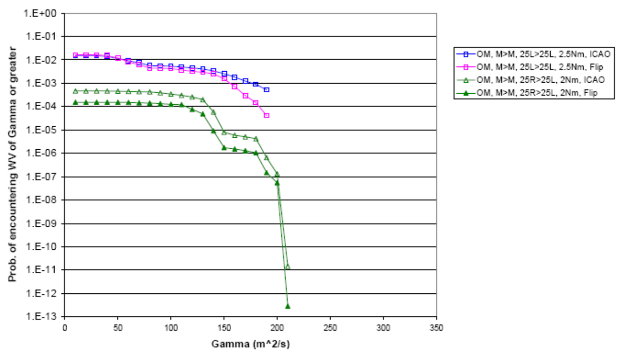

FIG 6. RDMS Safety Argument Medium Following Medium at Outer Marker

Relative safety assessments are often preferred over absolute safety assessments when hazard frequency is difficult to absolutely quantify without an unacceptably long data collection period. The FRA example demonstrates that relative risk assessments may also be preferred when hazard severity is difficult to quantify. The FAA wake turbulence research team is working with EUROCONTROL to define wake hazard severity criteria. Given the frequency of wake encounters in today's operations, multiple wake encounter severity levels are anticipated. Until such time, implementations of reduced wake separation solutions are likely to require otherwise unnecessary mitigations to address uncertainties in the hazard severity assumptions.

5.2. Critical Elements

Safety arguments have to be simple, easily communicable, and have a basis in today's operations. Based on experience gained by the FAA wake research team and the guidance provided by SMS, the hierarchy for easier acceptance of safety case arguments are listed below:

1) Use data first. Most easily accepted by stakeholders. When data is collected for 2 or 3 more or less independent variables, 10^{-6} to 10^{-9} is achievable in a reasonable amount of time (1-2 yrs) with field deployments.

2) Use models to combine probabilities when complexity requires it.
3) Only when absolutely necessary, use models to fill in tails of distributions to get to required likelihoods

The application of these critical elements to near-tem solutions is more obvious than for mid and far term solutions. If sufficient data can be directly collected to predict the wake encounter mitigation performance of the procedure, models may not be required to fill in the performance distributions. How does this apply to wind-based mid-term solutions?

The components of WTMD which are already a part of the NAS (ASOS sensor, RUC products, and the host automation platform and display platform) have historical performance data which can be used. Prototyping of development elements, such as the wind forecast algorithm, also provide an opportunity to collect performance data. The final component of the system that contributes to the overall system's ability to alleviate the risk of a wake encounter can be measured from the collection of relevant wake behaviour data. The overall performance of the solution may be determined by data alone. Figure 5 shows how the nominal performance of the system can be depicted from the perspective of functional flow.

Required system performance often is driven by safety requirements. These safety requirements will dictate the probabilities (or number of 9's) to which the system performance is assigned. The most demanding of these requirements is the risk of a catastrophic outcome, and must be managed to 10^{-9} likelihood. Through direct measurement of the performance of 3 or more independent system components, each with a failure likelihood of 10^{-3} or less, an overall system performance of 10^{-9} can be directly measured. Uncertainties in the assumptions of independent performance or in the performance e measurement of any one component can be managed through additional modelling to fill out the probability distributions.

5.3. Successes

SOIA was identified as a potential solution for operations at SFO by a number of stakeholders. ALPA, NATCA, FAA Flight Standards, United Airlines and SFO worked together to develop and implement this solution. While ultimately designed for ceilings as low as 1600 ft and 4 miles visibility, the initial (current) implementation allows operations to ceilings as low as 2100 ft - an evolutionary step towards the ultimate conditions. SOIA was also successfully implemented on RWY 6R/L at Cleveland-Hopkins International Airport (CLE) and at STL 30R/L where in both cases the offset approach was on a higher glide slope than the straight in approach. This puts the trailing aircraft in a natural position to fly above and land beyond the lead aircraft, and thus establishes as a part of the solution a mitigation that pilots use every day in visual approaches. SOIA at both airports provides capacity increases of about 15 aircraft an hour over single runway capacity in less than visual conditions. Implementation at CLE 24R/L was not as successful and the next section discusses some lessons learned.

The STL procedure for dependent staggered approaches using reduced separation was approved for STL in June 2007. This success was achieved at STL where threshold displacement assures wake avoidance for trailing aircraft on the higher approach. Successful implementation of SOIA on the 6R/L end of the CLE CSPRs was also achieved by using the argument that the threshold displacement at CLE assures wake avoidance. At the opposite end, where the trailing aircraft would be on the lower approach, wake avoidance was assessed to be provided by applying a maximum separation limit. A controller tool may be required to ensure the trailing aircraft stays within the maximum separation window, keeping the trailing aircraft ahead of the wake of the leading aircraft. Partial relief from weather delays caused by reduced ceiling was realized for SFO. Down to a ceiling of 2100 ft, the procedure keeps aircraft laterally separated until a point where the trailing aircraft can safely assume visual separation responsibility and therefore wake avoidance responsibility. Additional relief from even lower ceilings may be achieved through controller tools. These are the kind of tools that may resolve the needs for CLE.

5.4. Lessons Learned

Based on experiences gained from start to finish on the STL waiver, through observations on the development and acceptance of SOIA at SFO, STL and CLE, and through experience gained to date on WTMD, the following lessons were learned:

- Obtain consensus from wake and other research experts on the analysis approach as well as the safety arguments.
- Early involvement from stakeholders (users and oversight authorities)
- Document clearly the rationale for the safety assessment results and participate in applications of findings from one site to another (e.g., CLE)
- Well prior to implementation of a proposed change, begin monitoring key assumptions and uncertainties that are a part of the safety arguments for that proposed change.

Early involvement of stakeholders provided a sense of ownerships of the solution. Involvement of signatories early in the process provide feedback on data collection and analysis plans and help smooth the process of oversight acceptance of the proposed change.

6. REFERENCES

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