# CAPACITY AND WAKE VORTICES

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## Abstract

*Aircraft wake vortices can pose a threat, especially in the terminal environment where aircraft operate in close proximity. Vortex separation standards preclude hazardous encounters, but are oftentimes very conservative. A key to increasing airport capacity is to know when vortices are not a hazard so that aircraft can land and take off with closer intervals. A conference was held in London to address the capacity and wake vortices issue. This paper provides a brief overview of the highlights of the oral presentations.*

## 1 Introduction

As the aviation community recovers from the events of September 11, 2001, airport capacity limits will once more become a critical factor affecting the growth and efficiency of air transportation. Many factors influence capacity -- climatology, runway configurations, traffic mix, etc. Ultimately, either the number of runways must be increased or the spacing between aircraft using existing runways must be reduced.

The economic benefits of reduced wake turbulence separations at capacity-limited airports are substantial. Wake vortices limit in-trail spacing between aircraft on approach, restrict the use of closely spaced parallel runways, and restrict departure and intersecting runway operations. Research programs in the United States, Canada, and Europe have endeavored to understand wake vortex behavior and to use this knowledge in alleviating airport capacity limitations caused by overly restrictive wake turbulence separation standards.

An international conference on Capacity and Wake Vortices was held September 12-14, 2001, at the Imperial College of Science, Technology, and Medicine in London, UK. The conference brought together researchers, technologists, and the aviation community to address the impact of aircraft wake vortices on aviation system capacity. This paper will summarize the highlights of the presentations (there were no written papers) and comment on the progress of key topics since the conference. Abstracts of the presentations can be found in the Wake Vortex Bibliography at http://www.volpe.dot.gov/wv.

## 2 Conference Presentations

The subjects addressed at the conference included descriptions of the capacity problem and strategies for the congested airports (3 sessions), recent investigations of vortices from fixed-wing aircraft (2 sessions) and rotorcraft (3 sessions), progress in remote sensing of wake vortices (1 session), modeling of vortex behavior (3 sessions), and consideration of possible methods for controlling vortex behavior (1 session).

### 2.1 Capacity and Strategies

George Donohue (George Mason University) opened the presentations with a discussion of the effect of wake-caused aircraft separation on air transportation capacity. The current separation system seems overly conservative; a 15% increase in capacity could be achieved without danger to safety. The current state-of-art sensors and vortex prediction and warning algorithms should be incorporated into Federal Aviation Administration (FAA) weather and air traffic management decision support system software. However, accurate predictions of wake vortex locations and decay rates remain a difficult problem, since the runway wind direction variability is intrinsic to the randomness of the atmospheric turbulent boundary layer. It is a challenge to predict the runway wind direction accurately out to 30 minutes – the time required to begin the spacing of arrival aircraft, which is approximately 200 miles from the airport. Based on theoretical calculations and the field results observed in the National Aeronautics and Space Administration (NASA) Dallas-Fort Worth experiments, the wake vortex decay rates can be predicted better than wake vortex locations. The eddy dissipation level in the atmospheric turbulent boundary layer is a more stable quantity than the wind direction. He recommended that a warning of wake vortex circulation intensity above background should be incorporated in the FAA Integrated Terminal Weather System.

Stefan Wolf (German Air Line Pilots Association) addressed issues of capacity vs. safety from a pilot's view. Wake vortices are invisible to the pilot and a cause of uncertainty. He wants to stay above and land beyond them. He has to plan ahead and anticipate the wake vortex hazard. He also needs to analyze the situation based upon his experience. Pilot input is required for scientific research, air traffic management providers, and aircraft manufacturers. In 1998, the International Federation of Air Line Pilots Associations issued a policy statement that included:

- A general commitment to serious efforts allowing a safe reduction of the standard wake turbulence separation minima;
- Support for the results of international research activities contributing to the development of a wake vortex warning/avoidance system;
- Need for airborne wake vortex detection systems; and
- Need for ground-based wake vortex advisory and warning systems.

Neil May (National Air Traffic Services Limited) reported a case study of runway capacity constraints at Heathrow Airport. The major constraints are: (1) in-bound and out-bound traffic flow, (2) pilot performance (time to land and move out to a taxiway), (3) Air Traffic Control procedures, (4) runway configurations, (5) weather conditions, (6) airport layout, and (7) environment (12:00 to 6:00 AM, no operations). Increasing the capacity and reducing time delay requires: (1) smoothing the demand of in/out-bound traffic flow, (2) pilot education, (3) better controller operational procedures, (4) providing infrastructures to reduce both pilots and air traffic controllers' workload, and (5) implementing a wake vortex separation distance change.

George Greene (FAA) presented the FAA's research strategy to enhance air traffic system capacity. FAA's wake turbulence research program (2001 to 2010) has been influenced by the National Airspace System (NAS) Operational Evolution Plan need for assessment, the NASA near/long term research program, the introduction of new large aircraft, and the international wake vortex research program. Special topics include near term research on closely spaced parallel runways for San Francisco International Airport, introduction of the simultaneous offset instrument approach (SOIA), evolution of NASA's Aircraft Vortex Spacing System (AVOSS) technology for operational use, wake safety simulation, and international cooperation.

Jens Konopka (German Air Navigation Services) gave an overview on the concept of the Wake Vortex Warning System (WVWS) used at Frankfurt/Main Airport on runways 25L and 25R (separated by 518 meters). The measurement of the prevailing meteorological conditions and subsequent forecast of wake vortices motion between the two glide slopes are accomplished. A wind/temperature radar (1.3 GHz) provides the necessary data to extend the forecast along the entire final approach path of the two glide slopes. An alternative approach is presently in field trials based on the concept of High Approach Landing System/Dual Threshold Operation (HALS/DTOP) Project. The system ensures that aircraft approaching runway 25L use a new threshold displaced by 1500 meters (denoted 26L) and thereby always stay 80 meters above a leading aircraft on 25R. This 80-meter shift ensures the aircraft's flight corridor will be clear of wake turbulence.

John Leverton (American Helicopter Society International) examined the use of vertical flight to improve airport capacity by using civil tilt rotor/helicopter to operate in the unused airspace on the side of the airport. Although the use of rotorcraft seems to be a real solution to reduce airport/airspace congestion, other factors like the cost, noise, passenger appeal, icing clearance, and wake vortex interaction need to be addressed. The initial cost of the rotorcraft is high compared to the fixed-wing aircraft, but it can be compensated by the slot value. The noise generated by blade/vortex interaction is a major issue to get community acceptance. Current research has made great progress in noise reduction. FAA uses 700 feet (ICAO uses 820 feet) for runway separation between rotorcraft and fixed wing aircraft to avoid wake vortex interaction. More research is needed to better define the separation distance. He estimated that the use of rotorcraft may free up to 20% of the slots.

David Rutishauser (NASA Langley Research Center) presented an overview of AVOSS, as demonstrated at the Dallas/Ft. Worth (DFW) Airport in July 2000. AVOSS is to determine the spacing required to prevent wake vortex encounters based on the ambient weather conditions. The vortices from 61% of the 2301 landings at DFW exited the corridor in less than 50 seconds. Only 8% led to the situation where the vortex predictor underestimated the time for the vortices to exit the corridor (the vortices can translate outside the corridor, descend below it, or decay to less than 90 $m^2$/sec). Development of a research effort leading to a Wake Vortex Advisory System with limited capability (i.e., operate only in certain weather conditions) is underway.

Anton de Bruin (NLR) described a probabilistic approach to evaluate the wake vortex risk as a function of the separation distances between aircraft landing on a single runway. The methodology is being validated using wake vortex incident data collected at Heathrow Airport. The ICAO/JAR risk event classification is used. Results of the initial Monte Carlo simulations indicate that navigation performance is not too critical, the primary weather variables are low turbulence and stable stratification, and the largest risk occurs at the runway threshold.

## 2.2 Fixed-Wing Vortex Investigations

Klaus Huenecke (Airbus DASA) pointed out that the dimension of aircraft wakes and the technological challenge of the new very large transport aircraft require both experimental and theoretical innovative techniques. Wind tunnels, towing tanks, and the free-flight facility of ONERA are used to observe the vortex flow field over a long time period allowing its long-time behavior to be analyzed and measures of a premature wake decay to be investigated. His studies with accurate models show that engine exhaust reduces the maximum vortex velocities, but not the total circulation, and delays rollup. Relevant aircraft factors are the weight, wingspan, wing loading distribution, engine position and spacing, engine thrust, exhaust shape and temperature, undercarriage, underbelly fairings, flap type, flap setting, position of outboard flap edge, use of ailerons, and the interaction of the exhaust with the flap and tip vortices.

Donald Delisi (NorthWest Research Associates) discussed his extensive laboratory studies and comparisons of his results with aircraft measurements. He underscored the care needed in interpreting low-Reynolds number studies and extrapolating those results to the high-Reynolds number aircraft case. Favorable comparisons of laboratory vortices with aircraft vortices and numerical simulations included vortex migration, in both non-stratified and stratified environments, vortex core size and circulation with vortex age, and the amount of turbulence in a vortex cell. Full-scale data does not yet exist to compare to laboratory studies of vortex separation with time and vortex lifetime in both quiescent and turbulent environments.

Leo Veldhuis (Delft University of Technology) is studying vortex structure and decay using particle image velocimetry (PIV) in a 142-meter water tank and a 1:48-scale A-340-300 model. An underwater camera system on the tank bottom has a traversing system, that allows the field of view to move during the measurements. Initially, vortices from the engine nacelles, the wing tip, and the winglet form and merge. The intense well-organized vortex persists for the entire observation time, indicating slow decay.

Alex Corjon (Airbus) introduced wake alleviation as a means to mitigate airport congestion. The intent is to prematurely age vortices through the use of alleviation devices on the wake-generating aircraft. Modification of certain parameters should lead to earlier development of short-wavelength instabilities (elliptic) or long-wavelength instabilities (Crow) causing more rapid vortex decay or lead to vortices which induce smaller rolling moments on encountering aircraft.

Will Graham (University of Cambridge) is conducting wind tunnel experiments on co-rotating vortex pairs. Prior to merging, the vortex cores increase in size while the separation decreases. Unequal strength vortices are seen to merge more quickly than equal strength vortices. His investigations suggest that three-dimensional effects are not strong, so vortex merging can be simulated adequately using two-dimensional flow computations.

Thomas Leweke (University of Marseilles), on the other hand, examined the short-wave instabilities of both co-rotating and counter-rotating vortices in a water tank. At Reynolds numbers above 2000, a short-wave three-dimensional instability develops due to an elliptic instability of the vortex cores; a generic feature of strained vertical flows. Counter-rotating vortices develop a strong exchange of fluid thereby decreasing the average circulation. Co-rotating vortices merge sooner. High Reynolds numbers lead to an increased level of turbulence in and around the vortices.

Roland Stuff (DLR) reviewed vortex breakdown and instabilities to introduce the Rayleigh-Ludwieg instability that occurs when destabilizing centrifugal forces dominate restoring pressure forces. He contends that the Rayleigh-Ludwieg instability could lead to new passive measures to alleviate the vortex hazard. Since the stability criteria are derived from the radial gradients of the swirl and axial velocity components, three-component PIV or stereoscopic PIV is needed to study the phenomenon.

## 2.3 Rotorcraft Vortex Investigations

Gird Meier (DLR Institute of Aerodynamics and Flow Technology) reviewed the mechanisms of noise generation for a typical helicopter. Two major noise sources are generated from the rotor blades. One is called the blade/vortex interaction (BVI) noise and the other the high-speed impulsive (HIS) noise. The first occurs mostly at low forward speed during the landing. The second occurs on the high speed advancing side where shock waves are formed near the blade tip. It is a challenge to predict the BVI noise accurately since the wake geometry is difficult to predict accurately. The HIS noise can be predicted accurately, in general. As for tracking the wake vortex, he proposed a new technique BOS (Background Oriented Schlieren) that enables field recording of density gradients. This method has been used successfully in observing vortex wakes of a helicopter in hover.

Leo Dadone (Boeing) addressed flow field issues relevant to airport operations when rotorcraft and fixed-wing aircraft share air space. Rotorcraft wake analysis has played a major role in the design of high performance, low vibration characteristics, and low noise vehicles. Dealing with airport environments, it requires different considerations that fall outside of the conventional wake modeling in rotor design. It involves new areas to be explored. For example, the far wake structure of a rotorcraft has not been systematically studied.

Lyle Long (Penn State University) reminded the audience that according to Moore's law computing power doubles every 18 months. He then reported his vision of using computer power to improve airport capacity. Since the prediction of rotorcraft vortex wakes is computationally intensive, it will take many years to reach real-time application. He believes by year 2022 computing power will enable a real-time prediction of a rotorcraft far wake and a virtual reality display in the cockpit.

Lakshmir Sankar (Georgia Institute of Technology) presented recent progress in modeling rotor wakes in hover and forward flight. The major difficulty in predicting rotor wakes is the numerical diffusion of the wake vortex. Finer grids may reduce the vorticity diffusion at the expense of computing time and memory. A hybrid method is used to separate the viscous zone near the blade surface and the near wake. A Lagrangean wake approach was proposed and implemented to capture the effects of a tip vortex once it leaves the viscous zone; it convects without diffusion in the inviscid zone and to the far field. The numerical results compared well with test data obtained from model rotor tests.

Frank Caradonna (US Army Aeroflightdyanmics Directorate) pointed out the new challenges in analytical and experimental rotor wake aerodynamics. Rotor wakes have properly constituted the largest single area of experimental study over the years, yet new phenomena are always being discovered. He presented the test results of vortex pairing during hover and low speed climb. This vortex pairing has been observed before, but has not been studied in detail. On the analytical side of the rotor wake study, the prediction of rotor wakes using Computational Fluid Dynamics (CFD) requires a fine grid to avoid numerical dissipation. This renders CFD impractical for routine calculations. However, two new concepts, vorticity embedding and vorticity confinement, reduce the need for a fine grid size and make CFD more practical for routine use.

Roger Strawn (US Army Aeroflightdynamics Directorate) described CFD results using 64 million grid-point computations for a UH-60A model rotor in hover. It required 138 hours on 112 SGI Origin 2000 processors in order to reach a steady-state solution. The prediction compares well with experimental measurements. Again, it demonstrated that the CFD modeling of rotor wakes remains a challenge.

Alan Bilanin (Continuum Dynamics) offered a different point of view to assess aircraft and rotorcraft wake flow fields for wake hazard applications. To meet key challenges, a family of high-fidelity vortex wake modeling methods must be developed for eventual incorporation into both off-line assessment tools and pilot-in-the-loop simulation. In particular, UNIWAKE and CHARM codes were mentioned. The UNIWAKE code captures the wake roll-up of fixed-wing aircraft including the turbulent mixing with engine exhaust and wake vortex motion down stream. The CHARM code uses fast multi-pole methods and tracks the development of a rotary-wing wake and its long time motion. Preliminary results from these codes show promise. However, additional wake measurements are needed.

Gordon Leishman (University of Maryland) presented a 3-component laser doppler velocimeter (LDV) measurement of vortex wake formation, initial structure, and viscous evolution of the vortex core of a model rotor in hover. The flow visualization of the blade tip vortex and its trailing sheet was obtained by using a laser light-sheet technique. The vortex core size is as small as 3% of the chord near the trailing edge of the blade and grows asymptotically. The axial velocity deficit inside the vortex core has the same magnitude as the swirl velocity initially and diminishes as it ages.

Roderick Galbraith (University of Glasgow) described experimental work on orthogonal interaction of a rotor tip vortex with a fixed airfoil that simulates a tail rotor. A particle image velocimetry (PIV) system was used to study the flow field of the tip vortex before and after the interaction of the airfoil. On one side of the airfoil, on which the axial flow of the vortex is toward the airfoil, a compressive pressure pulse forms on the airfoil surface first. Then it disappears and develops into a suction wave as the vortex convects across the chord. On the other side of the airfoil, there is increased suction throughout the convective process.

Kenneth McAlister (US Army Aeroflightdyanmics Directorate) presented his PIV study of the change of wake vortex structure with/without a small vortex generator placed near the tip of a hovering rotor blade. The most dramatic change occurred in the turbulence generator case that resulted in a 65% reduction in maximum vorticity and a core size that nearly doubled. However, the rotor performance suffers an 18% increase in torque.

Markus Raffel (DLR Institute for Aerodynamics and Flow Technology) reported on the development of the PIV system and its application to many different kinds of unsteady flow fields. Two experiments related to rotor vortex wakes were performed and presented. One is a detailed investigation of vortex formation from helicopter tips in a large wind tunnel. The second concerns the flow field around a propeller.

## 2.4 Remote Sensing of Vortices

Michael Harris (QinetiQ) presented the field trial measurements of aircraft wakes using lidar at several airports in Europe. A continuous wave (CW) $CO_2$ laser was used to scan vertically with a given angle. Lidar measures the line-of-sight velocity only, i.e., one component. The focus of lidar at wake vortices is critical initially; it requires an educated guess. Once tracked, it can get vortex data plus atmospheric turbulence for more than 60 seconds. The circulation strength and decay rate of the vortex can be estimated, but the level of uncertainty needs to be analyzed. A better approach is to use multiple lidars to track the wake vortices, but the time delay between two lidars is an issue. A wing-mounted lidar on a chase plane that can avoid ground turbulence and measure a wide range of vortex age was also discussed.

Stephen Hannon (Coherent Technologies) reported the functionality of the Wind Tracer, a unique pulsed infrared Doppler radar that generates high resolution, three-dimensional distributions of wind data. It was used at San Francisco Airport to track the wake vortex positions, circulation, sink rate, and decay rate. It can see vortices descending and rebounding from a shear layer. A robust autonomous, stand-alone operational system may be matured within the next five years.

Friedrich Koepp (DLR Institute of Atmospheric Physics) reported on a pulsed Doppler lidar system that has been developed and tested under Project MFLAME (Multifunction Laser Atmospheric Measuring Equipment). The feasibility test was conducted at Toulouse-Blagnac Airport. The detection of vortices generated by a large variety of aircraft has been successfully demonstrated up to a range of more than 2 km. This system can be integrated into an aircraft forward-looking system. However, fog may degrade the performance of a pulsed lidar.

Richard Heinrichs (MIT Lincoln Laboratory) presented the wake vortex measurements of the XV-15 tilt rotor aircraft with a CW coherent laser radar. This CW coherent laser radar was developed as a part of the NASA AVOSS program. The truck-mounted device can scan a large area (400 x 80 feet) via a continuous sweep focus to locate the vortex and then fine scan to track the vortex. The measurements of the XV-15 and Bell 205B wake have shown airplane-like wake structure, but the circulation as a function of distance seems different from those of an aircraft. Humidity seems to enhance the core size and velocity distribution.

## 2.5 Vortex Behavior Modeling

Thomas Gerz (DLR Institute of Atmospheric Physics) described the requirements for reduced aircraft separation systems based on atmospheric effects on wake vortex behavior and decay. He presented early results from the wake vortex forecasting and measuring project WakeOp. The vortices of a VFW-614 aircraft were measured and predicted for various aircraft configurations and meteorological conditions.

Fred Proctor (NASA Langley Research Center) presented analytical results for wake vortex transport and decay from the perspective of parallel runways. To predict vortex transport and demise for parallel runway systems vertical profiles of the ambient crosswind and the intensity of the ambient turbulence are used as inputs to the Terminal Area Simulation System (TASS). Strong crosswinds and weak ambient turbulence are the conditions for which the TASS yields the longest lateral vortex motion. The simulation also indicated that, in ground effect vortices exist for less than 6 non-dimensional time units.

Robert Robins (NorthWest Research Associates) compared the results from two simulations of vortex evolution. One simulation explicitly solved the equations of fluid motion while the other employed equations derived from a heuristic analysis of vortex evolution (a best-fit model derived from AVOSS measurements). Comparisons with full-scale data suggest that useful predictions of wake vortex development are possible.

Florent Laporte (CERFACS) discussed numerical simulations of large aircraft wakes in the near to extended near field (vortex rollup complete). The first simulation was an inviscid computation using a structured Navier-Stokes solver. The effects of various computational meshes were noted. The second approach used time-averaged experimental data as input to steady and unsteady simulations. Large Eddy Simulations and steady Reynolds-averaged Navier Stokes computations were compared and confirmed the existence of laminar vortex cores surrounded by turbulent fluctuations.

Florent Laporte (CERFACS), in a second paper, examined the instabilities of vortex models in the near and far fields. In the near field, flap and tip vortices merge into a single stable vortex. However, it is possible, according to the simulations, to develop a three-dimensional elliptic instability that would lead to unstable merging and a turbulent vortex. In the far field, simulations show the long-wavelength Crow instability as well as the short-wavelength elliptic instability. Certain wing designs might cause these instabilities and subsequently accelerate vortex decay.

Jeffrey Crouch (Boeing) reported on Boeing's efforts to force the breakup of vortices at a distance less than current separation distances. In their active system, aircraft control surfaces force flaps-down vortex instabilities leading to formation of vortex rings. Even if successful, there are still a number of issues to consider such as ride quality, control authority, when in their breakup are vortices benign, effectiveness near the ground, and how to demonstrate system reliability so that separation rules can be changed.

Henri Moet (CERFACS) described his study of the effect of three-dimensional ambient turbulence on vortex decay using temporal large eddy simulations. Turbulence affects the vortex circulations through various mechanisms: turbulent diffusion, creation of azimuthal structures of vorticity, exchange of vorticity between the vortices and the ambient turbulence, occurrence of large deformations, and the onset of instabilities. Current efforts are to include atmospheric stratification effects.

Gregoire Winckelmans (Catholic University of Louvain) described the Vortex Forecast System (VFS) sponsored by Transport Canada and developed by an international team. The VFS is a wake vortex prediction system based on the method of discrete vortices. VFS starts with an initial near wake and then models wake transport and decay, ground effects, non-uniform wind shear effects, and stratification effects. The system was tested using vortex data collected at Memphis and DFW, and the results compared well with those obtained by the AVOSS predictor model.

Laurent Jacquin (ONERA) examined the stability properties and unsteadiness of wake vortices. Promoting long-wave instabilities are the most promising means to render wakes harmless. He discussed the properties of various vortex-pair configurations to find the optimal vortex arrangements leading to significant amplification of initial perturbations. Short-wave instabilities affect the merger of vortices. He showed that basic flows involving only one length scale (e.g., Rankine and Lamb-Oseen vortices) that are often used to characterize short-wave instabilities are poorly representative of real wake vortices.

Abraham Elsenaar (NLR) used analysis to optimize the upper limit of the rolling moment induced by a vortex pair. The goal is to identify possible ways to reduce wake vortex strength through aircraft design. He found that the distance between the vortices and the Oswald efficiency factor (induced drag factor) are key factors in the rolling moment for an aircraft that flies into a vortex center. An inboard-loaded wing with a low induced drag led to the smallest aircraft separation distances.

## 2.6 Controlling Vortex Behavior

Philippe Spalart (Boeing) discussed reducing the wake-vortex hazard by modifying the wing of the vortex generator. Flow-control designs can be classified as active or passive. An active design, such as the Boeing system, involves varying the wing configuration cyclically to cause an instability, thus leading to an early wake collapse. A passive design uses a fixed device, like a winglet, to produce a weaker wake (wake alleviation) thus making vortex encounters less violent. Active or passive, any design changes will pose extreme challenges for testing and certification.

Ömer Savaş (University of California, Berkeley) described towing-tank experiments on vortex wakes of wings with outboard flaps. The intent was to generate control vortices for wake alleviation. He observed a rapidly growing instability between unequal strength, counter-rotating vortex pairs in the wakes of airfoils with outboard triangular flaps. Using flow visualization and PIV data, large decreases in the rolling moment and downwash on a following wing were measured for the triangular-flapped wings compared to rectangular-flapped wings.

Peter Bearman (Imperial College) has conducted experiments on wake vortex control in a water tank using flow visualization and a delta wing. Video sequences showed the long-wavelength or Crow instability develop. Perturbing the flow speed at the Crow wavelength caused the vortices to break down closer to the wing. But, if the wavelength is smaller or larger than the Crow value by some critical amount, the breakdown moved farther downstream. Thus, if artificial disturbances are to be introduced to control the wake vortex hazard, it is critical that the wavelength itself be carefully controlled.

Patricia Coton (ONERA) described the ONERA test facility that uses a catapult to propel a scale model. The model flies freely thus eliminating any wall or mounting interference. In the new facility, distances up to 200 wingspans downstream of the model are possible, thus covering current separation distances during the approach and landing phase. The flow patterns behind the model can be recorded by laser tomoscopy and PIV.

## 3 Epilogue

There are many wake vortex projects underway in Europe and the United States. Knowledge about wake vortex behavior is increasing, as the presentations at the conference attest. However, it will take time for the knowledge to be reduced to working systems. New runways and new or modified procedures, such as SOIA and HALS/DTOP, are the likely near-term capacity enhancing means.

Aircraft separation standards are conservative most of the time. Capacity improvements of the order of 15% are possible as shown by AVOSS. The present efforts to move AVOSS from the research mode to an operational mode represent the likely mid-term capacity solution.

Most of the conference dealt with potential long-term capacity-enhancing ideas. The research programs in wind tunnels, water tanks, and full-scale flight tests are to characterize aircraft wake vortices. Comprehensive analytical models of vortex evolution are being developed and refined. Means to cause an earlier onset of vortex instabilities (elliptic, Crow) are sought via analytical and experimental techniques. Perhaps some of the techniques will become the basis for active or passive vortex control systems on aircraft, which have their own testing and certification challenges.

Rotorcraft research is also in the long-term arena. The conference examined the increased use of rotorcraft to free up more slots for fixed-wing aircraft. But, the noise from the blade/vortex interaction is a continuing problem.

Capacity is a problem today at a few airports. Scenarios which project a doubling of air traffic over the next 20 years suggest that the problem will only get worse.