NASA/CP-97-206235

# Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop

*Edited by*
*Leonard Credeur and R. Brad Perry*
*Langley Research Center, Hampton, Virginia*

November 1997

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Proceedings of a workshop sponsored by the National Aeronautics and Space Administration, Washington, D.C., and held at Langley Research Center, Hampton, Virginia
May 13-15, 1997

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

November 1997

## Acknowledgments

The success of this workshop is due to the support and effort of many people in addition to the presenters and session chairmen. The editors feel that special recognition should be given to: Ben Barker for his initial organization and coordination of the workshop, Fred Proctor and Dave Hinton for pulling together multiple key sessions, Dan Vicroy for proposing and pushing the workshop concept, and Annie Wright for her administrative support during the workshop and afterwards in the publication of these proceedings.

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## Foreword

Air travel delay and traffic congestion at major airports, projected increases in air travel, and environmental restrictions on new airport construction, together with associated costs to the traveling public and to the air carriers, have led to an increased interest in maximizing the efficiency of the national airspace system. The National Aeronautics and Space Administration (NASA) is responding to this interest through its Terminal Area Productivity (TAP) program led by the NASA Ames Research Center. The major goal of the TAP program is to develop the technology which allows air traffic levels during instrument meteorological conditions to approach or equal levels presently achievable only during visual operations. Presently, a degradation in weather conditions which causes a loss of visual approach capability reduces capacity due to numerous factors. These factors include reducing the number of available runways and the longitudinal wake vortex separation constraints used by air traffic control (ATC) in the spacing of aircraft to a runway. Two major initiatives under TAP are the enhancements of basic ATC automation tools and the development of a wake vortex spacing system to improve terminal area efficiency and capacity. The NASA Ames Research Center is developing enhancements to the Center/TRACON Automation System (CTAS). Enhanced CTAS automation will provide an opportunity to dynamically alter the longitudinal wake vortex separation constraint as a function of both the weather effects on wakes and aircraft leader/follower pair types.

The Reduced Spacing Operations (RSO) subelement of TAP, led by the NASA Langley Research Center, is developing the Aircraft Vortex Spacing System (AVOSS). The purpose of the AVOSS is to integrate current and predicted weather conditions, wake vortex transport and decay knowledge, and wake vortex sensor data to produce dynamic wake vortex separation criteria. By considering ambient weather effects on wake transport and decay, the wake separation distances can be decreased during appropriate periods of airport operation. In a manual ATC system, a simplified form of the AVOSS concept may be used to inform ATC when a fixed alternate, reduced wake separation standard becomes safe. With the appropriate interface to CTAS, spacing can be tailored to specific leader/follower aircraft types rather than just a few broad weight categories of aircraft.

The AVOSS development program has as its target a field demonstration of a prototype AVOSS system in the year 2000. To support this goal, current plans include three increasingly complex AVOSS field deployments to be conducted at the Dallas-Fort Worth International Airport (DFW). The first deployment is scheduled for the September 1997 time frame.

The NASA First Wake Vortex Dynamic Spacing Workshop, conducted at the NASA Langley Research Center on May 13-15, 1997, focused on the AVOSS research and development underway to support the initial AVOSS deployment at DFW. Workshop sessions examined wake vortex characterization and physics, wake sensor technologies, aircraft/wake encounters, terminal area weather characterization and prediction, and wake vortex systems integration and implementation. A final workshop session surveyed the Government/Industry perspectives on the AVOSS research underway and related international wake vortex activities.

The Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop contain the presentations from the workshop. The workshop discussion on each presentation has been transcribed and included immediately following the subject presentation. The wrap-up panel discussion has also been transcribed and included following the workshop presentations. For additional information, contact Brad Perry, RSO Manager, at 757-864-8257; Leonard Credeur, Deputy RSO Manager, at 757-864-2021; or David Hinton, AVOSS Principal Investigator, at 757-864-2040.

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**Day 2: May 14, 1997**

**WAKE SENSOR TECHNOLOGIES**

Chairperson: B. Barker, NASA Langley Research Center

**Day 3: May 15, 1997**

## WAKE VORTEX SYSTEMS INTEGRATION AND IMPLEMENTATION

Chairperson: D. Hinton, NASA Langley Research Center



## GOVERNMENT/INDUSTRY PERSPECTIVE

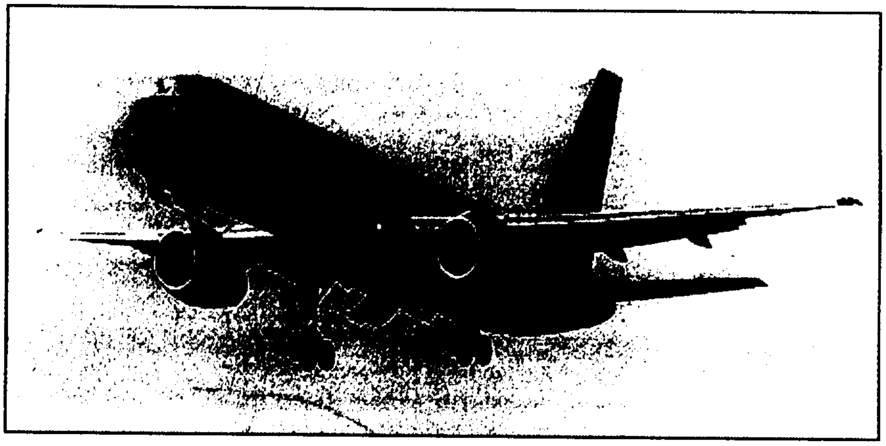
Chairperson: D. Hinton, NASA Langley Research Center

# Terminal Area Productivity

NASA AERONAUTICS

TERMINAL AREA PRODUCTIVITY

## Overview



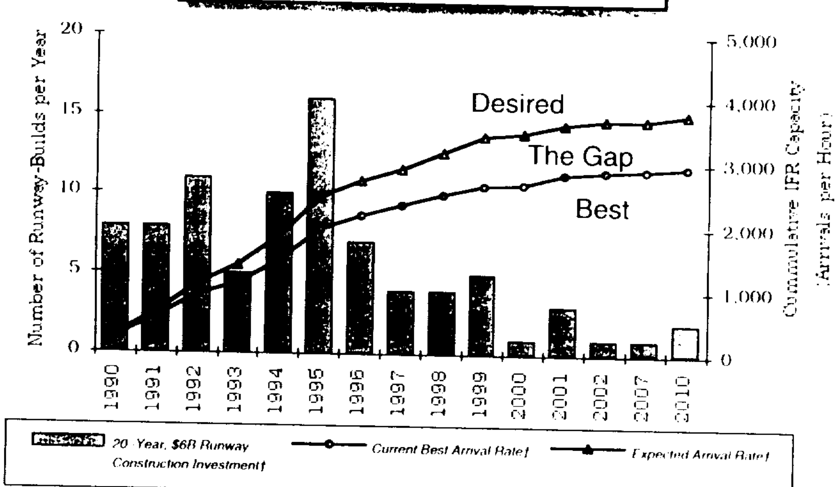
**Rose Ashford**
**AST Level II Deputy Manager**
**Ames Research Center**

## Challenge - The Capacity Gap

NASA AERONAUTICS

TERMINAL AREA PRODUCTIVITY

*"Sixty-six of the top 100 airports have proposed new runways or runway extensions to increase airport capacity."* †




† Reference "1990-91 Aviation System Capacity Plan" DOT/FAA/SC-90-1, September 1990

# Technology Benefits

Achieve safe clear-weather airport capacity in instrument-weather conditions

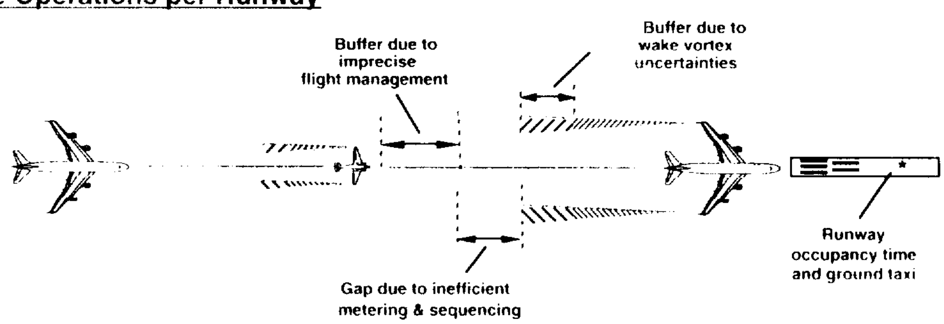
Objective:
With the U.S. airline and Aircraft Industries, the Airport Owners/Operators, and the FAA:

- Increase current non-visual operations for single runway throughput 12-15%
- Reduce lateral spacing below 3400 feet for independent operations on parallel runways
- Demonstrate equivalent instrument/clear weather runway occupancy time
- Meet FAA guidelines for safety

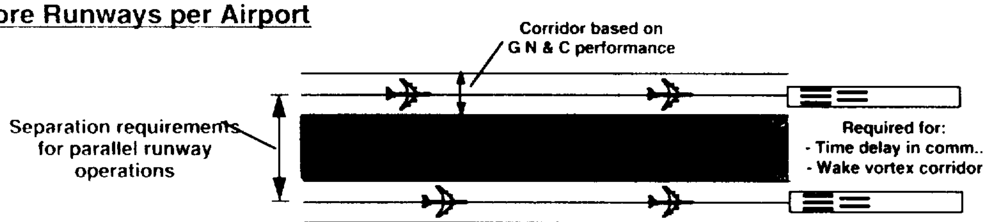


# Approach

## More Operations per Runway




## More Runways per Airport



NASA AERONAUTICS — TERMINAL AREA PRODUCTIVITY

# MAJOR END DELIVERABLES

- **Technology to reduce lateral and longitudinal spacing in non-visual conditions**
  - Aircraft Vortex Spacing System (AVOSS)
  - Airborne Information for Lateral Spacing (AILS) system

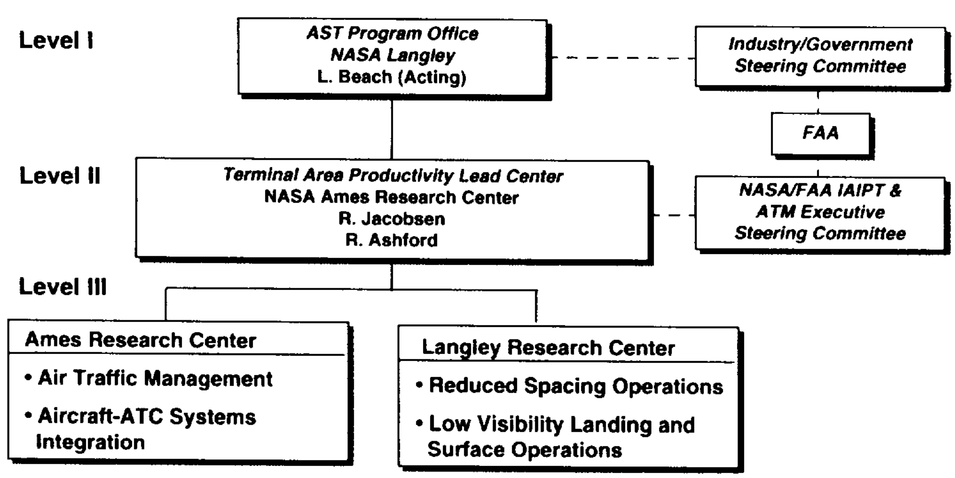
- **Automation/display aids to provide advisories to ATC controllers for optimal, conflict-free sequencing, scheduling, and control**
  - CTAS/FMS (Center-TRACON Automation System/Flight Management System) Integration
  - Dynamic Spacing
  - Dynamic Routing

- **Sensor/display/G & C technology to permit expeditious airport surface operations in Cat III conditions**
  - Roll Out and Turn Off (ROTO) system
  - Taxi Navigation and Situational Awareness (T-NASA) system
  - Dynamic Runway Occupancy Measurement System (DROMS)

- **Integrated technology validation for clear-weather capacity in instrument-weather conditions**
  - Cost-benefit analyses
  - Procedure and Safety Substantiation (PSS)
  - Integrated technology demonstrations

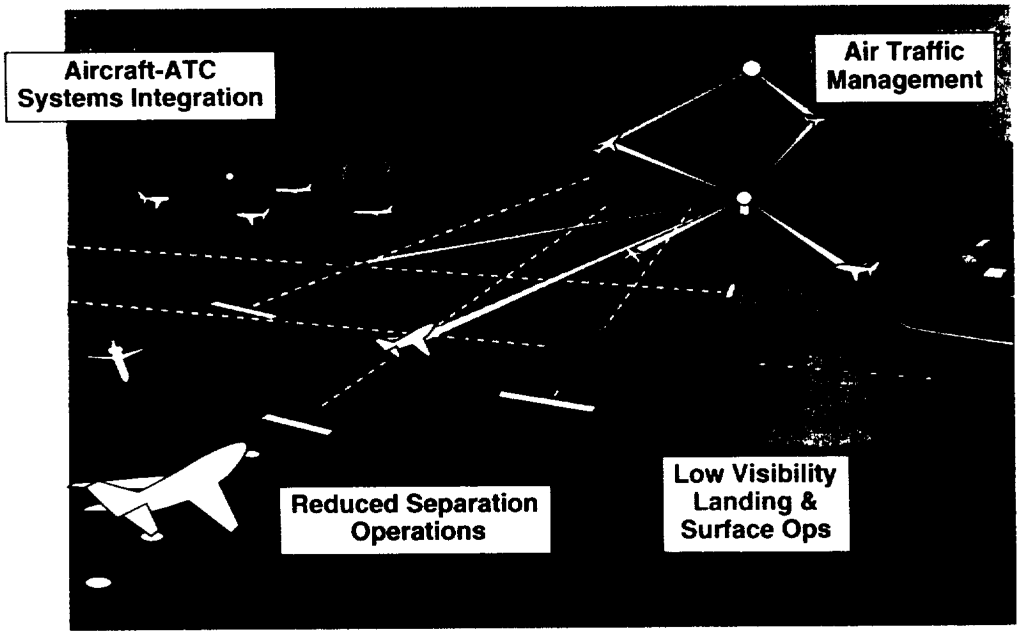
# Management Structure

NASA AERONAUTICS — TERMINAL AREA PRODUCTIVITY



# Program Elements





# Reduced Spacing Operations Overview

## NASA *First* Wake Vortex Dynamic Spacing Workshop

May 13-15, 1997

NASA Langley Research Center

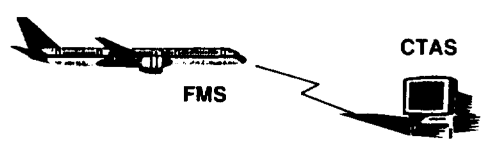

R. Brad Perry
Manager, Reduced Spacing Operations
NASA Langley Research Center


# Reduced Spacing Operations

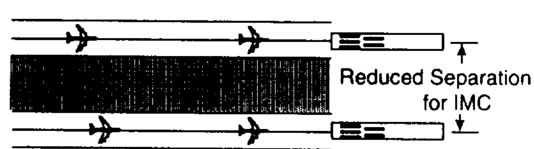
Terminal Area Productivity

## Reduced Spacing Operations (RSO) Research Areas:

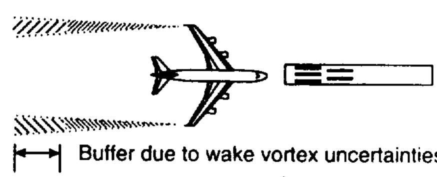
- Flight Management System (FMS)/Center TRACON Automation System (CTAS)




- Airborne Information for Lateral Spacing (AILS)




- Aircraft Vortex Spacing System (AVOSS)

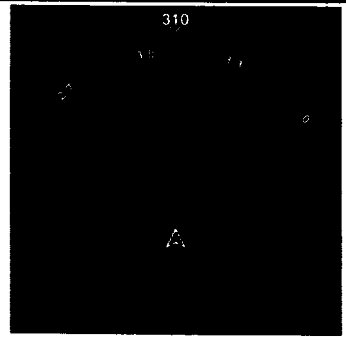


# Reduced Spacing Operations

Terminal Area Productivity

## B-757 FMS/CTAS Simulation

- Experiment will test trajectory, data link, new approach procedures in FMS, pilot and controller procedures in TRACON.
- Modifications to B757 FMS include new approach procedures and FANS-like data link.
- Modifications to CTAS include "frozen" route for FMS aircraft and data link capability.




*arrival path seen by pilot on Navigation Display*

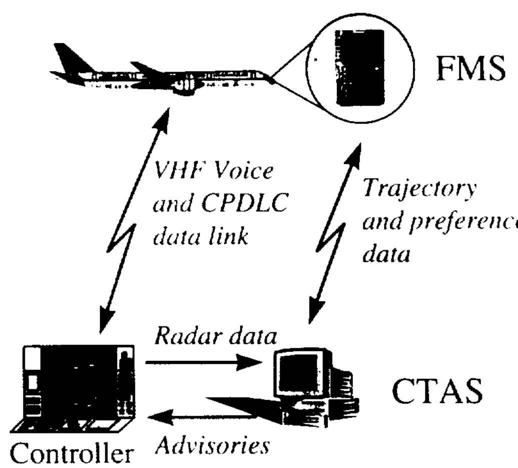
*arrival traffic seen by controller on CTAS display.*

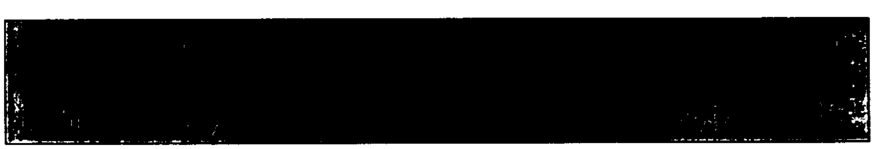
# Reduced Spacing Operations

Terminal Area Productivity

## FMS - CTAS Integration

| CTAS | FMS |
|---|---|
| Ground-based measurements. | Airborne measurements. |
| Computes conflict- free trajectories for all traffic. | Computes cost-efficient aircraft trajectory. |
| Provides discrete advisories to controller for all traffic to achieve desired arrival sequence and spacing. | Continuous airborne guidance for individual aircraft (improved arrival accuracy over CTAS alone). |

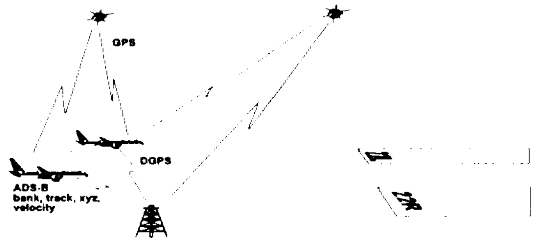


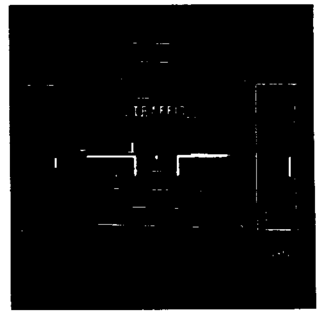
# Reduced Spacing Operations

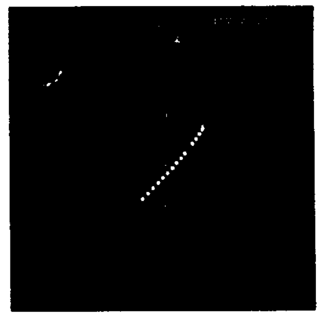
Terminal Area Productivity

## NASA Parallel Runway Operations Concept




- Primary responsibility for lateral separation resides in the flight deck. ATM has supporting role.
- Airborne conflict detection and alerts determined from ADS-B and DGPS information





TAP/Reduced Spacing Operations

# Reduced Spacing Operations

Terminal Area Productivity

## NASA Parallel Runway Results and Focus

- Positive simulation results for parallel independent runway operations in IMC at spacings of 3400' and 2500', and 1700' independent of wake vortex considerations
- Economic benefits and safety analysis studies being performed
- Future simulations to include the B-757 and B-747 simulators utilized in independent and dependent approaches in IMC
- Flight tests and demonstrations in the NASA B-757 planned

NASA B-747-400 Simulator

NASA Boeing 757

TAP/Reduced Spacing Operations

# Reduced Spacing Operations

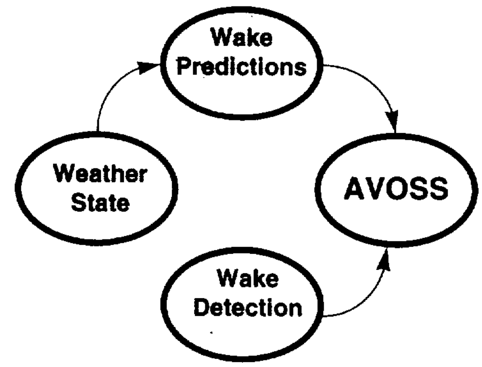
Terminal Area Productivity

## AVOSS Design

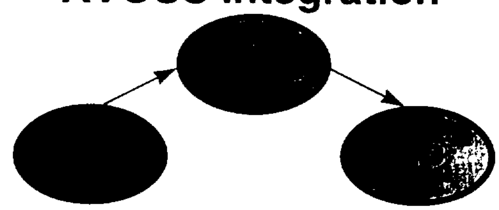
- NASA research supporting TAP goal of improving instrument operations capacity 12-15% while meeting FAA guidelines for safety
- Ground-based dynamic wake vortex spacing capability for capacity-limited airports*
- Separate aircraft from wake vortices (transport rules)*
- Also provide an option to separate aircraft from wake vortices of an operationally unacceptable strength (decay rules)*

**NASA Wake Vortex Research for Aircraft Spacing*, AIAA 97-0057

## AVOSS Subsystems

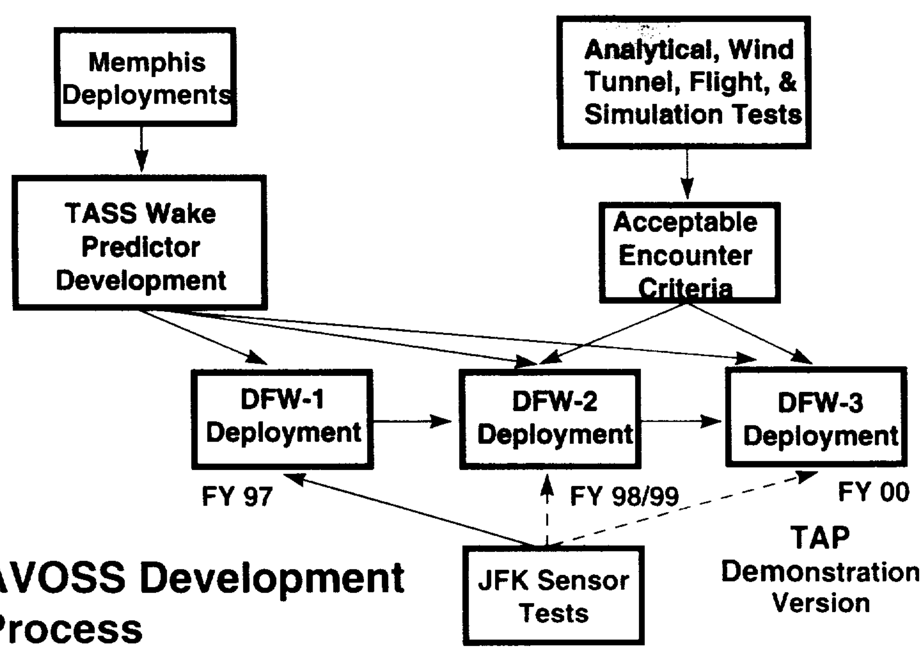



## AVOSS Integration



# Reduced Spacing Operations

Terminal Area Productivity




## AVOSS Development Process

## AVOSS Development and Demonstration Schedule

**1994-1996**

Concept development and research tools implementation

- CFD development and validation
- Memphis meteorological and Lincoln Laboratory CW lidar field systems
- Wake vortex wind tunnel experiments, flight tests, and simulations

**Present**

Initial AVOSS version development (transport separation only)

- CFD parametric runs underway
- NASA pulsed lidar validation underway
- Initial system deployment scheduled at DFW in August/September 1997

**1998-1999**

Second AVOSS version deployment at DFW (transport & decay separation)

**2000**

TAP demonstration of AVOSS at DFW (refined transport & decay separation, DROMS and laboratory CTAS interfaces)

**Questions and Discussions Following R. Brad Perry's Presentation (Manager, Reduced Spacing Operation, NASA LaRC)**

Buck Williams (Lockheed Martin)
How far from the airport is the AVOSS system supposed to cover?

Perry
That's a very good question. We are looking at the final approach corridor or what portion of that we need to cover to do the job, and do it well. AVOSS itself will be resident on the airport grounds. It's possible some of the supporting sensors will have to be adjacent to the airport property.

Williams
And how far out does the final approach corridor extend?

Perry
Typically 5 to 6, sometimes 7 miles, and we're going from an altitude of ground level up to 1500 ft. above the ground.

Bob Zoldos (Air Transportation Assoc. America)
Who is funding this research?

Perry
It is a NASA funded effort.

Zoldos
If you had more funds available, would that expedite the operations?

Perry
Simply yes. This is a clear situation where more is better.

Zoldos
How much more money do you need?

Perry
I will have to get back to you. We did have a joint activity with the FAA early on and that funding went to zero, so we are carrying this program entirely on NASA funding. The main resource limitation right now is the human resource. We are very limited in the number of NASA researchers that are on this effort. AVOSS will need further iterations and prototyping beyond our fixed focus program completion in the year 2000 before it can become operationally real. Ability to work more closely with the FAA to prototype and implement it would expedite operational deployment.

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# Aircraft Vortex Spacing System (AVOSS) Concept and Development

David A. Hinton
NASA - Langley Research Center

First Wake Vortex Dynamic Spacing Workshop
May 13-15, 1997

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# AVOSS Goal

- Support TAP goal of improving instrument operations capacity 12-15 % while maintaining safety.
- Provide dynamical aircraft wake vortex spacing criteria to ATC systems at capacity limited facilities with required lead time and stability for use in establishing aircraft arrival scheduling.
- System development and concept demonstration.

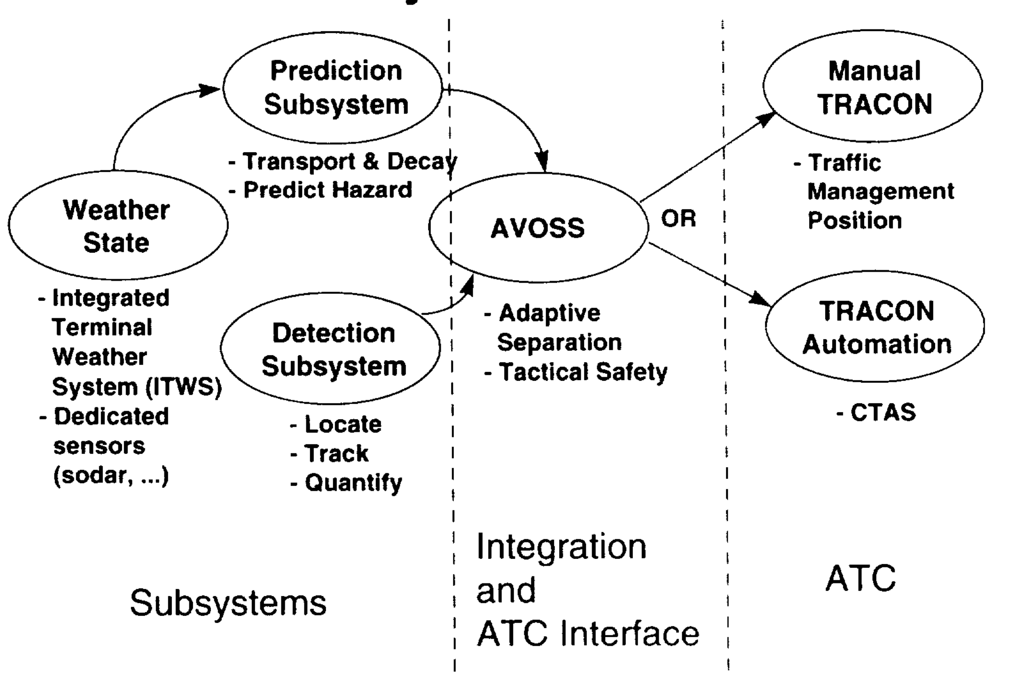
# AVOSS System Concept

- Separate aircraft from <u>encounters</u> with wake vortices of an operationally unacceptable <u>strength</u>.

---

- Define protected corridor from outer marker to runway and predict time for vortex to clear. ("Transport Time")
- Define operationally unacceptable wake strength and predict time to decay. ("Decay Time")
- Combine and provide to ATC automation. ("Residence Time")
- Monitor safety and provide predictor feedback with wake vortex detection subsystem.

# AVOSS System Architecture

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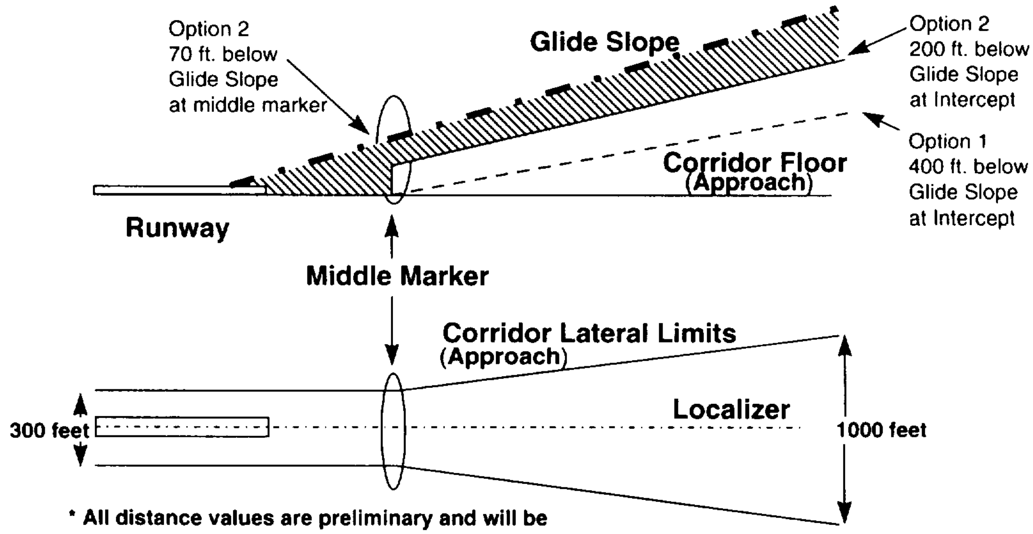
# AVOSS Corridor Geometry




* All distance values are preliminary and will be refined by research process and industry consensus.
* Departure separations based only on lateral motion and decay.

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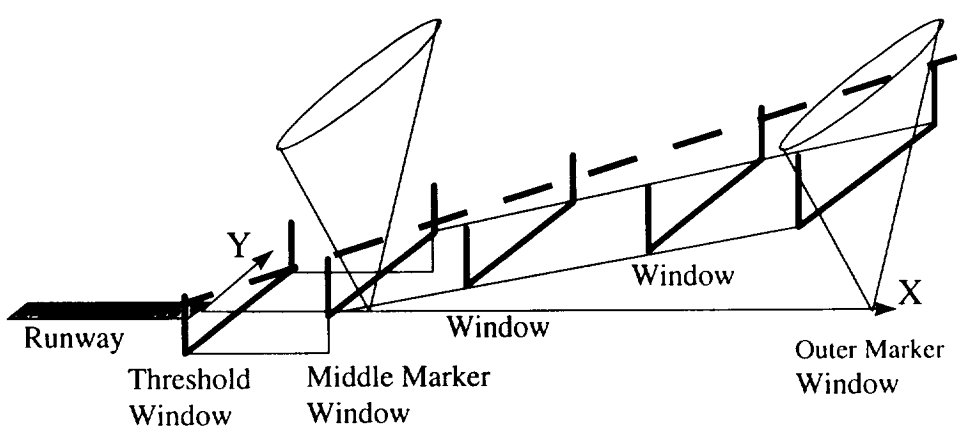
# Corridor Prediction Windows

- Predict wake motion/decay at multiple approach windows:
  - Differing winds, turbulence, thermal lapse rates.
  - Differing aircraft navigational accuracy.



# Wake Prediction and System Stability

- Wake prediction is of possible range of wake motion/decay based on:
  - Weather parameter statistics.
  - Synoptic weather.
  - 30 to 60 minute statistics.
  - Nowcast.
  - Vertical atmosphere profile.

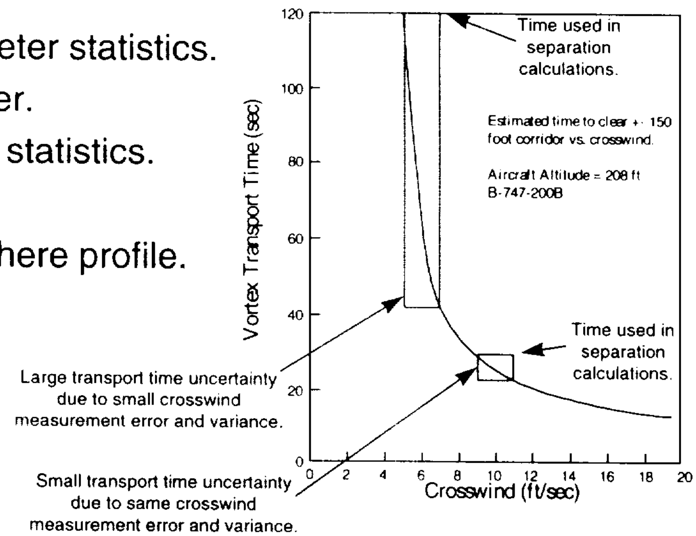
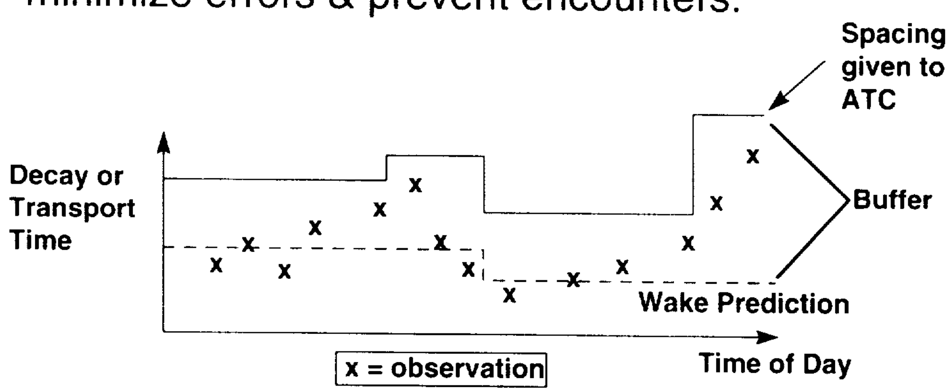



Figure based on *Aircraft Wake Vortex Characteristics from Data Measured at John F. Kennedy International Airport*, Eberle, Brashears, Zalay, Shrider, Love; FAA-RD-78-47, 1978

# Wake Sensor Feedback

- Track actual vs. predicted transport and decay times.
- Modify predictor variables or buffers to minimize errors & prevent encounters.



# Technical Challenge, General

- Safely provide meaningful separation reductions, to values in range of 60 seconds, in presence of atmospheric parameter uncertainties.
- Provide this reduced spacing in adequate domain of airport operations to justify cost.
- Provide architecture that can accept improved systems and knowledge base post-TAP.

# U.S. Separation Standards

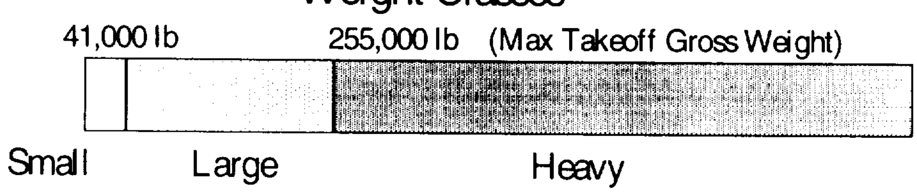
After July 1996

Reduced ROT Documented.

(Distances in Nautical Miles)

| Following Aircraft | Leading Aircraft | | | |
|---|---|---|---|---|
| | Heavy | B-757 | Large | Small |
| Heavy | 4 | 4 | 2.5 | 2.5 |
| Large | 5 | 4 | 2.5 | 2.5 |
| Small | 5, 6T | 5 | 3, 4T | 2.5 |

Weight Classes



# Approximate Separation Time Intervals

Based on Standard Separation, Constant Airspeed of
120kt (Small), 140 kt (757/Large) & 160 kt (Heavy).

| Following Aircraft | Leading Aircraft | | | |
|---|---|---|---|---|
| | Heavy | B-757 | Large | Small |
| Heavy | 90 - 90 | 106 - 90 | 72 - 56 | 94 - 56 |
| Large | 129 - 145 | 103 - 103 | 64 - 64 | 86 - 64 |
| Small | 150 - 188 | 150 - 171 | 90 - 120 | 75 - 75 |

Time spacing at Outer Marker -
Time spacing at Threshold, seconds

# Risk Assessment, Weather Systems

- Low risk of current weather sensing for AVOSS testing and concept demonstration.
  - ITWS
  - Sodar
  - Radar Profiler with Radio Acoustic Sounding System.
  - Meteorological tower.
- High resolution Nowcast is a significant advance in forecasting technology:
  - Ongoing research is encouraging.
  - FAA Aviation Weather involvement appropriate.

# Risk Assessment, Predictor Algorithms

- Wake motion can be reasonably estimated in most situations.
- We must understand the exceptions, i.e., shear-induced wake rising, for safety.
- Decay modeling is less mature.
- Predictive algorithms are not the "tall-pole" for AVOSS. Ability to estimate motion & decay will likely outpace supporting weather system development and acceptable wake strength consensus.

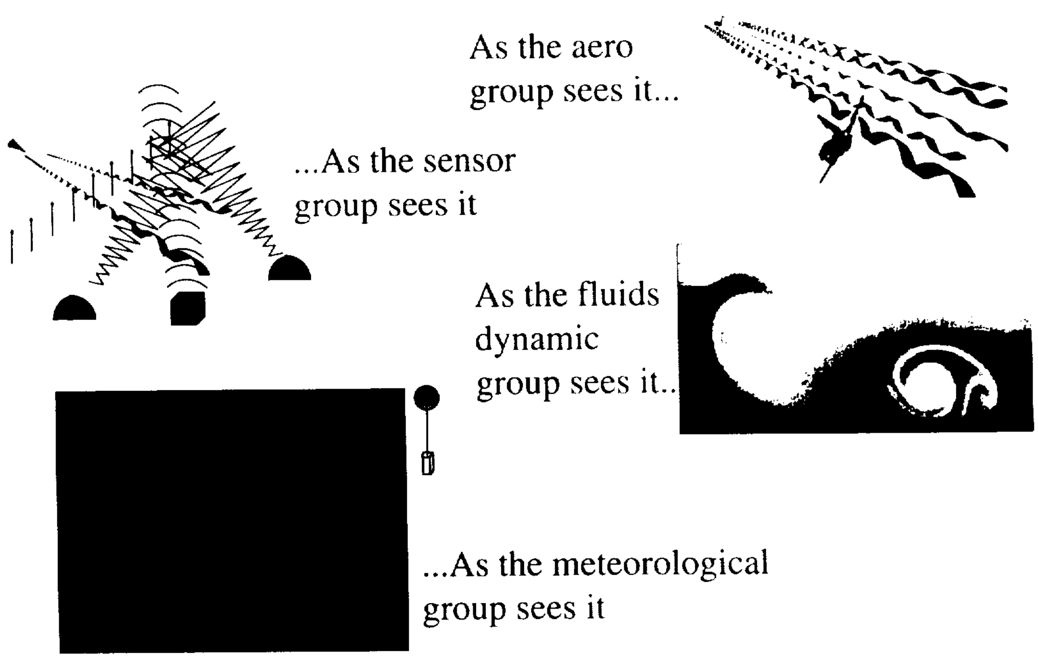
# Risk Assessment, Acceptable Wake Encounter Definition

- Low probability of consensus on acceptable wake encounter, validated models, and completed fleet assessment by year 2000.
- HOWEVER: ATC systems and industry will not be ready for decay-based reduced separation by the year 2000 either.
- AVOSS provides hooks for decay-based separation reduction as well as switch to disable this feature.
- This effort is critical to establishment of minimum wake sensor requirements, even for a system based only on wake motion.

# Risk Assessment, Wake Sensors

- Concept demonstration sensors are available. All-weather operational sensors not yet available. Low risk to a concept demonstration.
- Current sensor abilities will enable wake monitoring in substantial subset of instrument operations (haze, light fog, ceilings between 600 and 2000 feet....).
- A foul-weather or in-cloud sensor capability may well have significant benefits for a post-TAP operational test bed system.
- First-order observable wake strength parameter definition and fleet thresholds required to establish minimum wake sensor performance.

# Dynamic Spacing Systems



# The Challenge

- What useful knowledge can each discipline provide today, to build dynamic wake spacing system?
- What knowledge gaps must be filled for a minimally useful system?
- What features can/should be introduced as enhancement to an operational system (i.e., decay-based spacing reduction)?
- Will the community (ALPA, APA, ATA, FAA, NTSB) accept less than full approach path predictions & monitoring given current data?
- Is there a simpler/better system concept?

**Questions and Discussions Following David Hinton's Presentation (AVOSS Principle Investigator, NASA LaRC)**

Jerry Robinson (Boeing CNS/ATM Research)
Do you envision that the size of the corridor could be reduced through improved navigation such as DGPS?

Hinton
Yes. There was a little footnote at the bottom of my corridor slide. That is a proposal based on PRM monitoring data, navigational accuracy as it exists today. We must consider in that corridor size how far away from airplanes does the wake have to be. Airplane wing spans are getting so big that they may have to stick out both sides of the corridor. The aviation community has to feel comfortable, ALPA, APA, airlines, etc. I plan to perform sensitivity studies as function of corridor size by year 2000 and let industry and FAA decide on width. I do agree size should decrease with bettter navigation.

Jerry Robinson
I have a second question. Which ATC facility would receive information from AVOSS. Is it TRACON facility or both TRACON and Center?

Hinton
I can't answer that question completely since I don't design controller interfaces. We will have the Ames people, Barbara Kinki and Rhonda Slatery, here Thursday to discuss ATC aspects in more detail. However, it is my belief that TRACON position is the one that needs it. Center may want it for advance information to anticipate TRACON operation.

Dennis Bushnell (NASA Langley)
Have you considered the airport sites specific roughness distributions as they affect both the weather and the subsequent affect on the vortex, and possibly altering the sites specific roughness to help you in this matter?

Hinton
We are aware that the AVOSS architecture with specific sensor compliment will be site specific. We are doing some studies at the 10 TAP airports and we are starting to look at things like ceiling probability distribution.

Bushnell
The roughness is put in specific motions which will alter the vortex in very specific ways which you will not have included in your similar spetra modeling of the turbulence affect?

Hinton
We have to take this in stages. There will be a concept demonstration at Dallas. There will be validation of our predictions. If our predictions of first order effects are

not right, we are going to prove it at Dallas, then there will be post-TAP efforts required for site specific adaptation for this system. There are airports with ravines off runway or large bodies of water nearby which have implication more for sensor system and weather system than prediction system.

Alexander Praskovsky (National Center for Atmospheric Research)
You said you are satisfied by current meteorological observations. What are the parameters and range that you would want to get in real time or nowcast that would be sufficient for your system?

Hinton
We are looking at a profile from the surface to the glideslope intercept point which is roughly 1600 ft. above the ground for wind, speed and direction, temperature, wind gradients and may need turbulence statistics. But at this point we don't know the scale length or how high they would be required.

Praskovsky
What parameters of turbulence do you need?

Hinton
I will leave that to the wake vortex experts. I don't think there is an answer to that yet.

Praskovsky
I have a second question. In your last transparencies, the last question was what is a better alternative? What is your purpose, to understand physics of wake vortex or do you want to create real time operation system? These are two different purposes. Which is your goal?

Hinton
The purpose is to gather the data or knowledge required to build a real time system. It is not necessarily to understand every nuance of wake behavior and to understand the first order effects and effects that will most rapidly increase capacity.

Praskovsky
What kind of logic do you use in your system integration decision?

Hinton
Initially we are looking at an approach corridor with pre-defined windows at multiple stations along the approach. We are taking the weather profiles, the statistical uncertainty in the weather data, predicting the wake motion out of those corridors, the range of possible motions, putting together a separation matrix that, if followed, will provide the spacing at each window for all the aircraft. There are other layers that have to be put on top of that such as hysteresis. If separation changes to lower value, we can't go back three minutes later and give ATC another value. There will also be safety logic. For example convective activity within so many miles which could affect our atmospheric parameters. There are many layers to that question.

David Shedrinick (Transport Canada)
Do you have any intention of incorporating flight data monitoring and getting appropriate weather met information data linked to ground?

Hinton
We would like to do that, I don't know that it's feasible for our concept demonstration. The Integrated Terminal Weather System has the capability to ingest down link data. One problem is currently the data comes down every 1000-2000 ft. We need wind data more on the order of every 100 ft.

Jan Demuth (FAA - Flight Standards)
You indicate that getting consensus on an operationally acceptable strength is a key piece. Why can you not incorporate a concept of no encounter in your system?

Hinton
We can, the question is what is no encounter. If we are tracking a wake, and it's decaying and decaying and finally it is hiding in the atmospheric turbulence, but we are still tracking it, is it a hazard? If we want to track the wake completely out of the corridor we have to tell the sensor what it's operation requirements are and what to consider a vortex. We have to understand some minimal strength below which it is no longer considered an event. In terms of thresholding, let's say it stalls right on the center line, we could have a system down the road that a DC10 can penetrate this level, B727 has a weaker level and a B737 even weaker level and when wake has decayed sufficiently we can let the DC10 through. That is an issue and I understand that is a difficult consensus to come to. But there is another issue that says we are going to track it out of the corridor and let planes through once it has left. But if the sensor is losing the wake while it is still considered a threat, then we don't know where it's gone, or how to validate our predictions. So we have to understand what is considered an event to the pilot one way or another.

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# HISTORY OF WAKE VORTEX RESEARCH: PROBLEMS AND ACCOMPLISHMENTS

GEORGE C. GREENE

NASA First Wake Vortex Dynamic Spacing Workshop
May 13-15, 1997

# OUTLINE

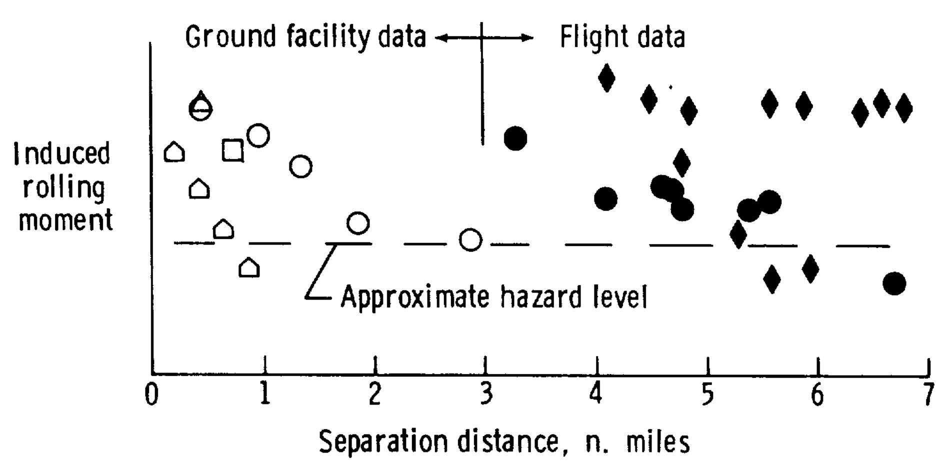
- History and accomplishments
  - Wake physics
  - Other areas
- Remaining problems

# EARLY WIND TUNNEL AND FLIGHT TESTS

Produced:

- Operational guidance for wake avoidance
- Excellent flow visualization
- Mixed results for wake alleviation
- Refinement of decay wake theories

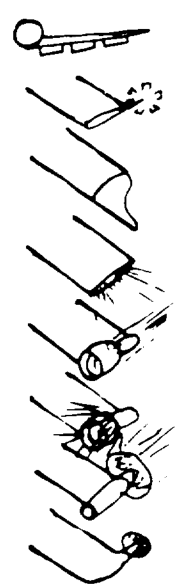
**B747/ SMALL AIRCRAFT WAKE HAZARD**



*WAKE VORTEX*

## VORTEX ATTENUATION

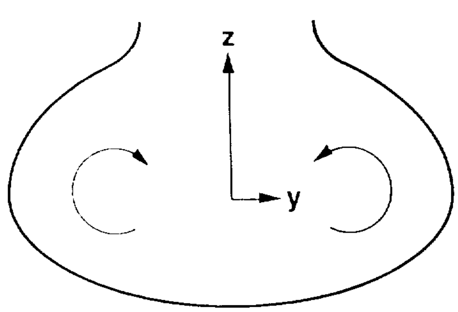
- FLAP VARIATION
- SPLINE DEVICE
- WINGTIP VARIATION
- WINGTIP BLOWING
- WINGTIP TURBOFAN
- REVERSE THRUST
- WINGTIP TURBOPROP
- WINGTIP VORTEX TURBINE



# JOHN YATES' ANALYSIS

- Betz rollup model often used to estimate vortex structure from wing lift distribution
- Betz model uses "invariants" of motion
- Yates' analysis evaluates changes in "invariants" during rollup
- Yates' analysis provides insight for wake modification studies

# CURRENT UNDERSTANDING OF WAKE ROLLUP AND DECAY




John Yates' eqn.

$$\frac{d\Gamma_r}{dt} = -\int_{-\infty}^{\infty} (z-\bar{z})\frac{w^2}{2}\Big|_{y=0} dz + 2\nu\Gamma$$

where $\Gamma_r$ varies with vortex core size

# “CROW” INSTABILITY

- Crow’s analysis described an instability mechanism observed in the atmosphere
- It suggested that wake decay could be enhanced through some form of instability
- It started a research thrust in vortex stability that continues today

# VORTEX “BOUNCE”

- Vortices do not always descend and may occasionally “bounce” above the flight path of the generating aircraft
- The cause of vortex “bounce” in ground effect is understood although “worst case” conditions are not known
- Vortex “bounce” at altitude is not well understood

# TOWER FLY-BY TESTS

- Attempted to measure decay of "peak" velocity in wake for different aircraft types
- Test technique is of questionable value
- Tests demonstrated conclusively the importance of atmospheric environment

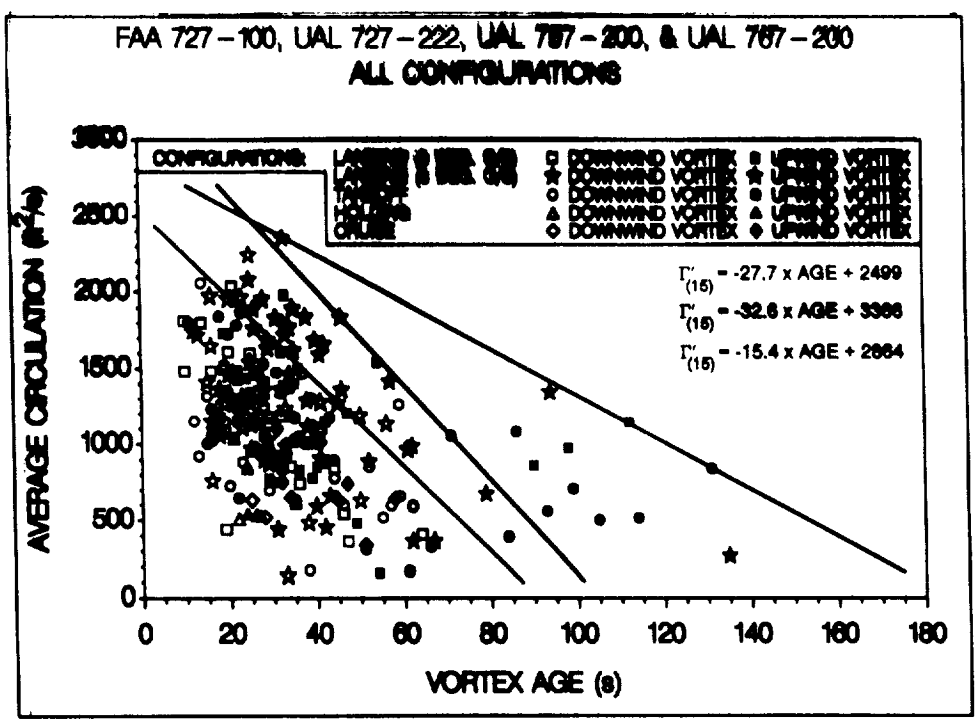



**Figure 58.** Average vortex circulation (Γ') for a radius of 15 ft as a function of vortex age. Red, blue, and green symbols and lines indicate B727-100/-222, B757-200, and B767-200 data, respectively. The lines indicate the outer bounds of the data envelopes as specified by the corresponding colored equations.

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# SIGNIFICANT EVENTS

- Establishment of the UK Wake Vortex Incident Reporting System
- Development of the Vortex Advisory System (VAS)
- Establishment of the US government/ industry team

# REMAINING QUESTIONS

- What are we doing now in VMC?
- How do we quantify safety/capacity changes in the system?
- How do we best use "science" in an operational system?
- What criteria will we use for "REALLY BIG" aircraft?

# SUMMARY

- Significant progress has been made in understanding vortex behavior but much remains to be done
- The primary challenge is to bring “science” into operational use
- Success will require cooperation from a diverse group of organizations

**Questions and Discussions Following George Greene's Presentation (NASA LaRC)**

Tim Dasey (MIT)
I would like to put a challenge to the FAA or other people in the audience about what the U. S. could and should be doing about wake vortex reporting systems. I see no evidence of a system that can be used by scientist to analyze incident rates. I would like to know where FAA is going with such a system. I feel that an operational system will not come unless we can at least measure how safe the current system is.

Greene
I am not sure what the question was, but the answer is yes.

Robert Ash (ODU)
In your view, where did the models in the wake vortex have the biggest weakness? What do you see as the problem?

Greene
For many years we concentrated on trying to calculate how the wake rolls up behind an airplane and what you can do to modify it. In my view there has been very little progress in that computation capability in 50 years. It is difficult to know how the rollup is affected if you move an engine or change a flap system. We said weather has a big effect on top of this, and we try to add weather effects. I think we have turned the corner in bringing meteorology in at the get-go. It is an extremely difficult problem and a three dimensional problem. These codes have shown us some phenomenon we either forgot about or hadn't thought much about. For example, the effect of wind shear and other weather phenomena. One of the challenges is that can we bring those codes to a point that you have confidence in them, enough confidence to use for operational situation.

Amolak Jain (STC)
Unless you understand each of the many pieces, I don't know if you can solve the complete problem. We must spend the time understanding the physics of the many pieces to get answer.

Greene
I agree it is a difficult problem that takes a long time to solve. I would like to comment on Reynolds number effect as an example. Whenever you have a difficult problem to solve, we often think of it as university research problem. In universities, facilites often have low Reynolds numbers. You want to simplify the problem and look at one vortex. I'm not sure research that looks at a single vortex is revelant to the problem, period. I think that some of the thing "learned" in low Reynold number experiments will have to be unlearned for real operational use. I agree that it is something that takes a long time, I think you have to be very careful to make sure that you are studying it in the environment that will give you an operational answer. Let me illustrate that. At approach speed, a B747 will fly across this room in one second and has a Reynolds number of 50 million, and if you slow the airplane down so the Reynolds number was

50,000, it would take 15 minutes to fly across. I think you have to be very careful in the long-term studies that you do it in the right facilities and right framework

# WAKE-VORTEX PHYSICS: THE GREAT CONTROVERSIES

P. Spalart, Boeing Commercial Airplane Group



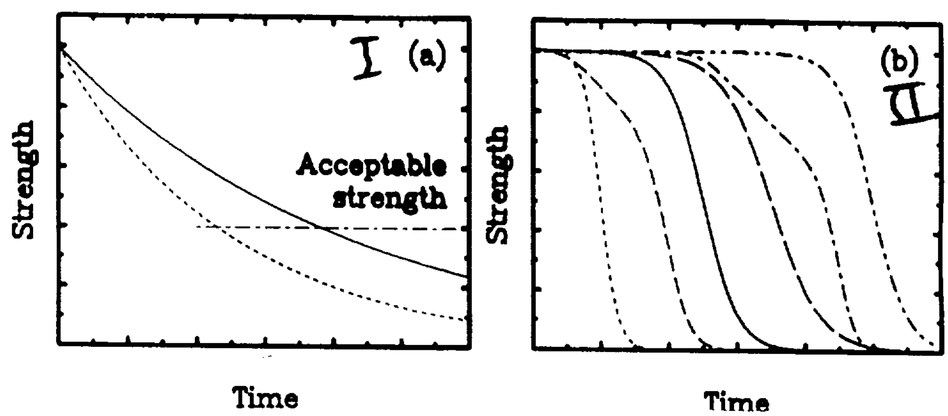
- Do vortices decay?
- Why does ATC work today?
- Do wakes ever rise?
- What is the effect of stable atmospheric stratification?
- Are the vortices bathing in turbulence?
- How much can happen to ONE vortex?
- Passive or active control strategy?

- Ground rules: I tried to clearly summarize conflicting opinions. They may appear extreme, but I believe each is held by serious people in the field.

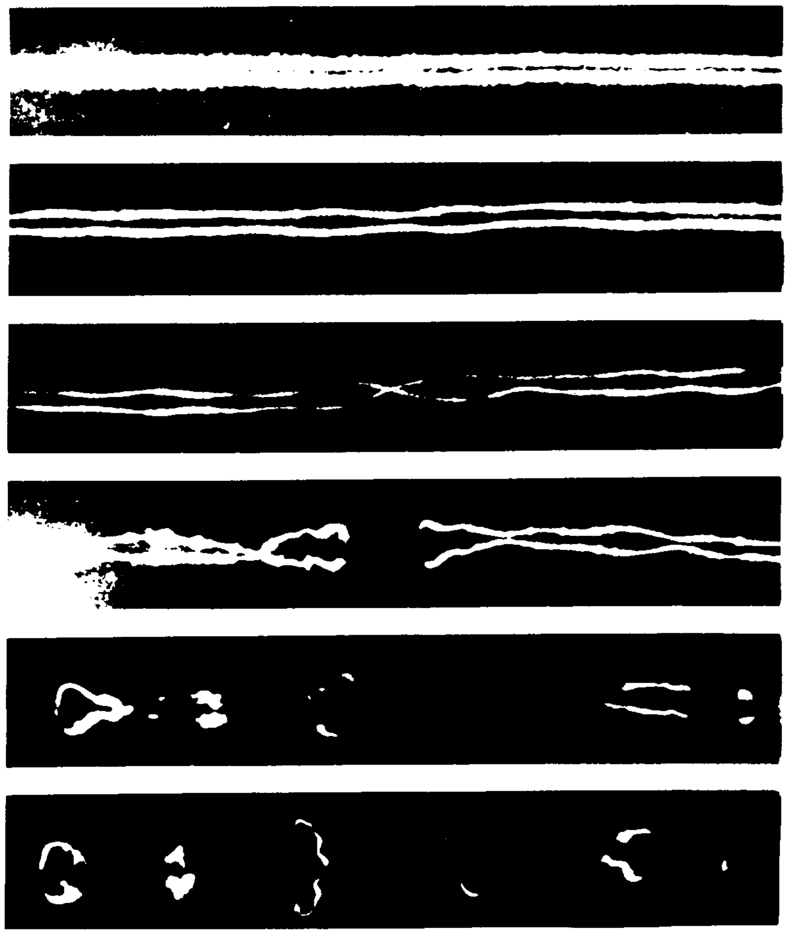
## DO VORTICES DECAY?

- **Position A:**
  - The strength of the vortices (peak velocity, circulation) immediately begins a predictable gradual decay, exponential or even linear.
  - The hazard potential decays significantly on the time scales of interest (say, two minutes).
  - Atmospheric effects (ambient turbulence, stratification) often accelerate the decay, again at a predictable rate.
  - The Navier-Stokes Equations could be missing something.
- **Position B:**
  - In a quiet unstratified atmosphere, the vortices preserve circulation, and lose very little kinetic energy or hazard potential in two minutes.
  - They turn into rings by Crow instability, and then collapse.
  - The collapse time is stochastic, with a wide scatter, and sometimes exceeds the regulatory separation.
  - Ground effect and stratification create opposite vorticity and thus drain the kinetic energy, but the initial vortices remain distinct.

Two views of wake-vortex physics



Van Dyke Book



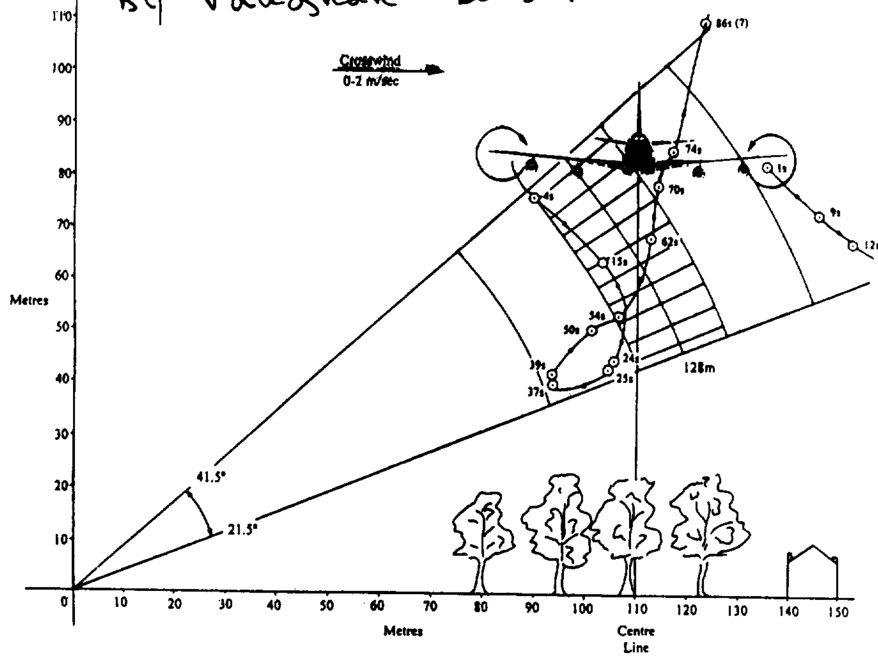
## WHY DOES ATC WORK TODAY?

- **Position A:**
  - The leader airplane has a characteristic decay curve: wake strength as a function of time (or distance).
  - The follower has a characteristic wake strength, which it can tolerate.
  - Heavier leaders have higher curves.
  - Heavier followers have higher tolerance.
  - The two give a matrix of separations for model pairs, which is lumped into a few classes for ATC purposes.
- **Position B:**
  - Wakes in a quiet atmosphere have much too little decay to explain the current empirical matrix.
  - We AVOID the wakes, for many reasons: natural descent, side winds, early collapse.
  - The frequency of encounters depends on the far "tail" of some probability distribution, and will be very difficult to predict.
  - The Rebound Question will become paramount as navigation becomes more accurate.

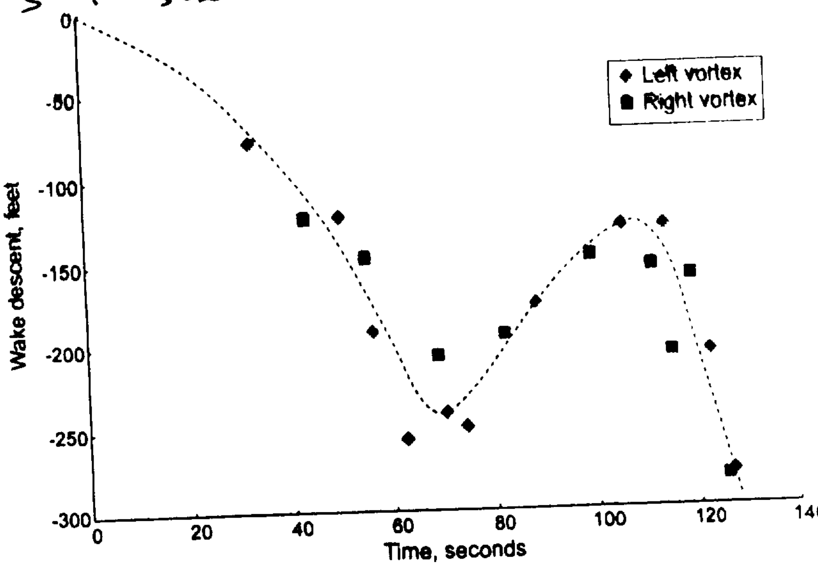
## DO WAKES EVER RISE?

- Pilot training: "you will not encounter the wake unless you fly below the leader's flight path" (modified in ground effect).
- **Exhibit I:**
  - Lidar measurements at LHR by Vaughan, Brown, Constant, Eacock, & Foord of DRA.
  - Not far out of ground effect, but still climbing through $110m$ AGL.
  - Authors state "extremely rare event, but not isolated" (other events the same morning), and invoke buoyancy.
- **Exhibit II:**
  - OV-10 Stereo-Camera + GPS measurements by Vicroy, Brandon, Greene, Rivers, Shah, Stewart, & Stuever of Langley.
  - Out of ground effect.
  - Authors invoke "local variations in the vertical wind, temperature, or turbulence".

Lidar measurements at LHK by Vaughan et al.




NASA Langley measurements GPS + stereo cameras.



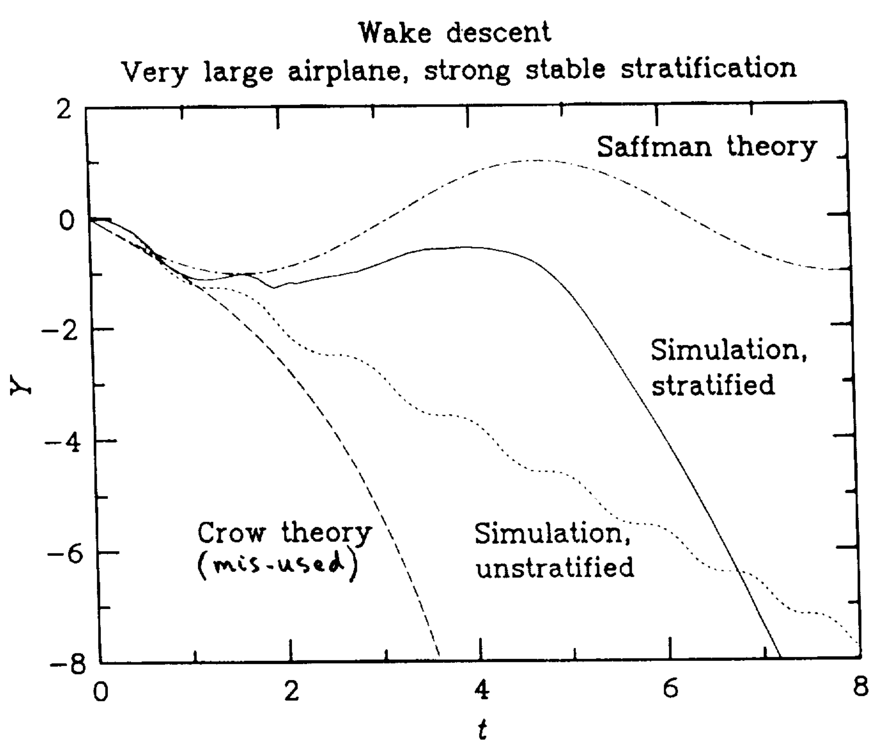

[redacted] - OV-10 measured wake descent of a C-130.

[redacted]

## WHAT IS THE EFFECT OF STABLE ATMOSPHERIC STRATIFICATION?

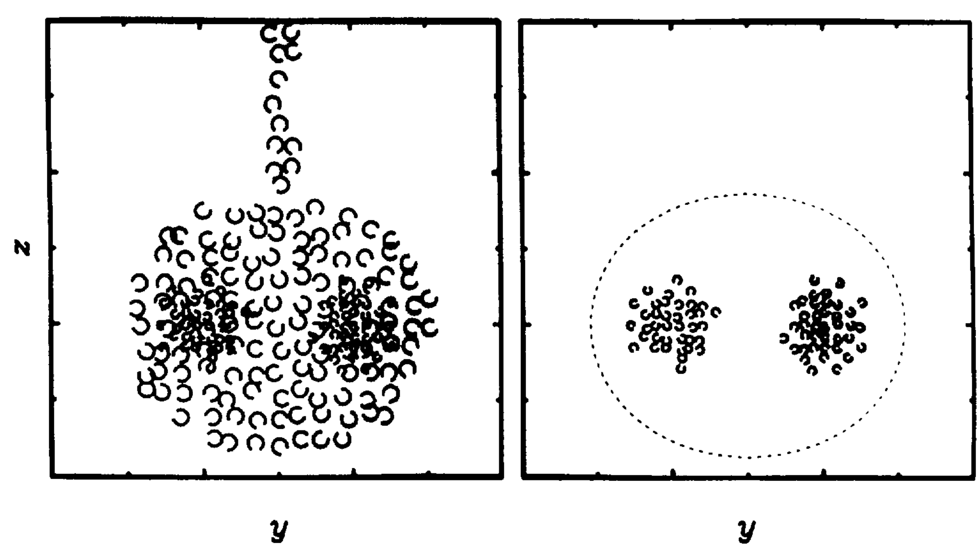
- **Position A:** The wake oscillates, roughly at the Brunt-Väisälä frequency $N$.
- **Position B:** The descent stops and the vortices have decayed after about 1/4 Brunt-Väisälä period.
- **Position C:** The descent continues, faster and faster.
- **Position D:** The descent slows for about 1/2 period, then continues, faster and faster.

- **Position $\alpha$:** The non-dimensional stratification number $N^* = 1/F \equiv N 2\pi b_0^2/\Gamma$ is $\ll 1$; the effect can be neglected.
- **Position $\beta$:** $N$ often exceeds $0.02 s^{-1}$; $2\pi b_0^2/\Gamma$ often exceeds $30 s$; $N^*$ can exceed 1; in rare cases, the wake rebounds to the flight altitude.



# ARE THE VORTICES BATHING IN TURBULENCE?

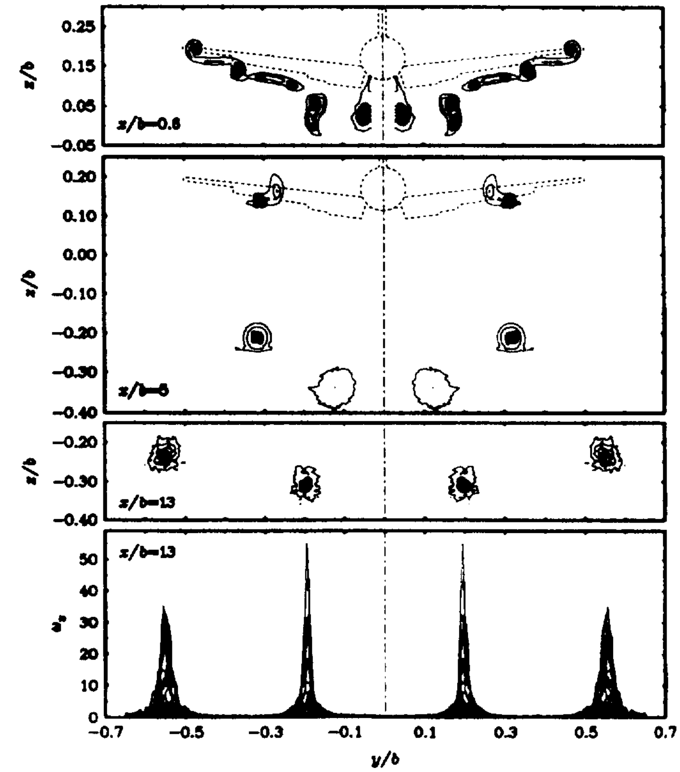
- **Position A:**
  - The "oval" of fluid which generally follows the vortex pair in its descent is "full of turbulence".
  - The turbulence diffuses vorticity, causing gradual cancellation on the centerline, and detrainment across the oval boundary.
- **Position B:**
  - With high wing aspect ratio, The vortical regions do not reach the centerline or oval boundary.
  - Fine-scale "nibbling" turbulence does not exist without vorticity.
  - "Fossil" turbulence from the boundary layers is damped by stretching and rotation, axial-flow differences rapidly diminish.
  - The vortices are so segregated that they become axisymmetric and nearly conserve their individual "angular momentum" $\int\int \omega\, r^2\, dydz$: they cannot grow.



# WAKE SURVEYS

## Airliner in approach condition, 767–like

## Test in DNW tunnel, The Netherlands



# HOW MUCH CAN HAPPEN TO one VORTEX?

- **Position A:**
  - "Alleviate" the vortex; reduce its peak velocity.
  - Use turbulence fueled by thrust or drag (engine or parachute).
  - Trigger instabilities of the core, spiral or varicose.
  - A vortex can be "destroyed", "cut", or "burst" by itself.
  - Flight tests show a vortex (smoke tube) disappear, often by the "sausage-and-pancake" process, and the other one last for minutes.
- **Position B:**
  - A vortex can change its identity only by merging with or cancelling another vortex (or vorticity created by ground separation or stratification).
  - Constraints on circulation, impulse, and angular momentum severely restrict how much a vortex can change.
  - "Sausage-and-pancake" is unexplained.

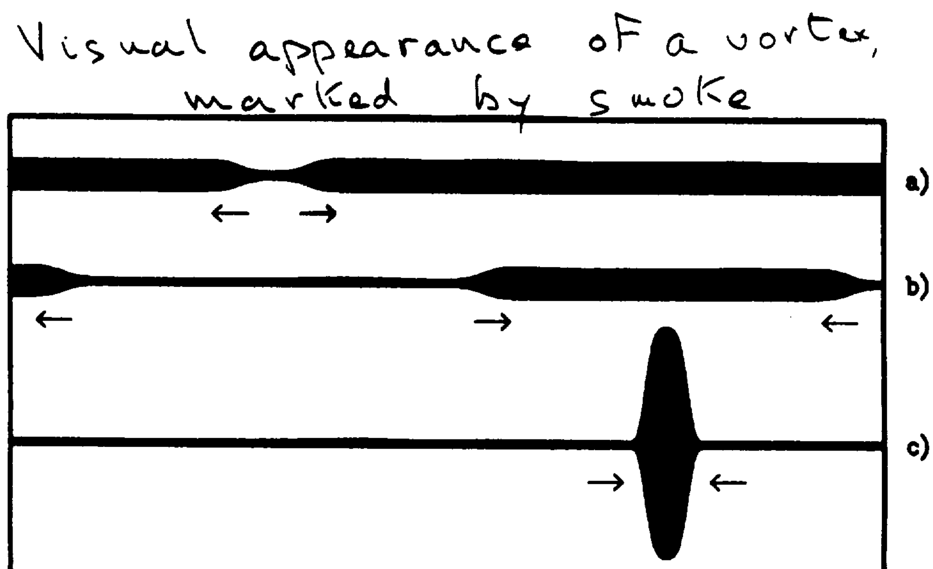



Figure 8: Sketch of vortex bursting, from a videotape of a NASA flight

# PASSIVE OR ACTIVE CONTROL STRATEGY?

- **Position A:**
  - "Passive" defined as: immobile devices such as winglets, fences, porous tips, feathers, blowing, and tip turbines.
  - Concept is to directly reduce the peak velocity, or to foster an instability that will.
- **Position B:**
  - A passive modification cannot change the "big picture" (rolling moment) unless it also changes the circulation or induced drag a lot.
  - "Active" defined as: cyclic motion of control surfaces.
  - Proposed by Crow in 70's, not used.
  - Simulations suggest the Crow instability is not fast enough for a collapse in 2 minutes (need to account for ring life).

**Questions and Discussions Following Philippe Spalart's Presentation (Boeing)**

Pal Arya (NCSU)
I have a comment on your question. Are vortices bathed in turbulence? Of course they are, and not just small scale turbulence, but turbulence eddies which are much larger than vortices, especially in day time in the convective boundary layer. If you consider vertical movement of some for these thermals or updrafts, they are strong enough to make vortices move up and would explain some of the phenomena that has been observed.

Spalart
I wasn't quite clear. What I meant was are they bathed in turbulence they themselves sustain. Given if the atmosphere were completely quiet, there would be turbulence that the vortices have created and are sustaining. That level would be scaling with the circulation of the vortices, not with anything the atmosphere is doing.

Arya
If the vortices are near the ground, the turbulence are always there.

Spalart
Some days the wind velocity will be a foot per second and we have peak velocities of two or three hunrdred feet per second. There will be days when atmosphere turbulence is too weak to matter. The question is, is there turbulence supported by the vortices by their core or the oval? Is there turbulence they always create themselves?

Arya
If you consider the turbulence that are the same size or larger, they are likely to distort or destroy the eddies. I have a question on the slide that showed vortices that came down and then up – was that day time in unstable condition, or more stable condition?

Spalart
The people who took measurements are in the room.

Dan Vicroy - (NASA Langley)
That was during the day time. I want to point out in that slide that there was a C130 flying at about 150 knots and an OV-10 was making measurements flying about 130 knots. We were continually falling farther and farther behind the C130 but we were moving forward so we are not moving through a constant chunk of atmosphere. The atmosphere is changing as we move forward. There may have been a local updraft in the region of 110 second or so.

Fred Proctor - (NASA Langley)
Dan, what were the atmospheric conditions?

Vicroy
I have temperature profile as well as TKE value which I think is about 0.3. I have that data and will bring it in tomorrow.

Proctor
In other words, it was a nice sunny day inside the planetary boundary layer.

Vicroy
Yes, they were all sunny days because we did our flights in pretty good visual conditions. I will bring in data so we can look at it tomorrow.

Susan Ying (McDonnell Douglas)
In your last slide you showed some passive and active control devices. Greene in his talk mentioned these designs should go into earlier stage rather than trying to correct after. In future aircraft, especially in megaliner where aircraft are becoming heavier and heavier, how would you forsee some design going into these aircraft? Would it have many segments of flaps, would it be extra devices?

Spalart
Well, you are not part of Boeing yet. Seriously, it must be said there is no official regulatory position on this, so we don't know what would please the FAA or the CAA when certifying the airplane.

Bob Ash (Old Dominion University)
You talked about peak velocity in core. Is the core breakdown a consideration also, that is peak velocity affect breakdown.

Spalart
I don't think we are sure. If it didn't exchange vorticity with its partner then circulation wouldn't change. In fact, if you stretch a vortex you increase the velocity in it. It would seem that a thin piece of smoke has more hazard than a fat one. I agree that a peak velocity would probably control the propagation velocity of these fronts but I can't explain the fronts, I don't think anybody can. That would be a good Ph.D. research subject. I might add in video often it happens to one vortex but the other lasts for another minute completely unchanged then it decides to have a crisis. It doesn't appear to be collaborative or the atmosphere because if that were the case both would have to kick in at about the same time.

Kenny Kaulia (Ariline Pilots Association)
The Boeing Company is currently planning new models of the 757 and 767. Are there any plans to do any certification flight testing or wake vortex testing?

Spalart
Not to my knowledge.

# PAST WAKE VORTEX INVESTIGATIONS AND DYNAMIC SPACING SYSTEMS

Ed Spitzer
James Hallock
David Burnham
Bob Rudis

## PAST WAKE VORTEX INVESTIGATIONS

THE EARLY YEARS (late 1960's to early 1970's)

- tower flybys (anemometers)
- flight tests (aircraft response, pilot judgment, LDV)
- wind tunnels (movies)

## PAST WAKE VORTEX INVESTIGATIONS

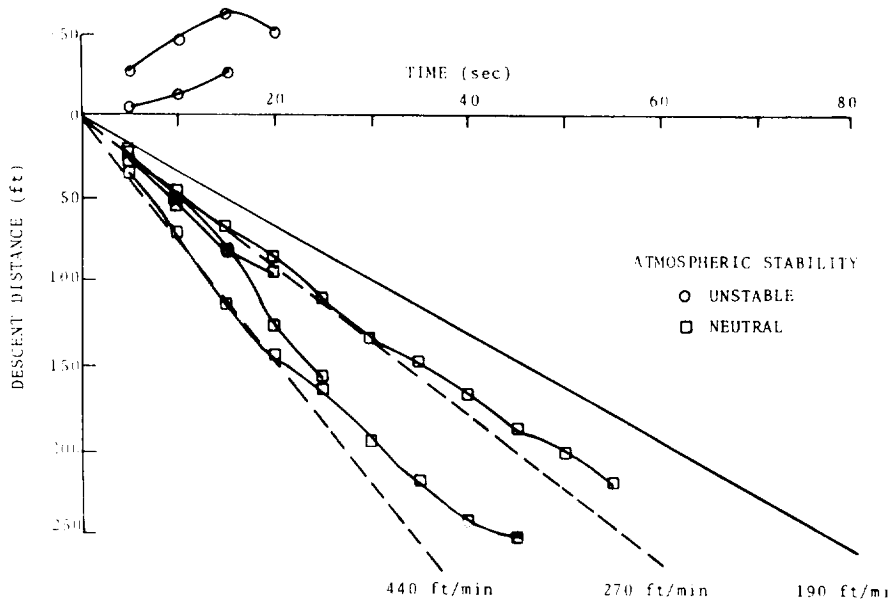
**THE ACTIVE YEARS (mid-1970's to early 1980's)**

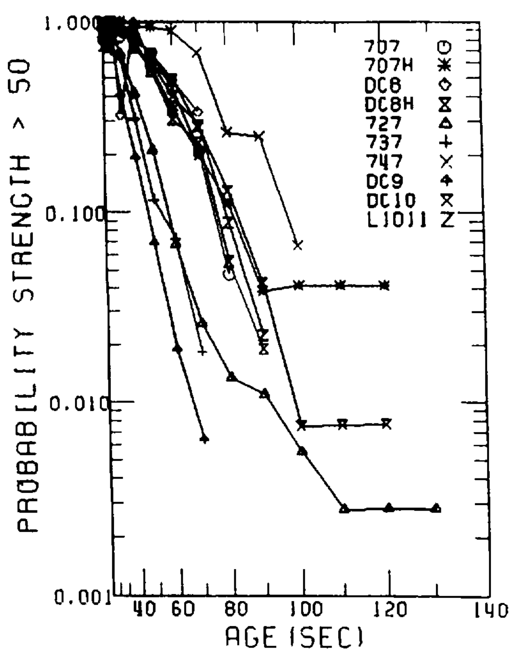
- tower flybys (anemometers)
  sensor calibrations
- flight tests (aircraft response, LDVs)
- wind tunnels and water tunnels (movies, LDV)
- airport measurements (anemometers, acoustic radar, LDV)
  - BOS
  - Mojave (Edwards, Rosamond Lake)
  - JFK
  - DEN
  - Moses Lake
  - LHR
  - YYZ
  - ORD

## PAST WAKE VORTEX INVESTIGATIONS

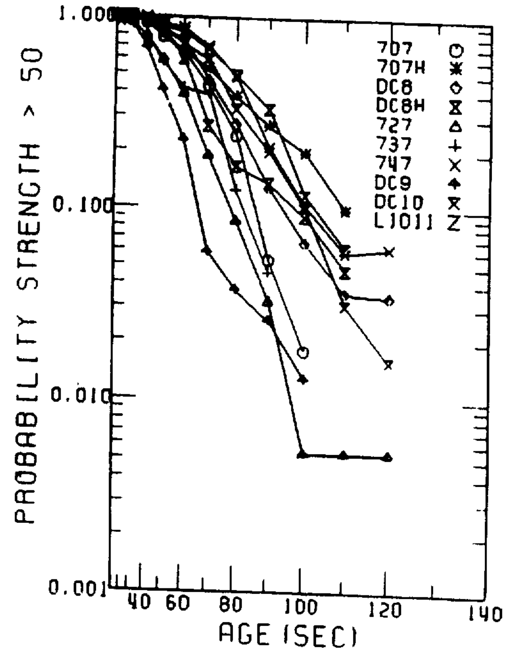
**THE LEAN YEARS (mid 1980's to early 1990's)**

- wind tunnels and water channels (movies, LDV, rolling moments)
- airport measurements (MAVSS, LDV)
  DFW
- tower flybys (anemometers, MAVSS, LDV)
  IDF
- flight tests (helicopter) (LDV, probe)

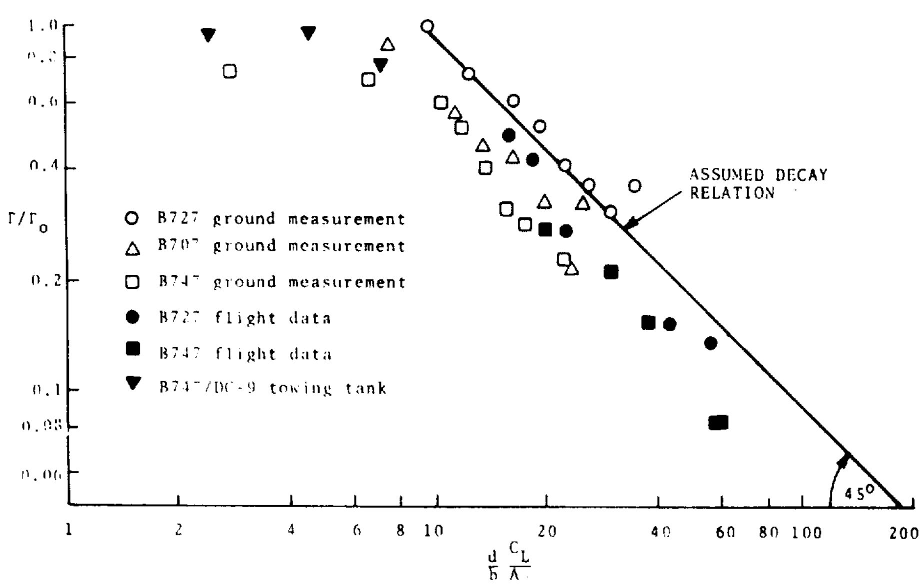



**Chicago Takeoff Data, Vortex #2: Averaging Radius=10m, Probability Vortex Strength >50 m²/s vs. Vortex Age**




**Chicago Landing Data, Vortex #2: Averaging Radius=10m, Probability Vortex Strength >50 m²/s vs. Vortex Age**



## PAST WAKE VORTEX INVESTIGATIONS

THE CURRENT YEARS (early 1990's to present)

- wind tunnels (rolling moments)
- airport measurements (anemometers, LDV)
  JFK
  MEM

## PAST WAKE VORTEX INVESTIGATIONS

- VORTEX PHYSICS
  - vortex motion and decay
    - aircraft effects
    - meteorological effects
    - decay modes
- SAFETY
  - separation standards very conservative most of the time
  - guidance material for pilots
- HAZARD DEFINITION
  - roll moment

## PAST WAKE VORTEX INVESTIGATIONS

- SAFETY ANALYSIS
  - comparative analysis
- VORTEX AVOIDANCE SYSTEMS
  - vortex advisory system (VAS)
  - vortex warning system (VWS)
  - wake vortex avoidance system (WVAS)
  - parallel runway vortex advisory system (P-VAS)

## PAST WAKE VORTEX INVESTIGATIONS

WAKE VORTEX BIBLIOGRAPHY HAS BEEN UPDATED TO EARLY 1997 AND WILL BE FOUND AT:

www.volpe.dot.gov/wv

PLEASE REVIEW YOUR DOCUMENTS AND SEND ADDITIONS, CHANGES, ETC. UPDATES WILL BE DONE PERIODICALLY.

Hallock@volpe1.dot.gov

## PAST WAKE VORTEX INVESTIGATIONS

### THE FUTURE YEARS (present to . . .)

- JFK test site
  test sensors
  special vortex studies
- DFW support for NASA/Langley
- Government/Industry team support
  classification
- Documentation of past efforts
- Databases (vortex and wind) on CD-ROM

<u>DOCUMENTATION OF PAST EFFORTS</u>

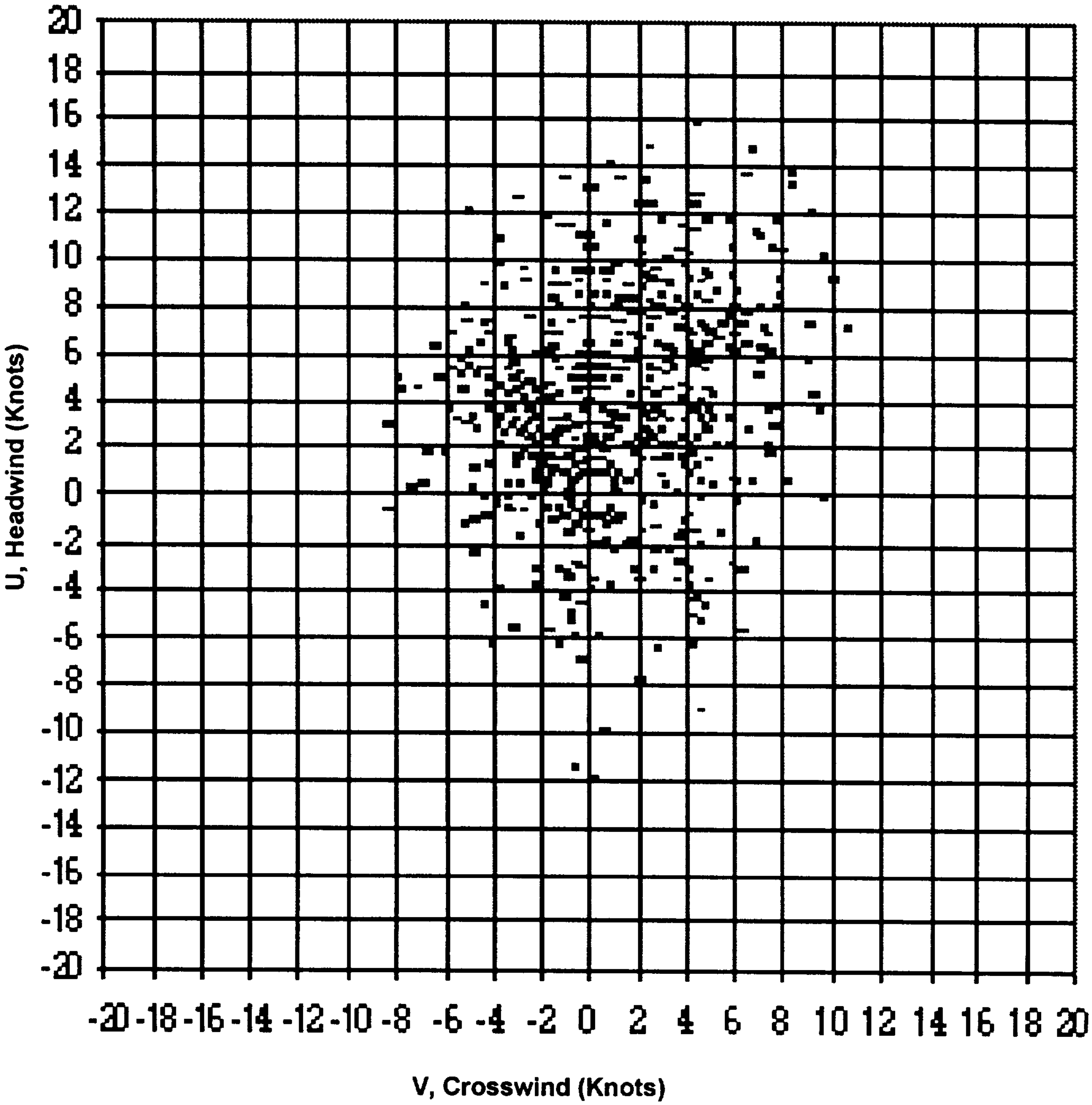
Wind Criteria to Relieve Wake Vortex Effects on Departure

Wake Vortex Characteristics of the Boeing 757

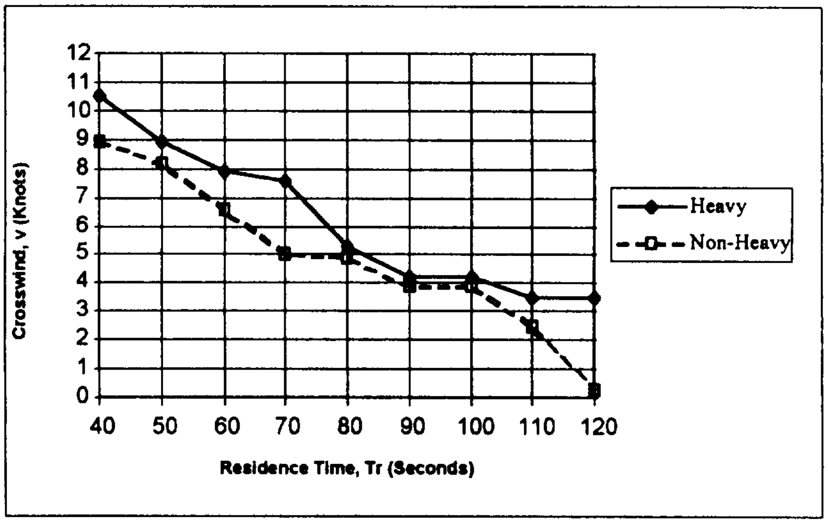
1990 Idaho Falls Wake Vortex Measurements
Vol. 1: Vortex Transport and Decay
2: Analysis Methods
3: Sensor Intercomparisons
4: Databases

Data Base of Ground-Based Anemometer Measurements of Wake Vortices at Kennedy Airport

# Wind Ellipse, Heavy Aircraft, $T_r >= 40$, $0 <= H <= 150$



## Wind Criteria to Relieve Wake Vortex Effects on Departure




**Crosswind vs. Residence Time, Heavy and Non-Heavy, Height < 150 Feet**

**DOCUMENTATION OF PAST EFFORTS (continued)**

**Analysis of Stalled Vortices**

**Requirements for Ground-Based and Airborne Vortex Systems**

**Analysis of Long Distance Motion of Vortices in Ground Effect**

**Study of Vortex Bouncing**

## DYNAMIC SPACING SYSTEMS

Administrator Goldin has set ambitious goals to:

... provide technology ... reduce aircraft accident rate by a factor of 5 with 10 years

... triple the aviation ... throughput, in all weather conditions in 10 years.

Safe, decreased wake vortex separations will be needed to reach these goals.

## DYNAMIC SPACING SYSTEMS

How assess safety of proposed changes in separation standards?

A safe separation model can be derived from an encounter hazard model and a vortex decay model*

*Burnham, D. and Hallock, J., "Wake Vortex Separation Standards: Analysis Methods", DOT/FAA/ND-97-4, May 1997

## DYNAMIC SPACING SYSTEMS

Today, we have two vortex-avoidance methodologies:

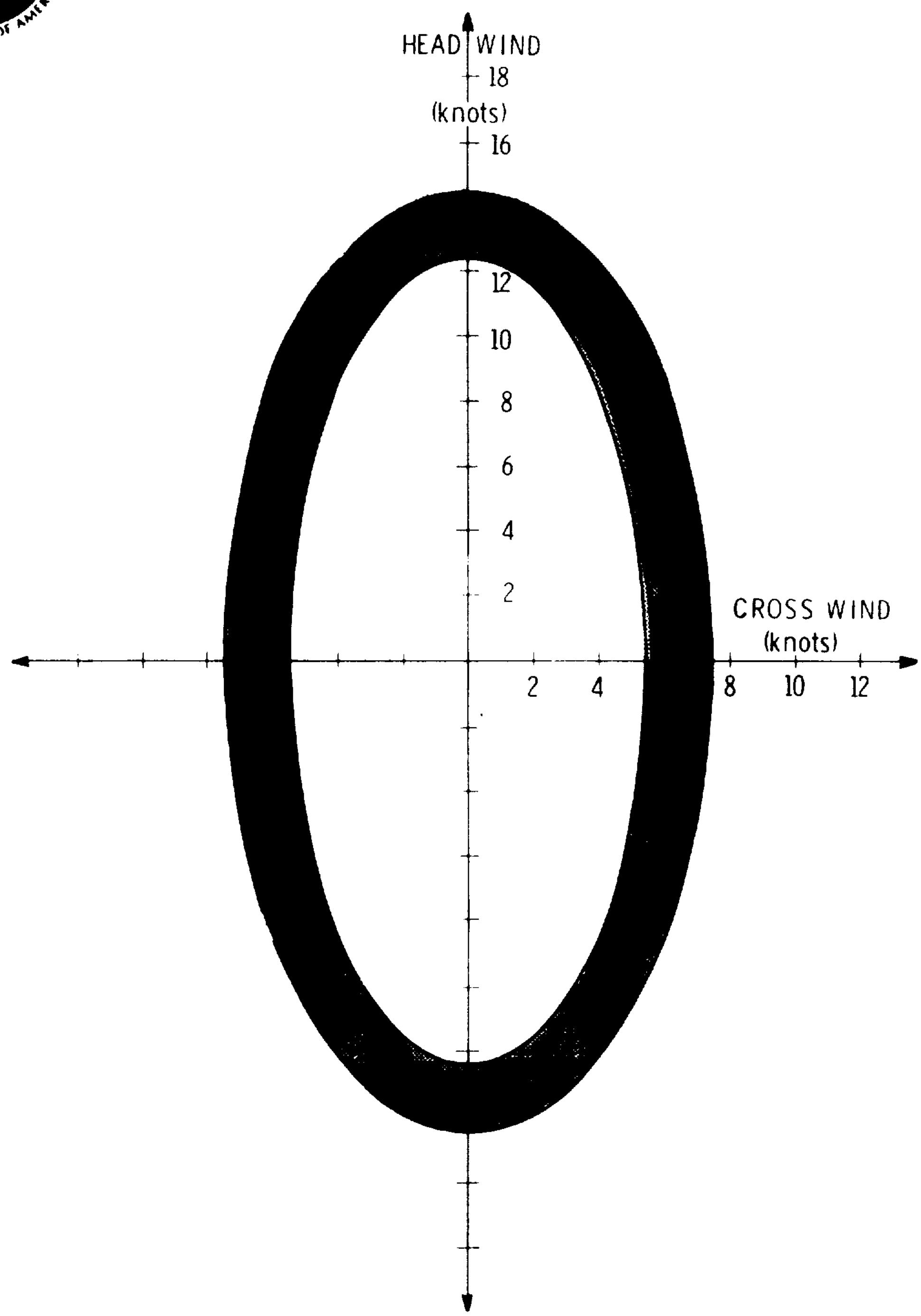
VFR operations
IFR operations

## DYNAMIC SPACING SYSTEMS

### VORTEX ADVISORY SYSTEM (VAS)

- Determines when 3nm separations may be used for all aircraft
- Based on wind measurements near the runway threshold
- Wind criterion based on 70,000 landing aircraft
- Most critical constraint - minimize number of transitions between reduced separations and normal separations

VAS ALGORITHM

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## DYNAMIC SPACING SYSTEMS

### VORTEX WARNING SYSTEM

- **Like VAS, but employs vortex sensors to verify that vortices not a problem for uniform 3 nm separations**
- **Most critical constraint - real-time vortex tracking and forecasting decisions.**

## DYNAMIC SPACING SYSTEMS

### WAKE VORTEX AVOIDANCE SYSTEM

- **Dynamic spacings depending on lead and following aircraft**
- **Needs to be integrated with ATC systems**
- **Need real-time vortex tracking and strength measurements, along with forecasting**
- **Most critical constraint - detailed hazard model**

## DYNAMIC SPACING SYSTEMS

### PARALLEL RUNWAY VORTEX ADVISORY SYSTEM

- Determines when parallel runways could be operated independently vortex wise.
- Stagger of runway thresholds critical.
- Have data on long distance vortex motion in ground effect.
- Germans have developed system for Frankfort Airport
- Most critical constraint - Forecasting crosswinds at least 10 minutes in advance

## DYNAMIC SPACING SYSTEMS

### OPERATIONAL IMPLEMENTATION REQUIREMENTS

- Coverage (TH, MM, OM, terminal area, ... )
- Missed approaches
- IFR/VFR usage

## Questions and Discussions Following James Hallock's Presentation (Volpe)

Dennis Bushnell (NASA LaRC)
What is the state of using aircraft load aleviation to reduce the hazard?

Hallock
It's an area I haven't thought about. You would have to design it for the worst case.

Lakshmi Kantha (University of Colorado)
Glad to know your are putting together a database on CD-ROM. I presume the data would be digitized, not scanned in.

Hallock
The answer is yes.

Kantha
The second question is do these impressive 70,000 measurement on wake vortex decay, transport, etc. also have adequate measurements of meteorologist conditions so one can connect the two?

Hallock
Initially, we only had wind. We had to go through a learning curve to appreciate meteorological impact. Some of the earlier measurements don't have complete data but later measurements include stratification, boundary altitude, etc. Some of the data is complete, some isn't.

Sydney Rennick (Transport Canada)
In your research of rolling moments and definition of danger area have you come up with percentage value of rolling moment capability?

Hallock
There were some tests done at NASA Dryden in the late 70's. The number that was come up with, if you can come up with the roll moment capability, is pretty good. We use half that value to be conservative. So the number is somewhere between half and full capability.

Rennick
Is anyone aware of any international standard that is being developed relative to roll moment defining value such as 50 percent or say 60 percent?

Hallock
I am not aware of it.

George Greene (NASA Langley)
Not only is there no standard but a given pair of airplanes will have different spacing in different countries.

Fred Proctor (NASA Langley)
You show significant decay, while in another plot position you show no significant decay followed by sudden demise.

Hallock - Most of what we see is that onslaught is driven by turbulence.

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14p.

# Decay of Wake Vortices of Large Aircraft

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## Introduction

A finite wing has three vortices: bound vortex, starting vortex, and the trailing vortex. It is primarily the trailing vortex/wake that can be very hazardous to following aircraft during cruise and especially during take-off and landing. This, in turn, gives rise to complex air-traffic-control and aircraft-handling problems. The safe longitudinal separation distance between consecutive aircraft is in part determined by the time interval the vortices require to decay and dissipate, or to breakup due to the onset of catastrophic instabilities (vortex linking or *burst*), or to be convected out of the flight path of the following aircraft by the combined action of their self-induced velocity and wind. These processes are strongly influenced by the meteorological conditions such as ambient turbulence, wind shear, stratification, humidity and precipitation which can considerably effect the lifetime of the trailing vortices. The elimination or the reduction of the intensity of trailing vortices has the added advantages of reducing drag and increasing the aerodynamic efficiency of the wing.

For an aircraft in landing configuration, extended flaps will result in variations in the spanwise circulation distribution, which will result in a multi-vortex wake topology. The proximity of the ground, cross winds, ground heating, etc. have profound effects on the development of this already complex problem. Suffice it to note that, vortex decay in the atmosphere in cruising conditions is significantly different from that in landing/takeoff conditions. Near the ground, the vortices strongly interact with the ground boundary layer, may acquire non-circular cross-sections, cause flow separation on the ground, give rise to oppositely-signed vorticity (with additional ground-vortex images) and rebounding (by forming a vortex dipole between the heterostrophic and homostrophic vortices).

Clearly, the determination of a safe aircraft separation is a very difficult problem and requires careful measurements in the field, meteorological data, and the reliable evaluation and interpretation of the results. The uniqueness of the problem comes not so much from the strong interaction between a man-made structure and the environment (normally, a bluff body problem), but rather from the interaction of the byproducts of this interaction with other bodies in a partially altered environment. It is also unique among the many complex and industrially challenging aerodynamics problems in the sense that the answer lies within a surprisingly small range of numbers (three to ten miles!), depending on who is following the leading aircraft.

### Methods of Hazard Reduction

Two possible avenues have been pursued to alleviate the wake vortex hazard:

(a) Avoidance: Installation of systems at terminal areas to warn aircraft of possible hazards. This is an expensive undertaking and can be implemented only at large airports where it is most desirable to increase the airport capacity by safely reducing the wake-hazard-imposed aircraft separations through intelligent instrumentation and numerical and physical experiments. Currently, an Aircraft Vortex Spacing System (AVOSS), based on the observed/predicted weather state, is being developed by NASA to determine the safe operating spacings between arriving/departing aircraft. It is in conjunction with this effort that a numerical model (TASS) is being devised. The field data (e.g., from the Idaho Falls and Memphis programs) are to be used for the validation of TASS to acquire sufficient degree of confidence in the power of prediction of the numerical model and, subsequently, in the development of parametric relationships for vortex transport and decay for a variety of aircraft (Perry et al., 1997; Proctor, 1996; Proctor et al., 1997, Vicroy et al., 1997).

(b) The modification of the trailing vortices and the overall wake of the aircraft in an effort to minimize their effects on the following aircraft and to improve the aerodynamic characteristics of the generating aircraft. In other words, if every aircraft cleaned up its own wake, there will not be a wake-hazard problem! This requires the accurate modeling of the evolution of the vortex structures with full account of the other vortex of the pair, the environmental conditions, and the ground proximity. If the vortex can be accurately modeled, then the possibility exists that the vortex may be tamed, for example, through the use of instabilities introduced into the flow or features added to the wing tips which control the size, velocities and the motion of the vortices, or features added to the landing strips. However, the work of the past few decades has proven that it is nearly impossible to modify the wake of the generating aircraft in such a manner that it becomes less hazardous to following aircraft, without affecting the performances of either aircraft. *The relationship between the vortex rollup and the spanwise distribution of circulation is highly indirect and nonlinear.* Thus, the changes in the aircraft geometry and changes in the topology of the vortex wake are not directly related. This unfortunate fact does not lead to any encouragement for wake-hazard alleviation through aircraft-design modifications. Our critical assessment of the known active and passive wake-vortex minimization devices has suggested that the numerous attempts made (e.g., the injection of additional vortices, the addition of devices to reduce or recover the swirl of the tip vortices, and changes in the geometry of the wing tips) did not result in *benign vortex wakes.*

In recent years, considerable *laboratory experiments*, and numerical simulations have been undertaken to assess the effect of the initial conditions, initial turbulence, stratification, sensitivity to shear layers (cross wind shear), ground effects, and the mutual interaction of a number of vortices. Most of these otherwise very valuable physical and numerical efforts are handicapped by several factors:

(a) Scale effects: too low Reynolds numbers, too low Mach numbers, tunnel-blockage or numerical-domain effects, inappropriate ambient turbulence in the tunnel or unreliable turbulence models in the codes.

(b) Lack of accurate data at realistic Reynolds numbers about the lifetimes of the vortex pair in a relatively clean environment, particularly at later times, after the onset of an instability or catastrophic event, such as vortex bursting or Crow instability;

(c) The lifespan of vortices was taken not to the times where the vorticity became almost uniformly distributed over a large area but rather to the times where the vortices have just undergone Crow instability and just touched and/or to the times where the vortices (one or both) have just undergone Burst. Thus, the final stages of the demise of vortices have been quantified only subjectively, through the use of a time-honored diagnostic: the flow visualization.

(d) There has been a confusion regarding "vortex breakdown" and "vortex burst". When we have first identified "burst" on a trailing vortex (Sarpkaya 1983; Sarpkaya & Daly, 1987), we have noted that it is a form of vortex breakdown, but *not* the breakdown observed in tubes. There are significant differences between the two. The bursts often remain stationary and the vortex filaments upstream and downstream of a burst remain practically unaffected. The core bursting in trailing vortices does not signal a transition from supercritical to subcritical flow. The causes and the structure of the bursts remain at best unknown. It may indeed be the manifestation of axisymmetric viscous modes of instability associated with an individual axial vortex. It often occurs in a periodic fashion while the vortex remains intact for long spatial distances which suggests that the expansion is taking place outside the viscous core. In short, the underlying mechanism of core bursting is not well understood. It is possible that one could induce them at will, accelerating the demise of the trailing vortices, if their causes were understood. However, this remains only a very remote possibility.

(e) Lack of reliable turbulence models, particularly for swirling flows. This point does not need further elaboration since the greatest road-block to CFD is agreed to be turbulence. Nevertheless, the idea is to solve the problem in spite of the lack of understanding of the physics of turbulence.

(f) Flight tests have usually been limited in both quantity and quality of information that can be extracted from them because of the difficulty in specifying the atmospheric conditions. In recent years, however, Lidar measurements, coupled with the simultaneous recording of the environmental conditions, provided the most reliable data base so far from which one could extract accurate enough information on *velocity, circulation distribution, displacement, decay, angular momentum, kinetic energy, and life-times* of the vortices and on the effects of *wind, ground, stratification, humidity and precipitation* . It is strongly hoped that this would lead to the careful assessment, validation, and improvement of the numerical simulations. Finally, it might be possible to compare the physics of the full-scale numerical and physical data with the results of the sub-scale wind-tunnel experiments to ascertain the differences (or surprises?) in the physics of the laminar and turbulent trailing vortices.

## Present Work

The recent studies dealing with the decay characteristics of wake vortices from jet transport aircraft used averaged circulation data, based on the Lidar velocity measurements (e.g., Hallock & Burnham, 1997). It has been concluded that turbulence can cause decay of the outer regions of the vortex; the overlapping regions of the vortex pair may enhance the decay; the countersign vorticity resulting from the Rayleigh instability (the change of sign of the circulation growth at some radial distance) may effectively annihilate the outer vorticity; the classical interpretation of vortex decay (viscous core diffusion with constant circulation) is inconsistent with the high Reynolds number turbulent vortex data; in the case of full-sized jet-transport aircraft, the vortex core often remains stable while the outer portion decays; the decay starts at the outer edges of the vortex due to counter-sign vorticity (resulting from buoyancy, wind shear, and ground boundary layer, generation of oppositely-signed vorticity, and vortex rebounding) and moves into smaller vortex radii; and that the outer vorticity may be both diffused and annihilated.

Even though, the explanations advanced came closer to the understanding of the physics of the underlying mechanisms, they fell short of providing a clear enough picture which could be used for numerical simulations (e.g., LES) and code validation. It is this objective that forms the essence of the present paper.

Representative data obtained in Memphis Field Program have been analyzed in as much detail as possible, without resorting to averaging. Each velocity profile (obtained at frequent intervals during a time period of about four minutes each) has been corrected for wind, shear, the proximity effects due to other vortex, and gently smoothened using a five-point smoothing scheme (sample plots are shown in Figs. 1-2). Then the circulation $\Gamma(r)$ was calculated at each radius (sample plots are shown in Figs. 3-4). In addition the evolution of turbulent vortices in a turbulent environment (a high-speed water tunnel) was investigated in detail for the sole purpose of understanding the mechanisms leading to the decay of vorticity at the peripheral region of the turbulent vortex (see Fig. 5).

The results have shown that (a) the vortex core is not a benign solid body rotation; (b) the core radius does not remain constant (a small increase in core radius leads to a sizable spread of vorticity because of high velocities near the core), (c) vorticity is present at all radii and the vorticity flux from small to large radius is an ongoing process at all times, (d) the vorticity transport by turbulence in all regions outside the vortex first leads to a circulation increase and then to a circulation decrease, (e) the outer region of the vortex is subjected to centrifugal/helical instability which leads to numerous tentacle-like vortex sheets of finite length, thrown away from the outer edges of the vortex core (resembling a spiral galaxy). The vortex peels off randomly and sheds vorticity along its length. This process may be enhanced by atmospheric turbulence surrounding the vortex, by the interaction of oppositely-signed vorticity in overlapping regions of the vortex pair, buoyancy effects, wind shear, and ground effects. However, the basic process remains effective even when some of these additional enhancement factors are absent. Figures 6-10 show representative plots of the evolution of circulation as a function of time at various radii. The fundamental differences between the decay of laminar and turbulent vortices are that (a) for a laminar vortex, diffusion is viscous and slow and, in the absence of turbulence, there is no decay-enhancing factors at the outer edges of the vortex; (b) for a turbulent vortex, the diffusion (near the edge and beyond the nearly-laminar core) is much larger, there is practically no region of the vortex which may be called potential (i.e., there is a continuous vorticity flux), and most importantly, a turbulent vortex sheds vorticity at its outer edges due to helical instability. A numerical model must strive to predict these observations and measurements. Furthermore, any attempt to enhance the decay of vortices must strive to intensify the turbulence near the core and the helical instabilities at the edge of the vortex. These may not lead to Crow instability, but may help to reduce the separation distance between leading and following aircraft.

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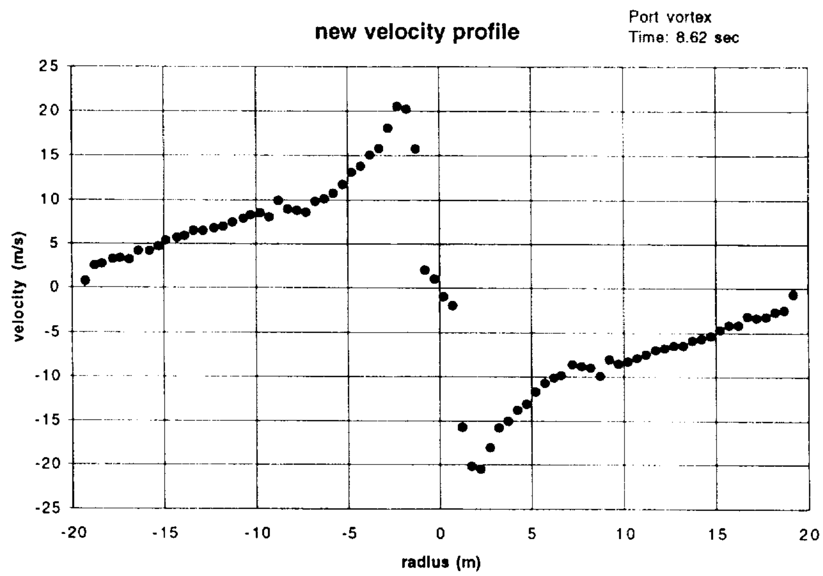


Fig. 1 Corrected velocity profile for t = 8.62 s.

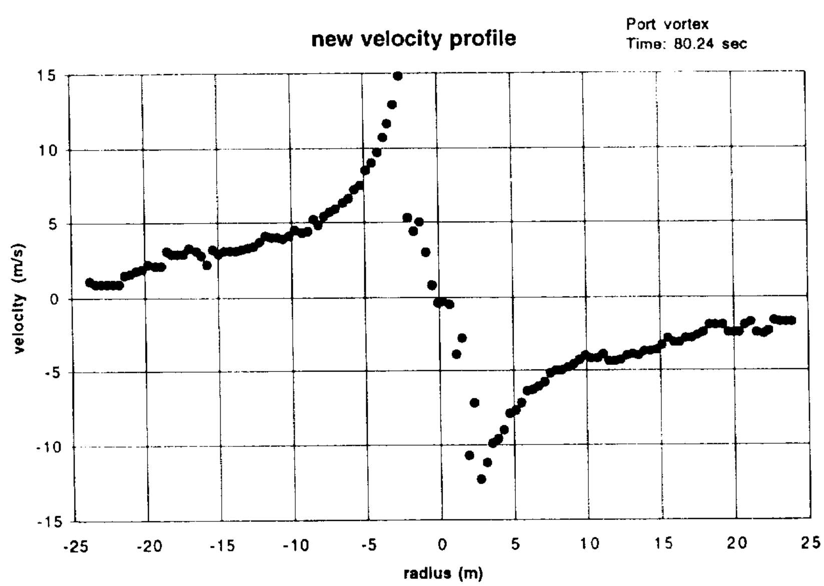


Fig. 2 Corrected velocity profile for t = 80.24 s.

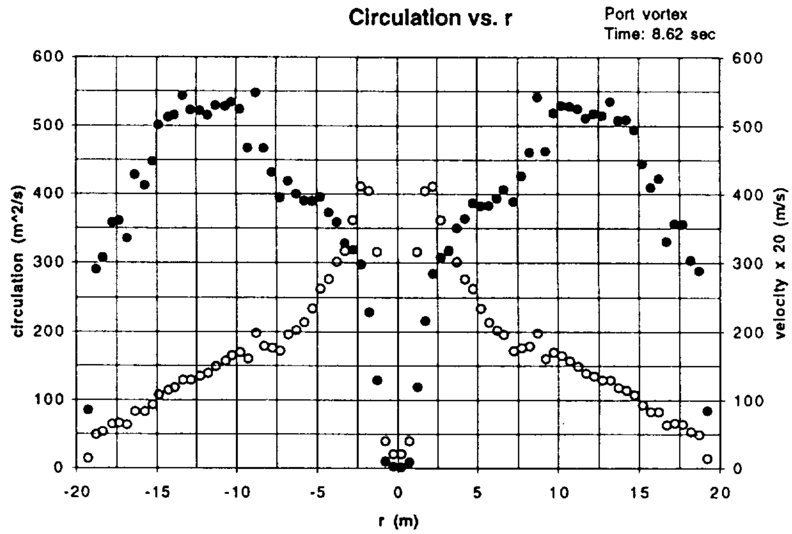


Fig. 3 Velocity and Circulation profile for t = 8.62.

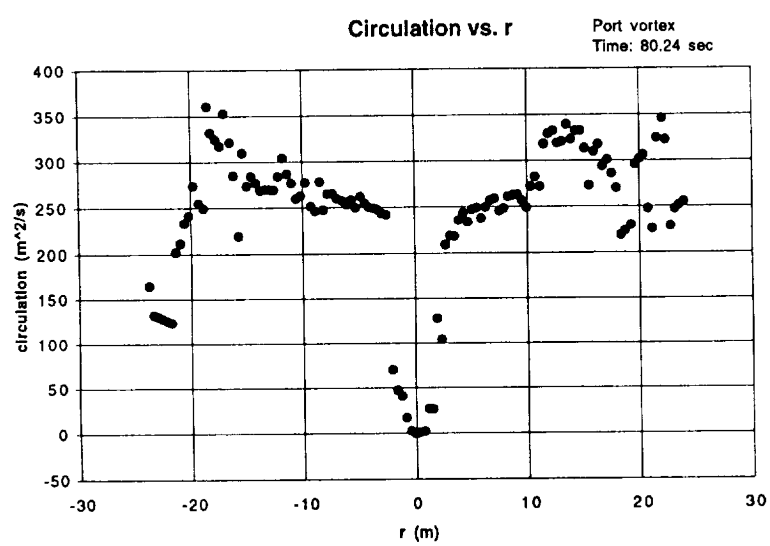


Fig. 4 Circulation profile for t = 80.24.

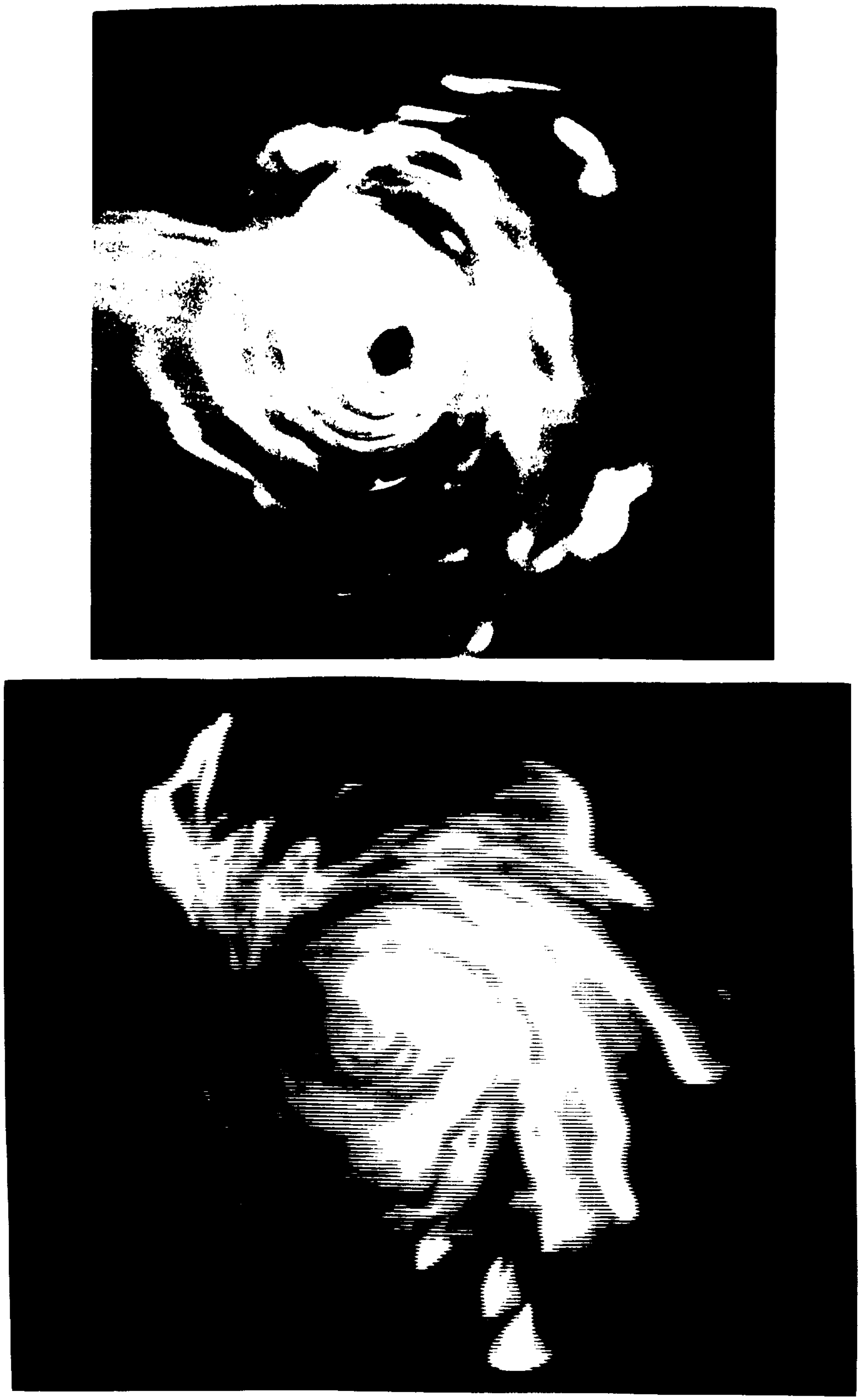

Fig. 5    Shedding of vorticity from the outer edges of a turbulent vortex.

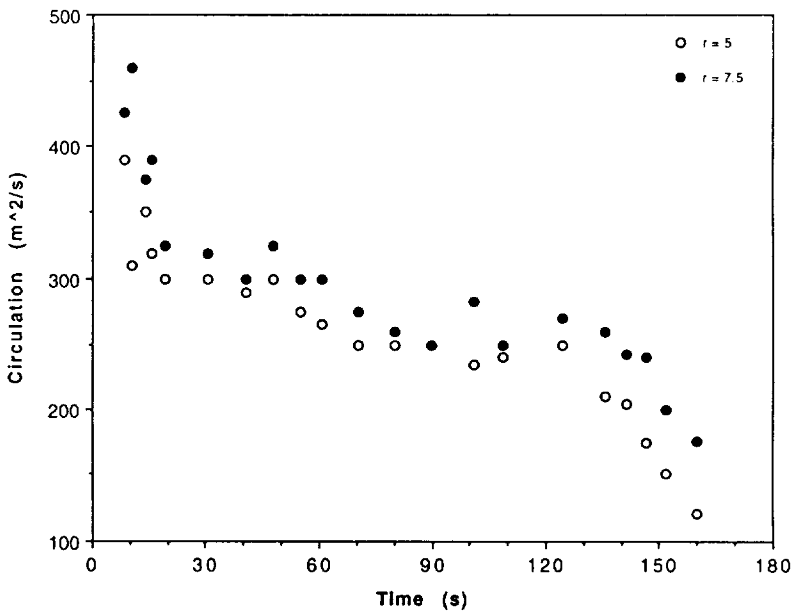


Fig. 6 Circulation versus time for r = 5 m and r = 7.5 m.

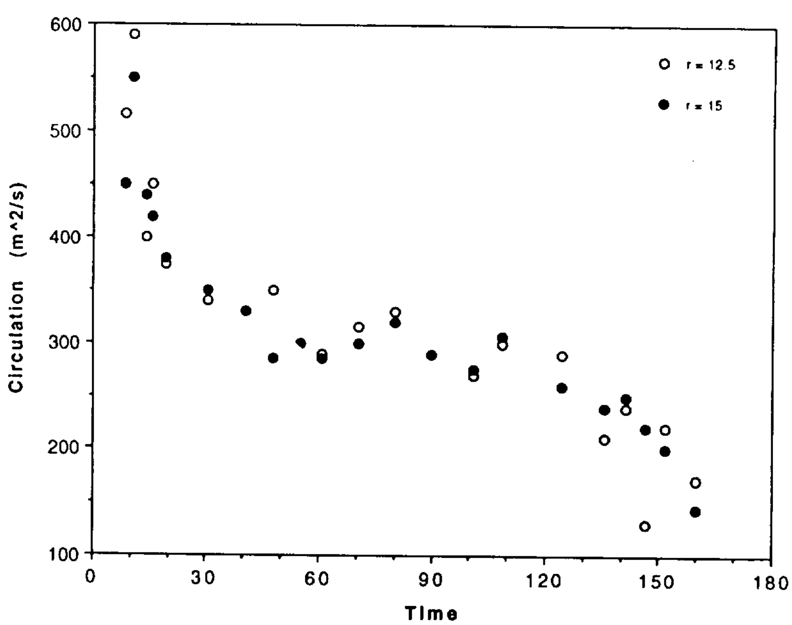


Fig. 7 Circulation versus time for r = 12.5 m and r = 15 m.

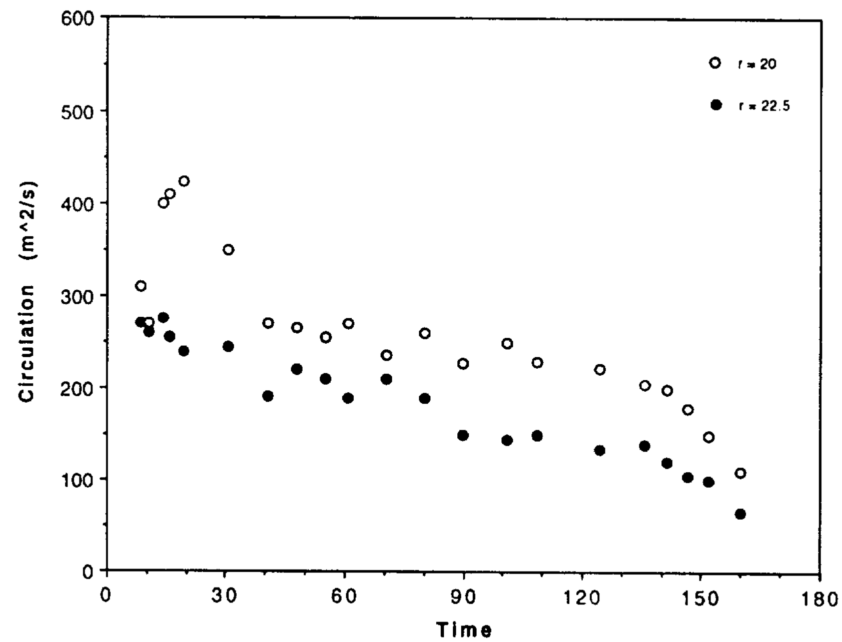


Fig. 8 Circulation versus time for r = 20 m and r = 22.5 m.

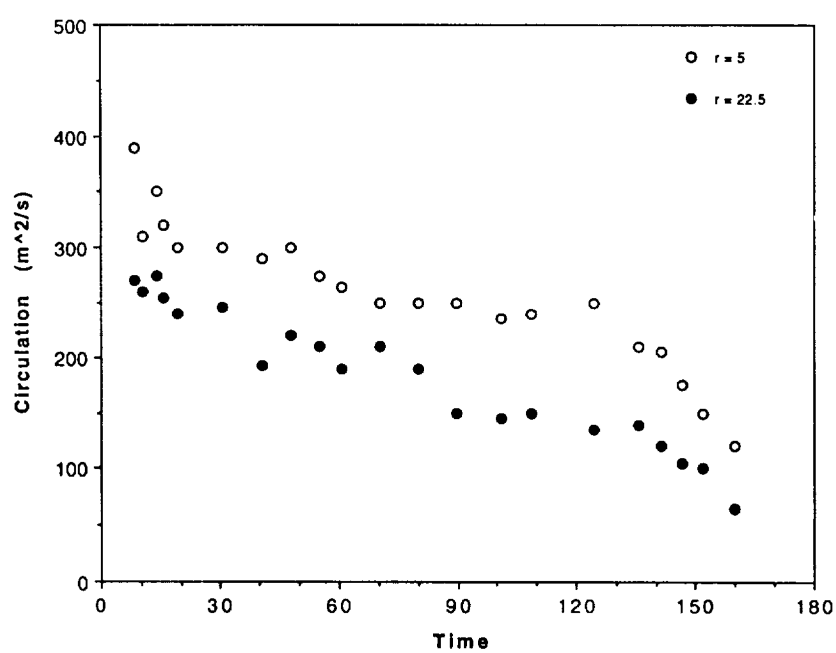


Fig. 9 Circulation versus time for r = 5 m and r = 22.5 m.

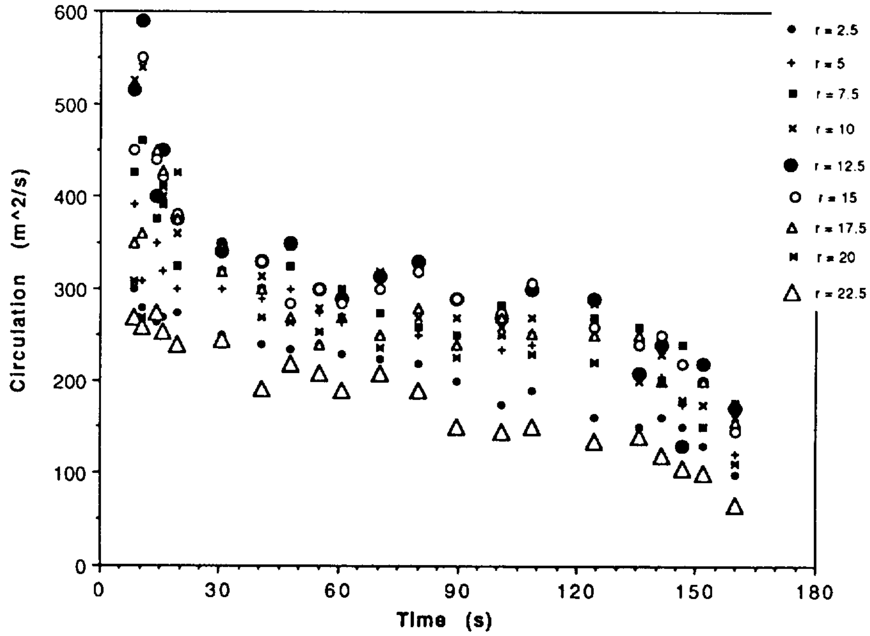


Fig. 10 Circulation versus time for various radii from r = 2.5 m to r = 22.5 m.

**Questions and Discussions Following Turgut Sarpkaya's Presentation (Naval Postgraduate School)**

Alexander Praskovsky (NCAR)
Thank you very much for a nice presentation. My question is, what do you call turbulence? Because when you say atmospheric turbulence can affect vortex, if scale is fine, it would be one effect, if scale is large it would be another effect. So how would you characterize atmoshperic turbulence?

Sarpkaya
I think chaos exists at some time because it involves men, computers, and nature playing a joint game of dice behind man's back when we try to reduce separation distance. In my slide, turbulence is characterized by a parameter called $\eta$. It like

$$\eta = \frac{2\pi(\varepsilon)^{\frac{1}{3}}(b_0)^{\frac{4}{3}}}{\Gamma}$$

(editors note - see AIAA 87-0042)

However in the studies shown on tape, characterized turbulence by two quantities. One the intensity of turbulence is $\frac{\left[\overline{(U')^2}\right]^{\frac{1}{2}}}{U_{rms}}$ plus the integral length scale of turbulence. The integral length scale in our experiments varied from 0.1 time the core radius to entire core radius. Then turbulence intensity varied from about 0.1 percent to as much as 10 percent. This is how we quantify turbulence.

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# The LaRC Wake Vortex Modelling Effort

318611


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18P.

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***HAMPTON, VA***



***NASA First Wake Vortex Dynamic Spacing Workshop***
***LaRC, Hampton, VA***
***May 13, 1997***



## Abstract

*The purpose of the modelling effort at NASA Langley, including goals, is outlined in this presentation. Included, is a description of the numerical model that is used for the NASA wake vortex modeling effort and the approach that is taken in order to achieve the stated goals. Also shown are: 1) a demonstration of using the model in a fog environment; 2) preliminary results from a 3-D simulation in a nonturbulent and thermally-stable environment with comparison to a comparable 2-D simulation of the same event; and 3) several validation cases from the Idaho-Falls and Memphis field studies where results from the 2-D version of the model are compared with Lidar and tower data.*

## Presentation Outline

I. Purpose of Numerical Modelling

II. Description Of Model

III. Modelling Approach

IV. 2-D Validation Cases

V. Summary

## AVOSS SPACING CRITERIA DEPENDENT ON:

1.) Vortex Lateral Transport — e.g., Strong Crosswinds Will Quickly Transport Wake out of AVOSS Corridor

2.) Vortex Pair Descent Rate — affected by Stratification, Vertical Gradient of Crosswind Shear, Turbulence, Vortex Decay Rate, etc.

3.) Vortex Decay — Affected by Turbulence (both ambient and internal), Ground Interaction, Stratification, Dynamic Instabilities.

# NASA WAKE VORTEX MODELLING

## PURPOSE

1.) To Use Validated Numerical Models For Contributing to Development of Parametric Model for AVOSS. To Derive Relationships Between Vortex Behavior and Atmospheric Conditions (NASA-LaRC, NCSU, Univ. South Alabama)

2.) To Develop A Short-Term Weather Forecast System For Predicting AVOSS Needed Parameters in Terminal Area (NCSU)

## Terminal Area Simulation System (TASS)

* Micro-scale/Meso-gamma Scale Atmospheric Model
* Large Eddy Simulation Capability
* Adapted for Use in Wake Vortex Program

# Wake Vortex Modelling Goals

* Evaluate TASS Model Utility for Investigating Wake Vortex Transport and Decay
* Evaluate Utility of 2-D vs 3-D Numerical Simulations
* Validate Model for Wake Vortex Transport and Decay
* Parametric Study of Wake Vortex Transport vs Meteorology with 2-D TASS
* Parametric Study of Wake Vortex Decay vs Meteorology with 3-D TASS
* Provide TASS Generated Data Sets for Sensor Trade-Off Studies

## TERMINAL AREA SIMULATION SYSTEM (TASS)

- 3-D LARGE EDDY SIMULATION (LES) MODEL (WITH 2-D OPTION)
- METEOROLOGICAL FRAMEWORK
- PROGNOSTIC EQUATIONS FOR:

| | |
|---|---|
| 3-COMPONENTS OF VELOCITY | PRESSURE |
| POTENTIAL TEMPERATURE | RAIN |
| WATER VAPOR | SNOW |
| LIQUID CLOUD DROPLETS | HAIL/GRAUPEL |
| CLOUD ICE CRYSTALS | DUST/INSECTS/TRACERS |

- 1st-ORDER SUBGRID TURBULENCE CLOSURE WITH RICHARDSON NUMBER DEPENDENCY
- SURFACE FRICTION LAYER BASED ON MONIN-OBUKHOV SIMILARITY THEORY
- CLOUD MICROPHYSICS

## TERMINAL AREA SIMULATION SYSTEM (TASS)

- Three-Dimensional, Time-Dependent, Nonhydrostatic, Time-Split Compressible Model (may be collapsed to 2-D)
- Primitive Equation / Non-Boussinesq Equation Set
- Lateral Boundaries -- Either Periodic or Open -- Open Condition Utilizes Mass-Conservative, Nonreflective Radiation Boundary Scheme
- Option for Nonstationary Domain -- Movable, Storm/Vortex Centering Mesh
- Explicit Numerical Schemes, Quadratic Conservative, Time-split Compressible
  *-- accurate and highly efficient, almost no numerical diffusion*
- Arakawa C-Grid Staggered Mesh, Vertical Coordinate Stretching Allowed

## TERMINAL AREA SIMULATION SYSTEM (continued)

- Ambient Conditions Initialized with Vertical Profile of Pressure, Temperature, Dew Point, and Wind Velocity
- Options for Surface Heat Flux Based on Latitude and Time of Day — Used for Simulating Diurnal Evolution of Atmospheric Boundary Layer
- Initialization Systems for Injection of Aircraft Wake Vortices (Does not model roll-up)
- TASS Model Applied and Validated Against a Wide Range of Atmospheric Phenomena -- History of FAA Acceptance, used in Windshear Certification

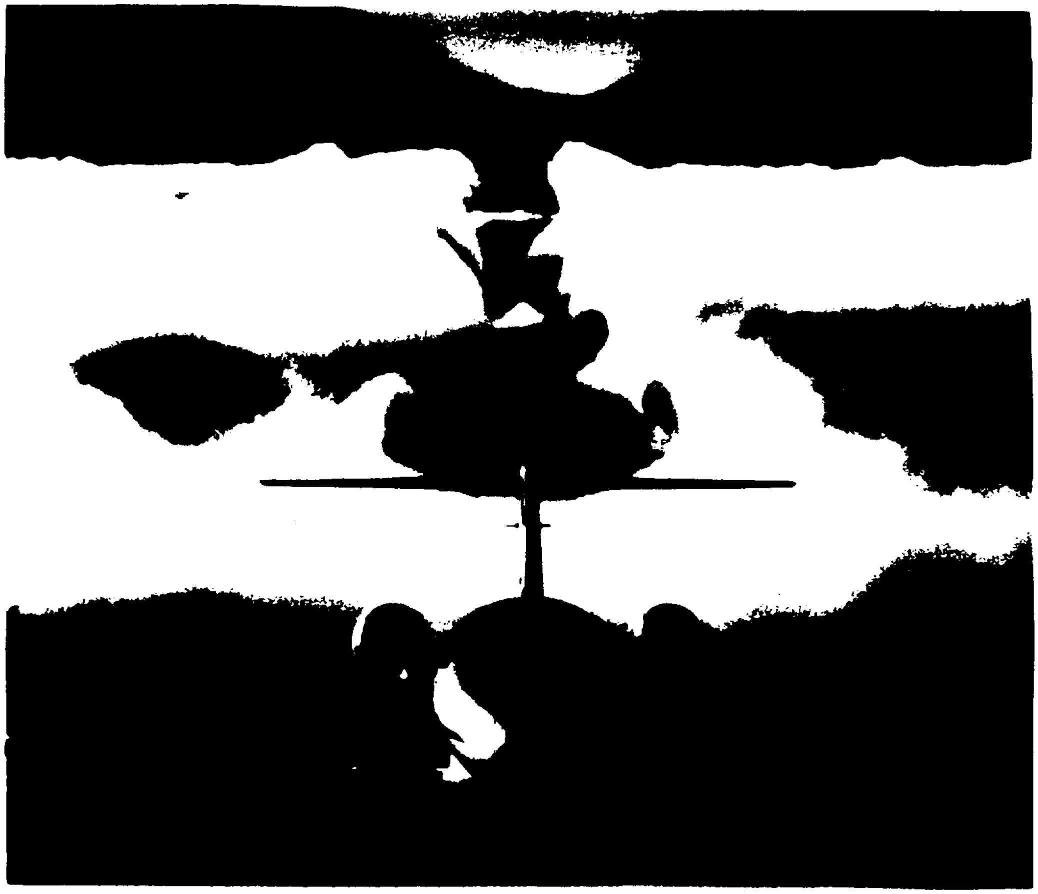
# TASS Numerics

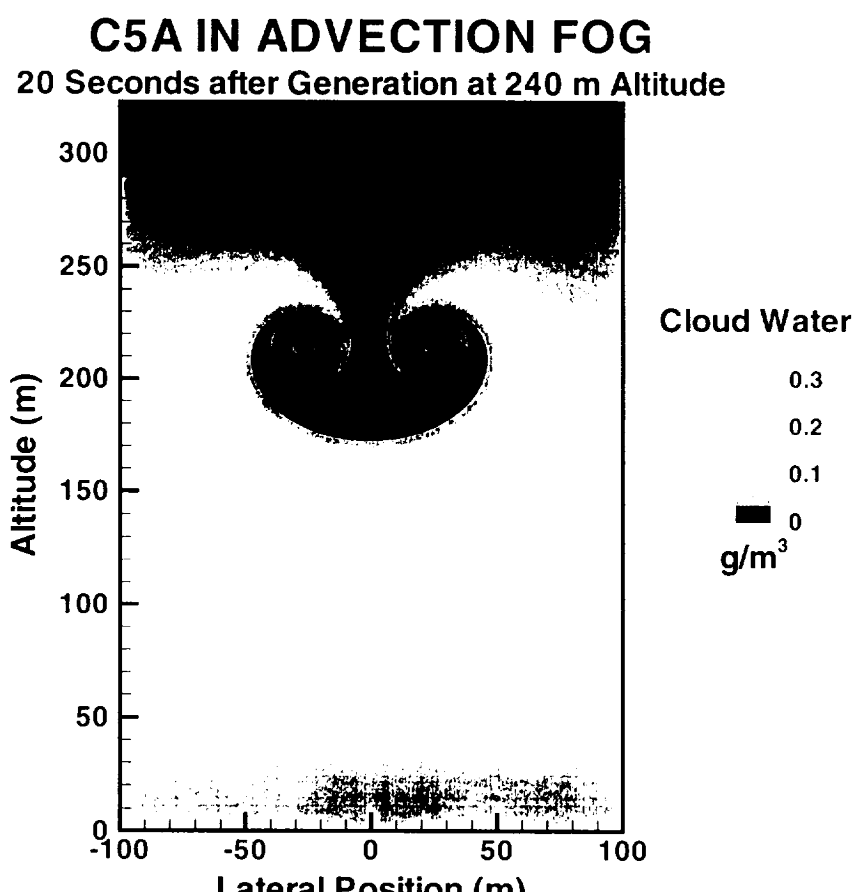
| Prognostic Variable | Time Derivatives | Space Derivatives |
| --- | --- | --- |
| Momentum and Pressure | Time-split with small time step for acoustic terms<br><br>2nd-order Adams-Bashforth: both large and small time steps | Centered, Quadratic-Conservative Differences -- with 4th Order Accuracy for Convective terms, remaining terms 2nd Order Accuracy |
| Potential Temperature, Water Substance, etc. | Third-Order time/space with Upstream-Biased Quadratic Interpolation | |

# TASS -- HISTORY

* **Development Began in 1983 For NASA/FAA Windshear Program:**
  - **Cumulonimbus Convection**
  - **Tornadic Storms & Supercell Hailstorms**
  - **Microbursts & Microburst Producing Storms**
  - **Reconstruction of Microburst Windshear Encounters**
  - **Windshear Data Sets Generated for:**
    1) **flight simulation**
    2) **sensor development and certification**

* **Over Past 4 Years, TASS Extended To:**
  - **Atmospheric Boundary Layer Studies**
  - **Wake Vortex Studies**




C5A IN ADVECTION FOG
20 Seconds after Generation at 240 m Altitude
Altitude (m)
300
250
200
150
100
50
0
-100
-50
0
50
100
Lateral Position (m)
Cloud Water
0.3
0.2
0.1
0
g/m3

# APPROACH — WAKE VORTEX SIMULATION

DNS (Direct Navier Stokes) — Sometimes Useful for Understanding Flow Dynamics, but not Practical for Atmospheric Simulations due to Reynolds Number Limitations

* Large Eddy Simulations — Allows Computation of all Resolved Scales with affect of Turbulence from Unresolved Scales Parameterized. Success Depends on Accuracy of Closure Model

* Domain Configuration: 2D vs 3D-Perodic vs 3D-Open

## APPROACH — WAKE VORTEX SIMULATION

### 2-D

Advantages/Capabilities:

* Excellent for Examining Wake Vortex Transport Vs Meteorology & Aircraft Type
* Capable of Simulating Important Interactions with Ground
* Can be Simulated at High Resolution with Minimal use Computer Time

Disadvantages:

* The Rate of Vortex Decay Upper Bounded — Thus Underestimated
* Does not Permit 3-D Coupling between Axial and Tangential Flow
* Does not Permit 3-D Instabilites such as Crow Instability
* Resolved-scale Turbulence is 2-D with Energy Cascading Upscale.

## APPROACH — WAKE VORTEX SIMULATION

## 3-D Perodic Wake Vortex

Advantages/Capabilities:
* Relatively Easy To Implement.
* Allows Vortex Interaction With Three-Dimensional Turbulence
* Permits Three-Dimensional Simulations Such As Crow Instability
* Requires Periodic (Cyclic) Lateral Boundary Conditions

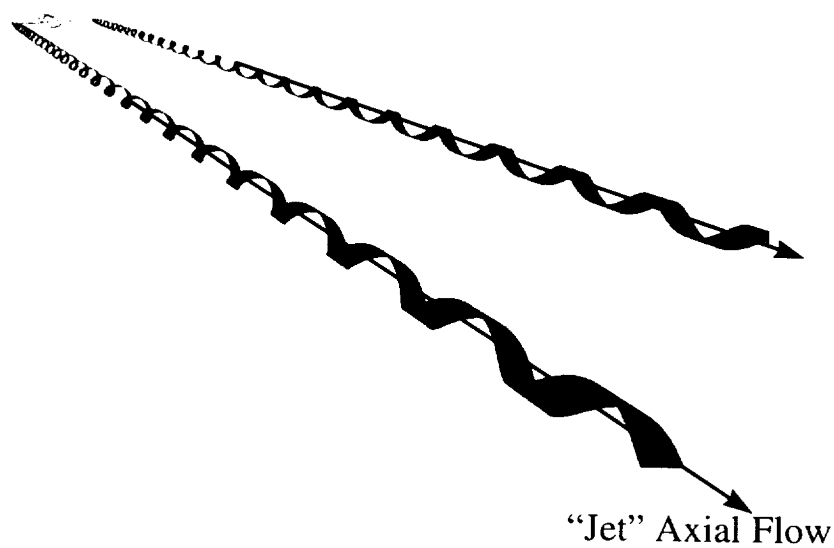
Disadvantages:
* Much more Expensive to Run than 2-D
* Prior to Linking, Vortex Pair has infinite Length.
* Vortex Ages (decays) at Roughly the Same Rate ( Real Trailing Vortex Ages (Decays) as Distance Downstream From Generating Aircraft)
* For Reasons Above, Does not permit 3-D Coupling (via Axial Flow) Between Older and Newer Sections of Trailing Vortex

## APPROACH — WAKE VORTEX SIMULATION

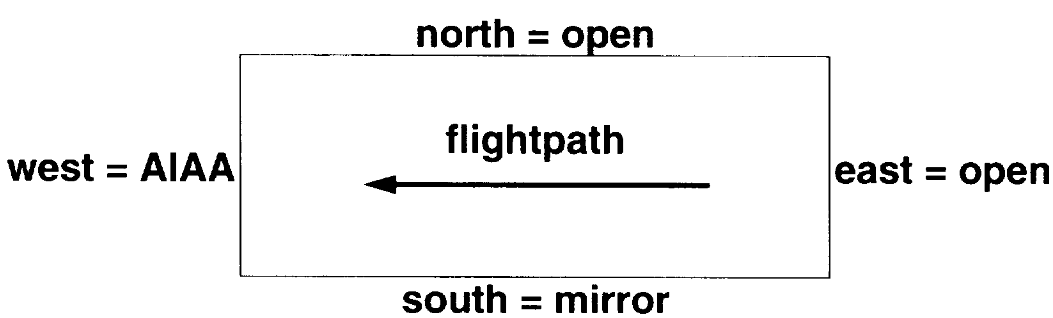
## 3-D Wake Vortex

Advantages/Capabilities:
* Most Realistic Approach
* Allows Transport of Vorticity Via Axial Flow Between Newer and Older Sections of Vortex
* Permits 3-D Coupling Between Older and Newer Sections of Trailing Vortex
* Allows Vortex Interaction With Three-Dimensional Turbulence
* Permits Three-Dimensional Simulations Such As Crow Instability

Disadvantages:
* More Difficult to Implement
* Requires Large Computer Resources — Pushes Current Supercomputer Capabilities
* Requires Open Boundary Condition on Downstream End

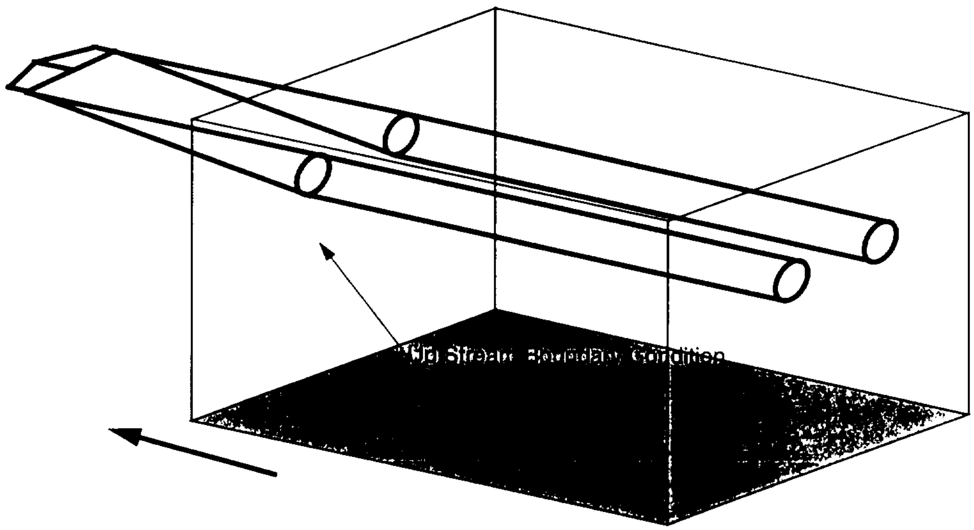



## INITIAL / BOUNDARY CONDITIONS



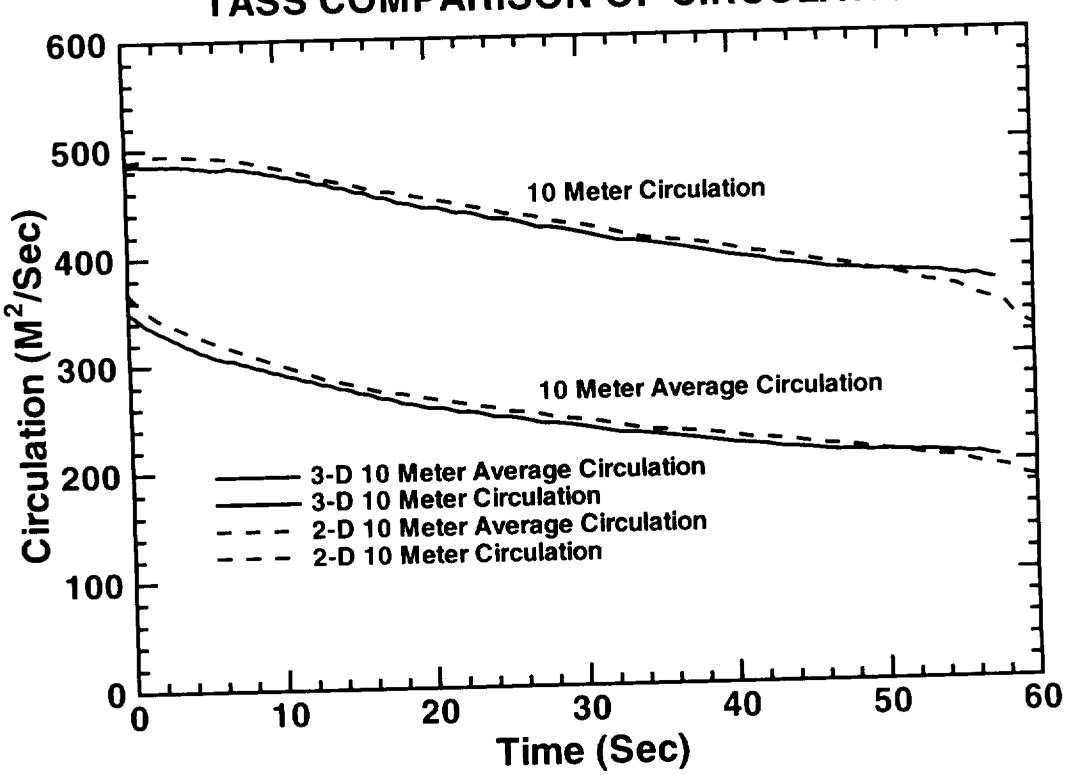

- Upstream boundary (west) fixed to AIAA vortex profile
- No axial flow allowed thru upstream boundary
- Vortex profile assumed on boundary extends thru domain along direction of travel
- Initial profile is independent of variation along the flight-path
- Domain moves at speed of aircraft

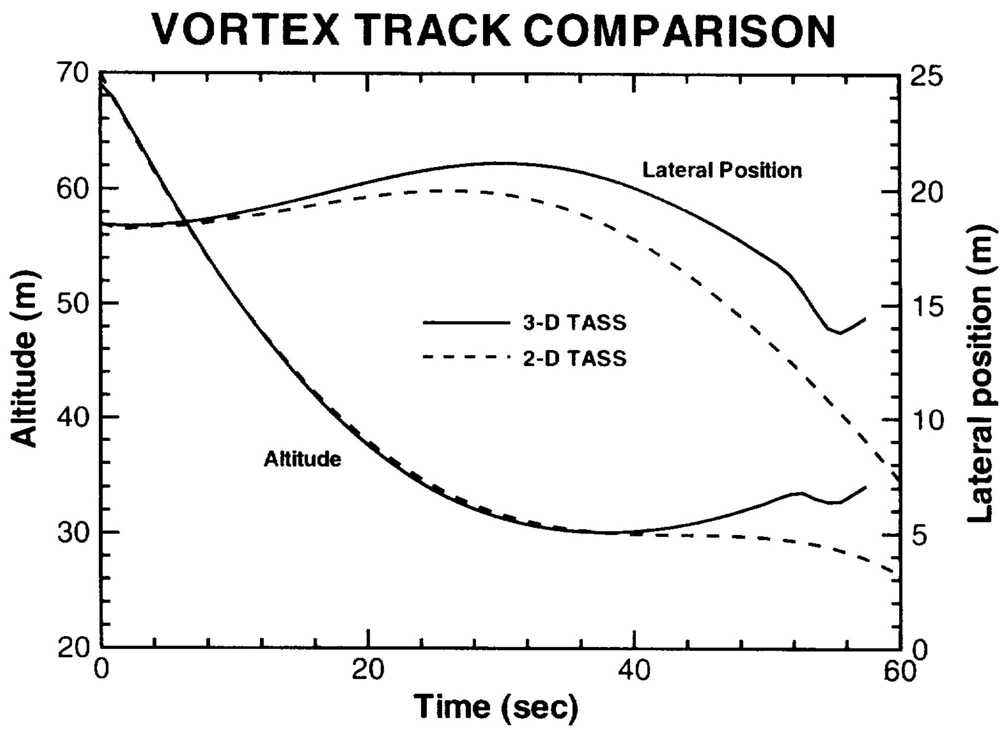
<u>PERSPECTIVE VIEW OF INITIAL DOMAIN</u>

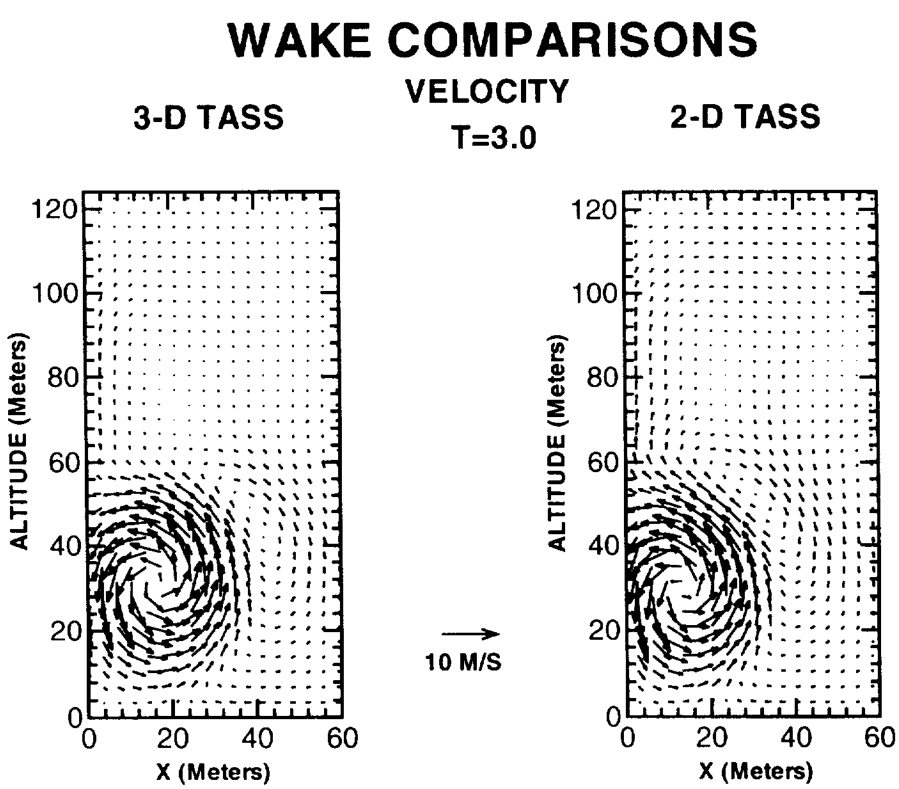


Domain Moves at the Speed of the Generating Aircraft

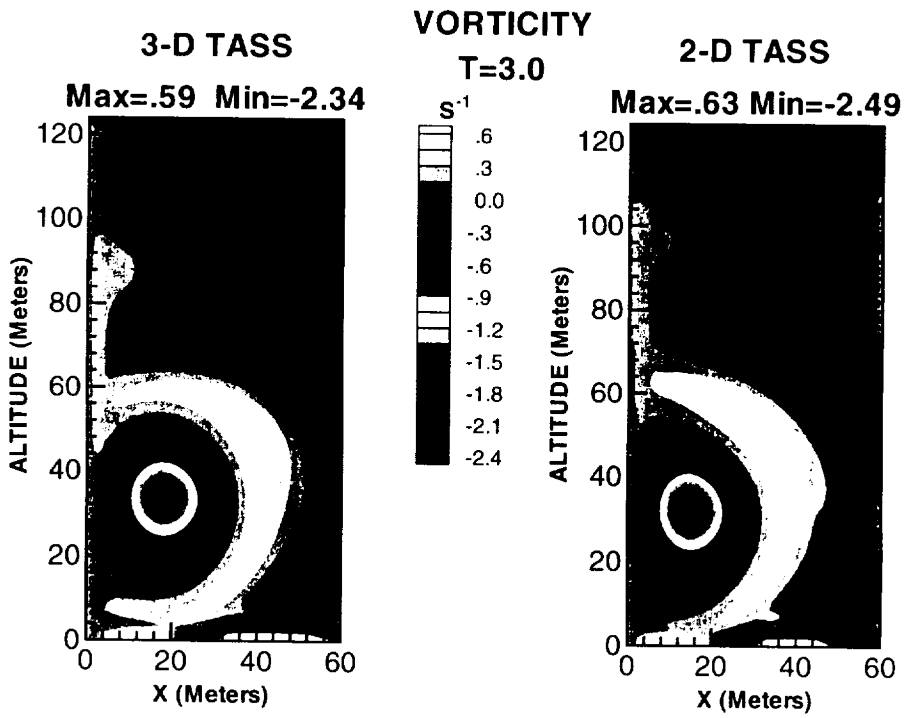
TASS COMPARISON OF CIRCULATION




VORTEX TRACK COMPARISON
Lateral Position
3-D TASS
2-D TASS
Altitude
Altitude (m)
Lateral position (m)
Time (sec)


WAKE COMPARISONS
VELOCITY
T=3.0
3-D TASS
2-D TASS
10 M/S
ALTITUDE (Meters)
X (Meters)

# WAKE COMPARISONS




# TASS 2-D VALIDATION CASES

---

### *INPUT DATA / ASSUMPTIONS*

PHYSICAL DOMAIN SIZE
- O HORIZONTAL (X): 150-300 meters
- O VERTICAL (Z): 100-250 meters

COMPUTATIONAL RESOLUTION
- O HORIZONTAL and VERTICAL 3/4 - 1 meter

INITIAL VORTEX SYSTEM -- Post Roll-Up Vortex Pair

Velocity field for each vortex according to Burnham-Hallock model with:

Initial height -- from observed height of generating aircraft

Vortex core radius -- assumes 5% of generating aircraft's span

Initial circulation and separation -- based on weight, span, and airspeed of generating aircraft (assuming elliptically loaded wing)

Ignores Flight Configuration

AMBIENT CONDITIONS
- O Vertical Profiles of Wind and Temperature from Meteorological Tower, and other atmospheric sensors -- near time of event
- O Not Initialized with Preexisting Ambient Turbulence

**Table 2. Idaho Falls Validation Cases.**

| IDF Run # & date | Aircraft & Configuration | Meteorological Conditions | Initial Vortex Parameters | | Environmental Parameters | | |
|---|---|---|---|---|---|---|---|
| | | | $\Gamma_{\infty}$ ($m^2$/s) | Generation Height (m) | $\Delta\theta/\Delta z$ (°C per 100 m) | *Crosswind Shear* ($10^{-2}$ $s^{-1}$) | Crosswind at $Z_i$ (m/s) |
| **# 9 9/25** | **757-200 landing** | **stable moderate shear** | 365 | 70 | 3 | 4.5 | 5.8 |
| **# 23 9/30** | **767-200 takeoff** | **stable low shear** | 370 | 76 | 5 | 1.0 | 1.7 |
| **# 31 9/30** | **767-200 landing** | **unstable low shear** | 375 | 70 | -0.2 | 0.02 | 2.0 |

**TASS vs IDF CASE-9 DATA -- B757-200, 25 Sep 1990, 0818 MDT**

(Stable with Moderate Shear)

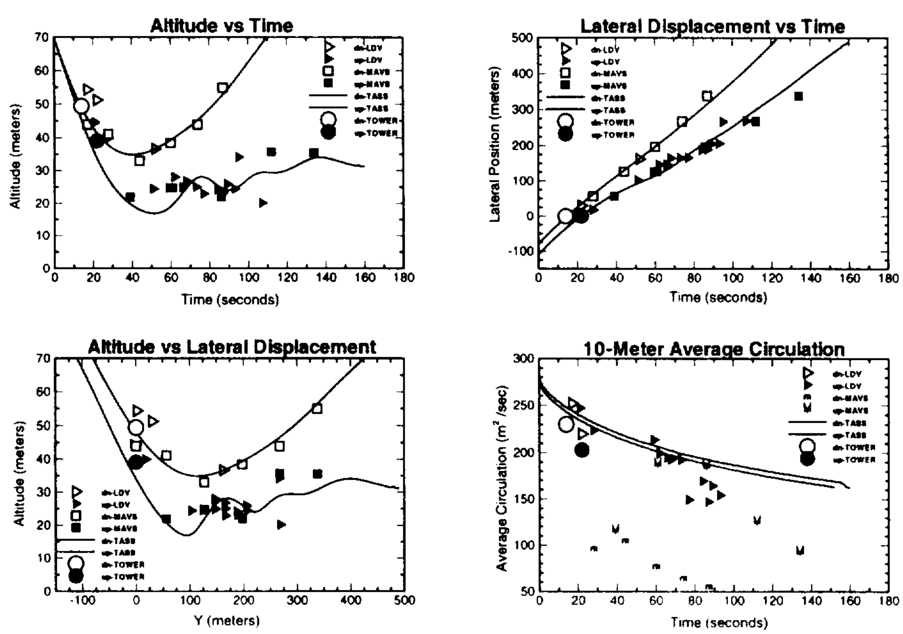
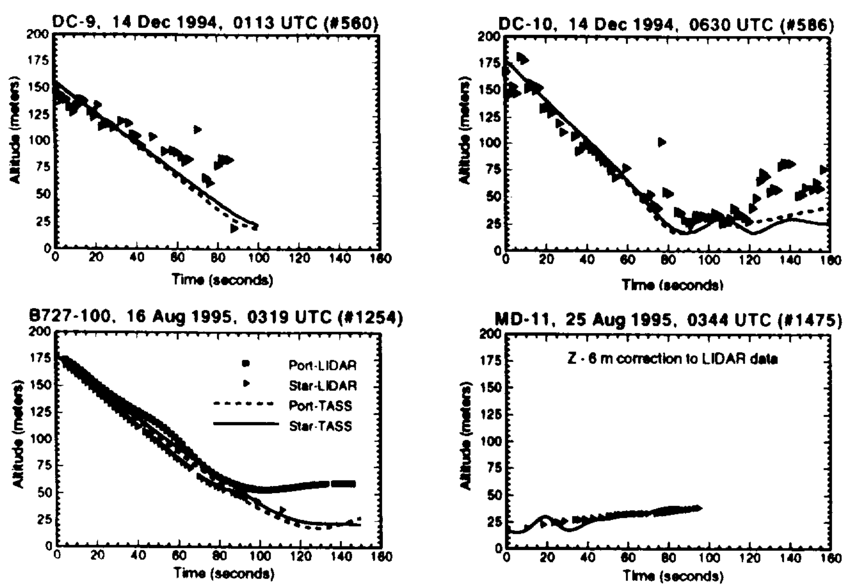


**Table 3. Memphis Validation Cases**

| MEM Run # & Aircraft Type | Date & Time (UTC) | Meteorological Conditions | Generation Height (m) | Crosswind | |
|---|---|---|---|---|---|
| | | | | Crosswind Shear ($10^{-2}$ $s^{-1}$) | $U$ at Generation Height (m/s) |
| # 560 DC-9 | 12/14/94 0113 | unstable weak shear | 156 | ~0 | 1.9 |
| # 586 DC-10 | 12/14/94 0630 | stable low shear | 178 | 1.6 | 4.4 |
| # 1254 B-727 | 8/16/95 0319 | stable weak crosswind | 178 | 0.6 | 0.5 |
| # 1475 MD-11 | 8/25/95 0344 | stable weak shear | 17.5 | 2 | 1.2 |

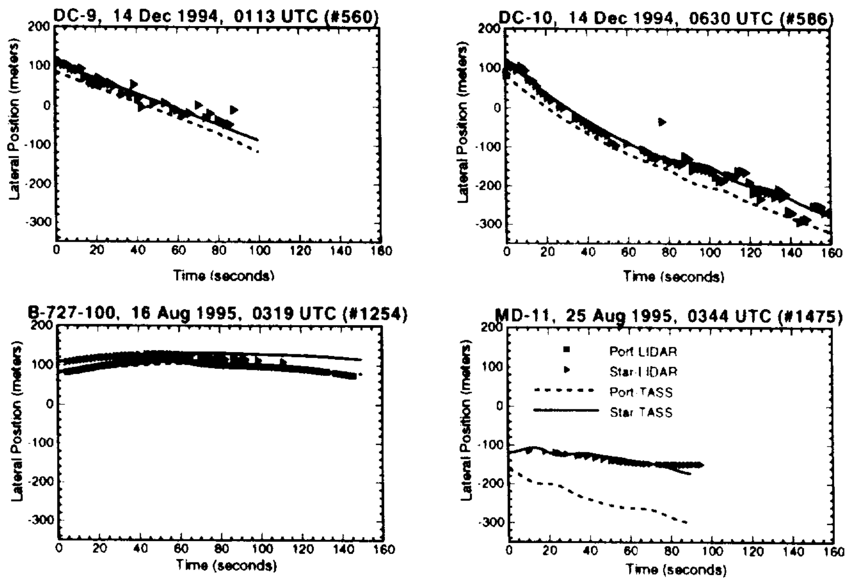
**TASS vs MEMPHIS LIDAR MEASUREMENTS**

Altitude of the Vortex Track vs Time



**TASS vs MEMPHIS LIDAR MEASUREMENTS**

Lateral Position of the Vortex Track vs Time




# SUMMARY

- Atmospheric Modelling System Adapted For Wake Vortex Problem
- Both 2-D and 3-D Approaches
- Two-Dimensional Simulations Excellent Tool For Investigating Wake Vortex Transport vs Meteorology
- Comparison Between Observations and Results from 2-D Simulations Show Good Agreement
- Three-Dimensional Simulations Necessary For Investigation of Vortex Decay

**Questions and Discussions Following Fred Proctor's Presentation (NASA Langley)**

Susan Ying (McDonnell Douglas)
In the simulations, do you always have two vortices from the upstream boundary conditions? And if so, how do you address the differences between different airplanes?

Proctor
What we assume for our initial condition is that the vortex is already rolled up and we don't try to model the roll-up process. That is beyond the model's capability. As far as what parameter are used to characterize aircraft, we take wing span, weight, and air speed using equation of elliptical loading to define initial circulation and use profile of Burham & Hallock's model.

Ying
So an airplane that doesn't have elliptical loading would not be useful.

Proctor
We have run quite a few cases in 2-D; different aircraft, different environment, some are takeoff, some are landing, some are flaps up, some are flaps down, and we get good agreement. So I can say in 2-D it doesn't seem to make any difference. I can't yet say that in 3-D because in 2-D I am talking of transport. In 3-D decay might be a different issue because takeoff or landing may affect core size which may affect decay.

Neal Fine (Engineering Tech Center)
Could you comment on occurrence of spurious losses of vorticity due to artificial viscosity either implicit or explicit, as well as finite grid size and how you dealt with those problems in your models?

Proctor
It is always a concern when doing numerical modeling that we may generate numerical artificats. In our numerical approach we used explicit numerical techniques because we wanted them to be very efficient timewise and we used quadratic conservation numerical techniques which conserve not only first order movements such as mass and momentum but energy as well. We did tests using analytical solutions, say Beltrami flow, which is a series of nonlinear vortices to look at possible problems of numerical dissipation. Essentially, we saw no dissipation. There is almost no loss of kinetic energy.

Fine
If I am not mistaken, Beltrami flow neglects the primary nonlinear term in equation of motion which is cross product of vorticity and velocity. Correct me if I am wrong here.

Proctor
It is a nonlinear problem which is simplified some to get an analytical solution. We have a report on that which I can give you if you are interested.

Alexander Praskovsky (NCAR)
What resolution or grid dize do you have?

Proctor
In 2-D simulation we run on the order of about 1 meter to 3/4 meter grid sizes. In 3-D simulation I would like to run the same, but because of computer limitations we are about 1.75 meters. Domain sizes were large enough to encompass wake system and for cases where there is strong cross wind, our model allows the domain to move with vortices.

Praskovsky
How are you going to incorporate atmospheric conditions with a domain of 60 by 120 even if it is good core? Atmospheric conditions start in kilometer range.

Proctor
Our approach of compiling this with atmospheric boundary layer will be discussed this afternoon and will be done with nesting techniques.

S7-02
313090
# Two Dimensional Parametric Studies of Wake Vortex Interaction With The Atmosphere

16 p.

318612

**FRED PROCTOR**

***NASA-LANGLEY RESEARCH CENTER***
***Flight Dynamics and Control Division***
***HAMPTON, VA***

***NASA First Wake Vortex Dynamic Spacing Workshop***
***LaRC, Hampton, VA***
***May 13, 1997***

## Abstract

*Results from parametric runs using two-dimensional TASS are presented. First, a set of experiments are presented that examine the sensitivity of the aircraft initiation height for an "in ground effect" case with weak crosswind. Interaction between the ground and the wake vortex produces an oscillatory rebound whose phase and amplitude are a function of the generation height. A second set of experiments are presented which examine the influence on crosswind shear. Shear layers, such as may be found between the nocturnal stable layer and the residual layer, can act to deflect vortices upward. Further investigation reveals that the second derivative of the crosswind can differentially reduce the descent speed of each member of a vortex pair, causing tilting of the vortex pair. If sufficiently large, the second derivative of crosswind can deflect the vortex pair upwards, with the sign of the second derivative determining which of the two vortices rises to a higher altitude. Linear shear, on the other hand, caused no change in the descent speed of the vortices; thus having no effect on the orientation of the vortices. Observed and model data from an actual case are presented in support of the conclusion regarding the influence of shear on rising vortices.*

# PRESENTATION OUTLINE

I. Ground Effect Sensitivity Experiments

II. Crosswind Shear Sensitivity Experiments
   A. Shear Zone
   B. Parametric Runs based on Polynomial Profile
   C. Idaho Falls Run 9

III. Summary

## GROUND EFFECT SENSITIVITY STUDIES

**MD-11 on 25 AUG 1995, Memphis**

**Case # 1475 at 0344 UTC on Runway 27**

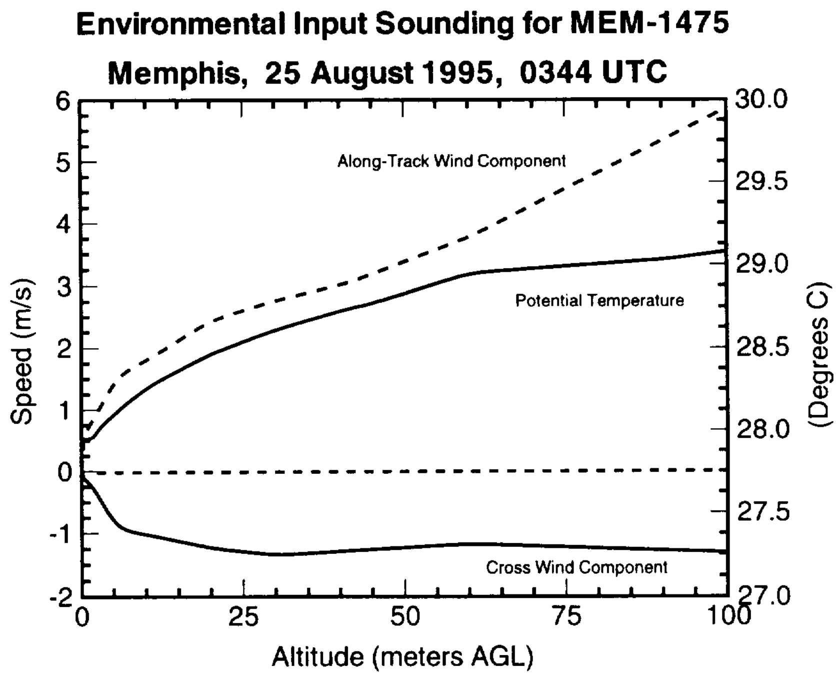
**Environment: Stable with Weak Crosswind**

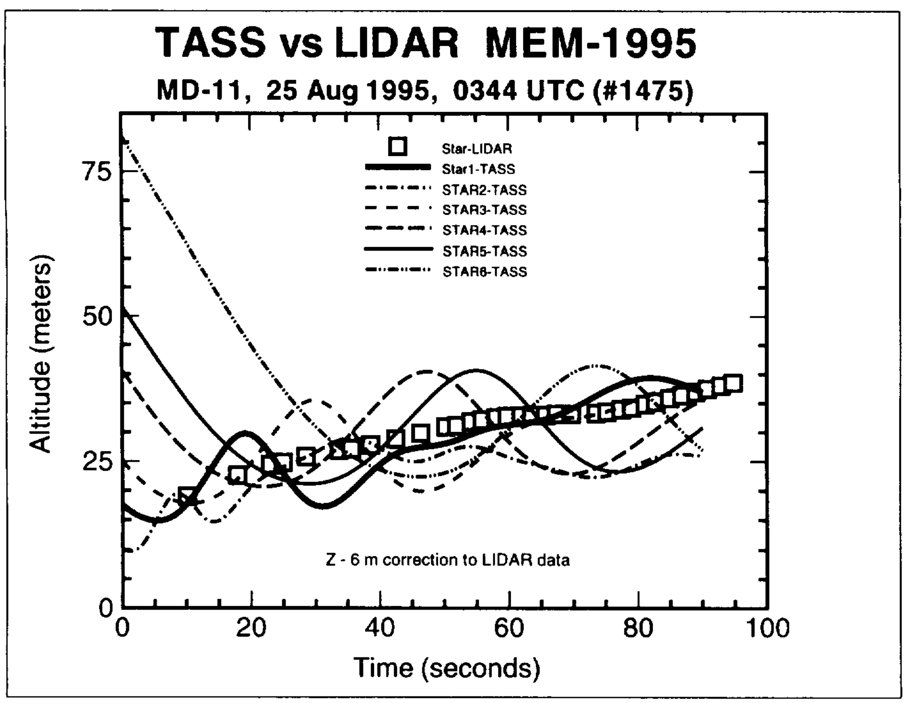
**Lidar Data for Starboard Vortex**

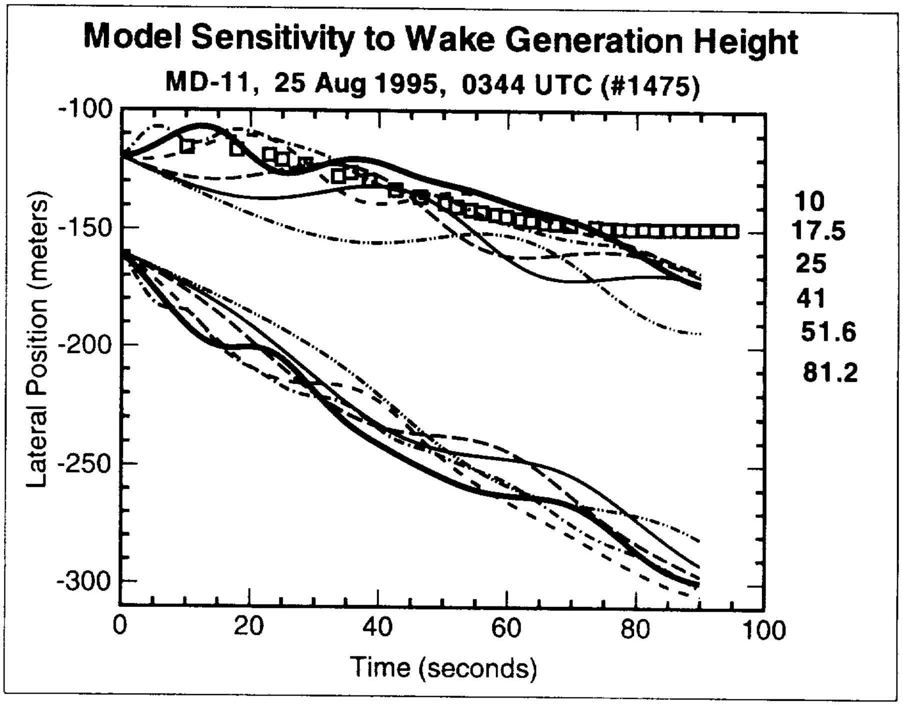
**O Sensitivity of Generation Height**

**Initiation heights: 10, 17.5, 25, 41, 51.6, 81.2 m AGL**

**Initial Vortex Separation: $S_o = 41$ m**


Environmental Input Sounding for MEM-1475
Memphis, 25 August 1995, 0344 UTC
Along-Track Wind Component
Potential Temperature
Cross Wind Component
Speed (m/s)
(Degrees C)
Altitude (meters AGL)
6
5
4
3
2
1
0
-1
-2
30.0
29.5
29.0
28.5
28.0
27.5
27.0
0
25
50
75
100


TASS vs LIDAR MEM-1995
MD-11, 25 Aug 1995, 0344 UTC (#1475)
Star-LIDAR
Star1-TASS
STAR2-TASS
STAR3-TASS
STAR4-TASS
STAR5-TASS
STAR6-TASS
Z - 6 m correction to LIDAR data
Altitude (meters)
Time (seconds)
75
50
25
0
0
20
40
60
80
100




## SUMMARY OF GROUND EFFECT SENSITIVITY STUDIES

**(valid for weak shear environments)**

- **Amplitude of Vortex Bounce Increases with Increasing Generation Height**
- **Phase or Oscillation Time of Bounce Increases with Increasing Generation Height**
- **For Generation Height Above *Initial Separation Distance*, $S_o$, Vortex Core Descends to Height $z = ½ S_o$ and Bounces upwards to $z = S_o$**
- **For Generation Height Below $z = S_o$, Vortex Core Descends to Height Less than $z = ½ S_o$.**

# SENSITIVITY TO ENVIRONMENTAL CROSSWIND SHEAR

## Wake Vortex Sensitivity to Ambient Vertical Shear

**Conditions**

**Experiments Assume Idealized Environment**

**Shear Contained Within Layer 10 m Thick between 60-70 M AGL**

**Winds Calm Below Shear Layer and Uniform Above**

**Temperature Isothermal Below Shear Layer and near Adiabatic Above**

**Aircraft: B-727-100 at 175 m AGL**

### Experiments:

**Crosswind Velocity Change of: 0, 1, 2, 3, 4, and 8 m/s**

## TASS SHEAR LAYER SENSITIVITY EXPERIMENTS

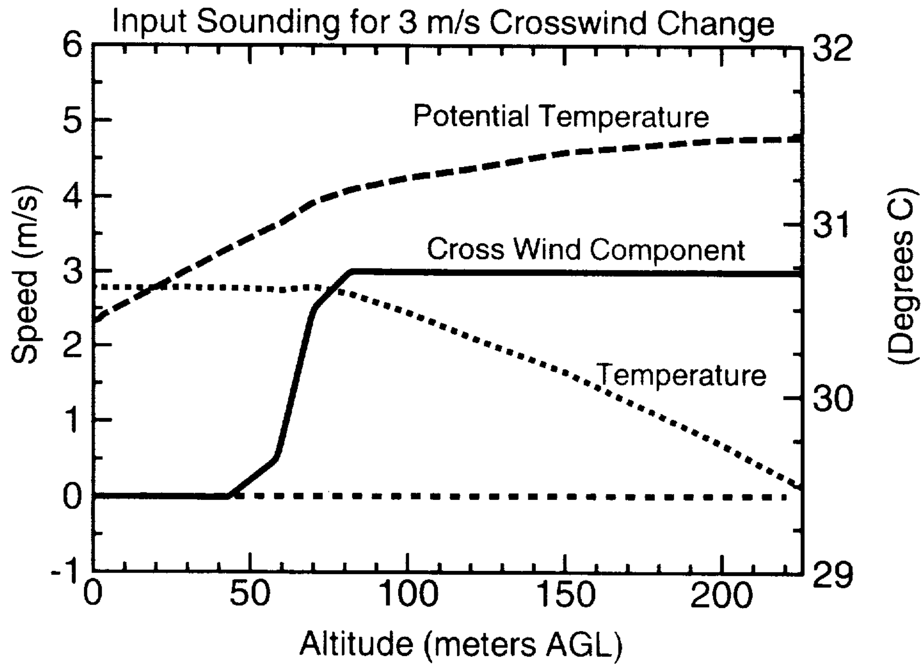
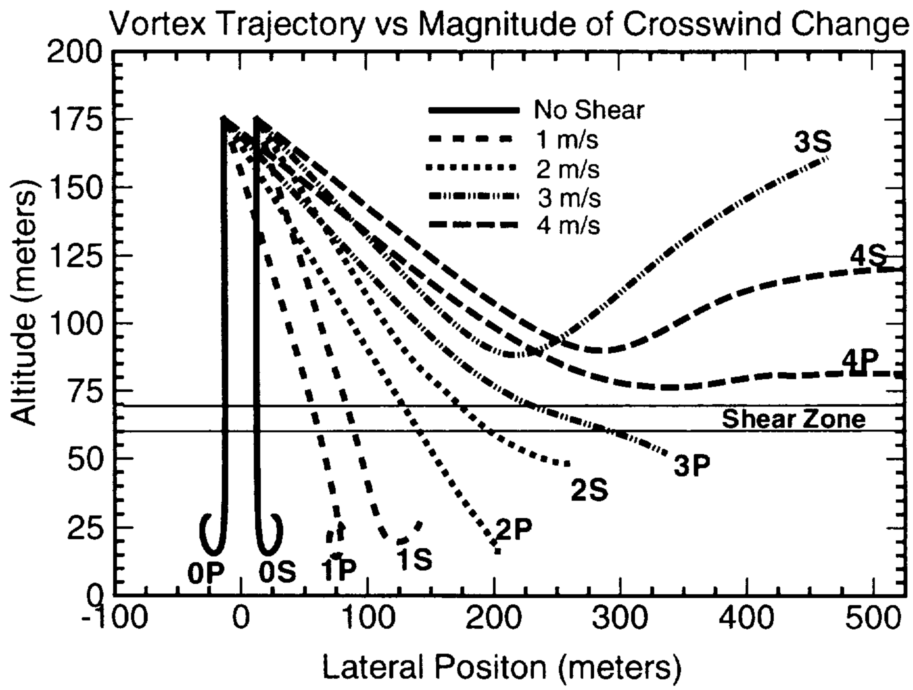



**Table 2.** *Assumed values for initial parameters.*

| Initial Conditions | |
|---|---|
| **Parameter** | **Value** |
| Generation Height | 175 m |
| Circulation ($\Gamma_o$) | 250 $m^2 s^{-1}$ |
| Vortex Spacing ($b_0$) | 26 m |
| Core Radius | 1.75 m |
| Numerical Grid Size | 0.75 m |

## TASS SENSITIVITY TO CROSSWIND SHEAR LAYER




## SUMMARY OF SHEAR-LAYER SENSITIVITY EXPERIMENTS

- **In Experiments, Thermal Inversion at 60 m AGL Almost No Effect on Descending Wakes**
- **Crosswind Shear Layer Acts to Decelerate the Descent of the Wake Vortex Pair**
- **Cross Wind Change Greater than 1 m/s Suppresses the Downward Descent of the Vortex Pair Produced by B-727**
- **Optimal Bounce with Crosswind Change of about 3 m/s for Vortices Produced by B-727**
- **Winds Measured Near Ground May Not Represent Wake Vortex Motion**
- **Due to Momentum Transport from Aloft, Wake Vortices May Move at Different Speed and Direction Than Surrounding Air**

## TASS PARAMETRIC RUNS

Parametric Runs for Crosswind Shear Only

Polynomial Profile — crosswind a function of height according to:

$$UE(z) = C_o + C_1 z + C_2 z^2$$

A. Linear crosswind profiles — assumes $C_o = C_2 = 0$
(wake generation height at 175 m)

B. Nonlinear profiles (wake generation at z=100 m)
i. with $C_o = C_1 = 0$
ii. with only $C_o = 0$

Aircraft Type:
B-727 with: $\Gamma_o = 250$, $b_o = 26$ m ($W_o = 1.53$ m/s)

Stratification:
Slightly stable with $N^* = 0.21$

**Table 3.4 TASS Run Profile Parameters**

| Grouping | Run name | Constants in Shear Profile | | | Shear Profile (eq #) | Vortex Initial Height (m) |
|---|---|---|---|---|---|---|
| | | $C_0$ | $C_1$ | $C_2$ | | |
| Non-Linear Shear | 727.s17 | 0 | 0 | 0 | 1 | 100 |
| | 727.s21 | 0 | 0 | .382757E-03 | 1 | 100 |
| | 727.s18 | 0 | 0 | .765515E-03 | 1 | 100 |
| | 727.s25 | 0 | 0 | -.765515E-03 | 1 | 100 |
| | 727.s19 | 0 | 0 | .153103E-02 | 1 | 100 |
| | 727.s20 | 0 | 0 | .229654E-02 | 1 | 100 |
| | 727.s22 | 0 | 0 | .382757E-02 | 1 | 100 |
| | dc10-30.s1 | 0 | 0 | .100475E-02 | 1 | 100 |
| | 727.s11 | 0 | -.765514E-01 | .382757E-03 | 1 | 100 |
| | 727.s9 | 0 | -.153103 | .765515E-03 | 1 | 100 |
| | 727.s24 | 0 | .153103 | .765515E-03 | 1 | 100 |
| | 727.s10 | 0 | -.306206 | .153103E-02 | 1 | 100 |
| | 727.s12 | 0 | -.459308 | .229654E-02 | 1 | 100 |
| | 727.s23 | 0 | -.765144 | .382757E-02 | 1 | 100 |
| | 727.s13 | 0 | -.568674E-01 | .382757E-03 | 1 | 100 |
| | 727.s14 | 0 | -.131094 | .765515E-03 | 1 | 100 |
| | 727.s15 | 0 | -.2847 | .153103E-02 | 1 | 100 |
| | 727.s16 | 0 | -.439436 | .229654E-0 | 1 | 100 |
| Step Shear | 727.shz2 | 2.0 | - | - | 2 | 175 |
| | 727.shz3 | 3.06 | - | - | 2 | 175 |
| | 727.shz4 | 4.59 | - | - | 2 | 175 |
| | dc10-30.shz4 | 3.01 | - | - | 2 | 175 |
| | dc10-30.shz4 | 4.02 | - | - | 2 | 175 |
| | dc10-30.shz5 | 5.02 | - | - | 2 | 175 |
| | dc10-30.shz6 | 6.01 | - | - | 2 | 175 |

3.3 Data Base Format

The data base is comprised of three Microsoft Excel files. Each file contains one of the three crosswind profile group. The three files are: Linear Shear Cases, Nonlinear Shear Cases, and Step Shear Cases

## TASS PARAMETRIC RUNS

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Polynomial Profile — crosswind a function of height according to:

$$UE(z) = C_o + C_1 z + C_2 z^2$$

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(wake generation height at 175 m)

B. Nonlinear profiles (wake generation at z=100 m)
i. with $C_o = C_1 = 0$
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Aircraft Type:
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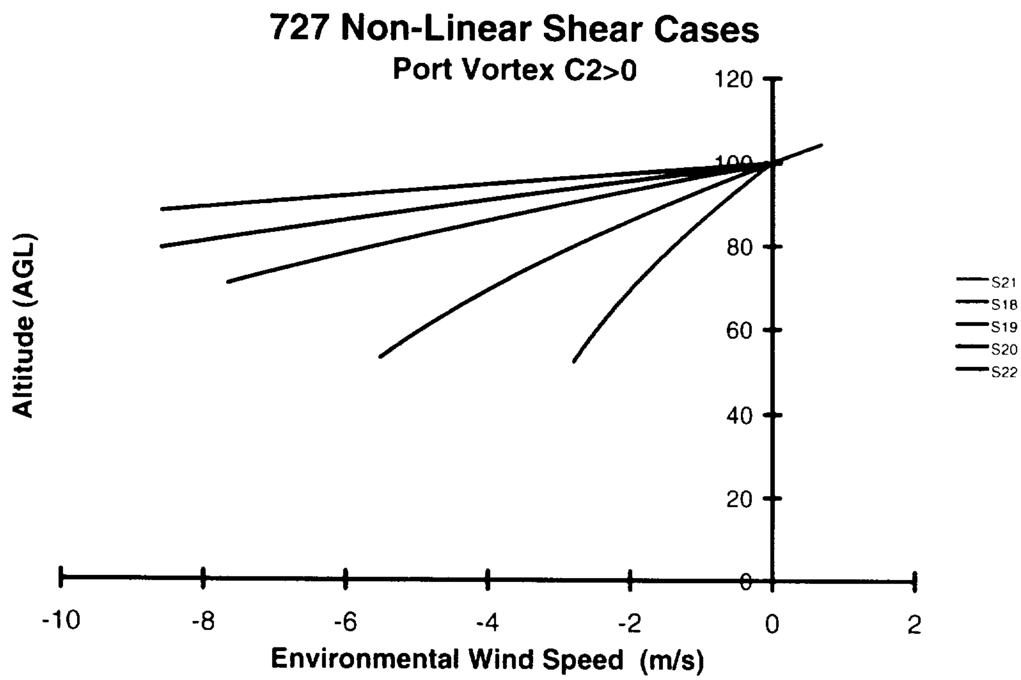
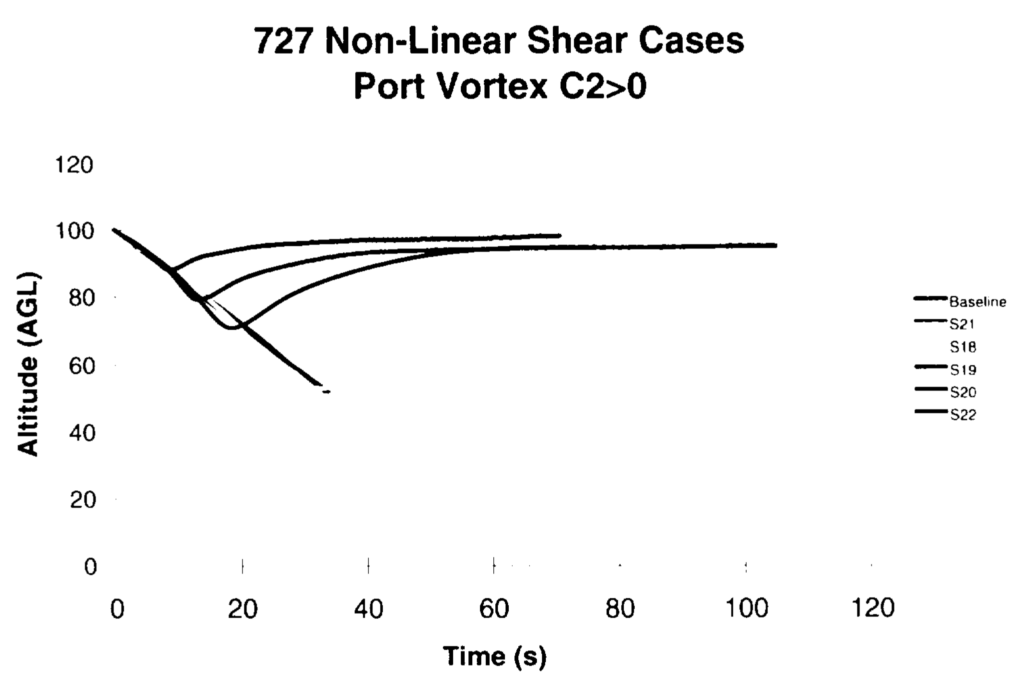
| | 727.s21 | 0 | 0 | .382757E-03 | 1 | 100 |
| | 727.s18 | 0 | 0 | .765515E-03 | 1 | 100 |
| | 727.s25 | 0 | 0 | -.765515E-03 | 1 | 100 |
| | 727.s19 | 0 | 0 | .153103E-02 | 1 | 100 |
| | 727.s20 | 0 | 0 | .229654E-02 | 1 | 100 |
| | 727.s22 | 0 | 0 | .382757E-02 | 1 | 100 |
| | dc10-30.s1 | 0 | 0 | .100475E-02 | 1 | 100 |
| | 727.s11 | 0 | -.765514E-01 | .382757E-03 | 1 | 100 |
| | 727.s9 | 0 | -.153103 | .765515E-03 | 1 | 100 |
| | 727.s24 | 0 | .153103 | .765515E-03 | 1 | 100 |
| | 727.s10 | 0 | -.306206 | .153103E-02 | 1 | 100 |
| | 727.s12 | 0 | -.459308 | .229654E-02 | 1 | 100 |
| | 727.s23 | 0 | -.765144 | .382757E-02 | 1 | 100 |
| | 727.s13 | 0 | -.568674E-01 | .382757E-03 | 1 | 100 |
| | 727.s14 | 0 | -.131094 | .765515E-03 | 1 | 100 |
| | 727.s15 | 0 | -.2847 | .153103E-02 | 1 | 100 |
| | 727.s16 | 0 | -.439436 | .229654E-0 | 1 | 100 |
| Step Shear | 727.shz2 | 2.0 | - | - | 2 | 175 |
| | 727.shz3 | 3.06 | - | - | 2 | 175 |
| | 727.shz4 | 4.59 | - | - | 2 | 175 |
| | dc10-30.shz4 | 3.01 | - | - | 2 | 175 |
| | dc10-30.shz4 | 4.02 | - | - | 2 | 175 |
| | dc10-30.shz5 | 5.02 | - | - | 2 | 175 |
| | dc10-30.shz6 | 6.01 | - | - | 2 | 175 |

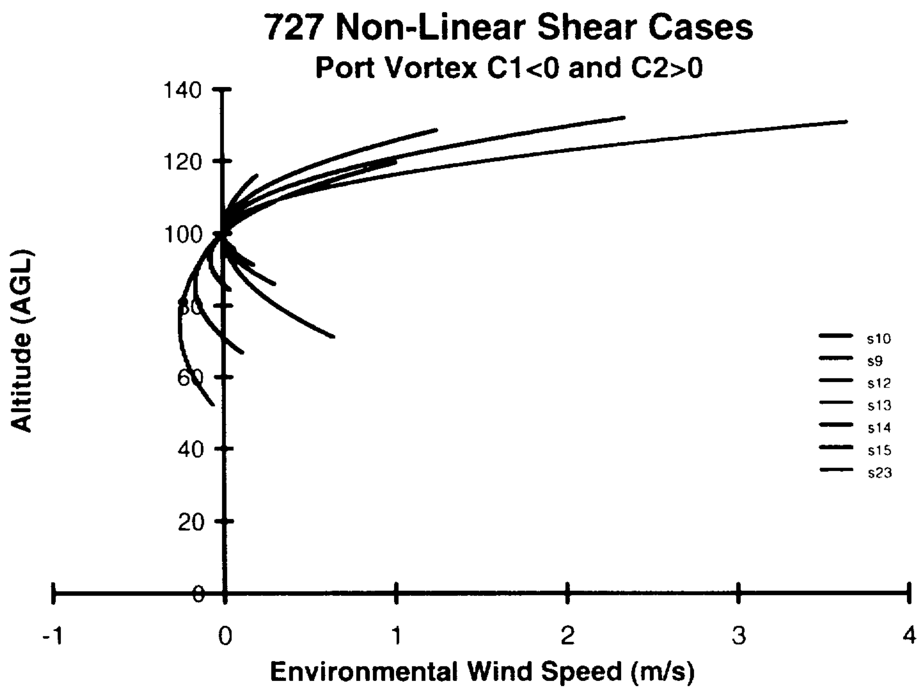
3.3 Data Base Format

The data base is comprised of three Microsoft Excel files. Each file contains one of the three crosswind profile group. The three files are: Linear Shear Cases, Nonlinear Shear Cases, and Step Shear Cases.


727 Non-Linear Shear Cases
Port Vortex C2>0
Altitude (AGL)
120
100
80
60
40
20
0
-10
-8
-6
-4
-2
0
2
Environmental Wind Speed (m/s)
S21
S18
S19
S20
S22

727 t vs z (c1=0)


727 Non-Linear Shear Cases
Port Vortex C2>0
Altitude (AGL)
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Time (s)
Baseline
S21
S18
S19
S20
S22


727 Non-Linear Shear Cases
Port Vortex C1<0 and C2>0
Altitude (AGL)
140
120
100
80
60
40
20
0
-1
0
1
2
3
4
Environmental Wind Speed (m/s)
s10
s9
s12
s13
s14
s15
s23

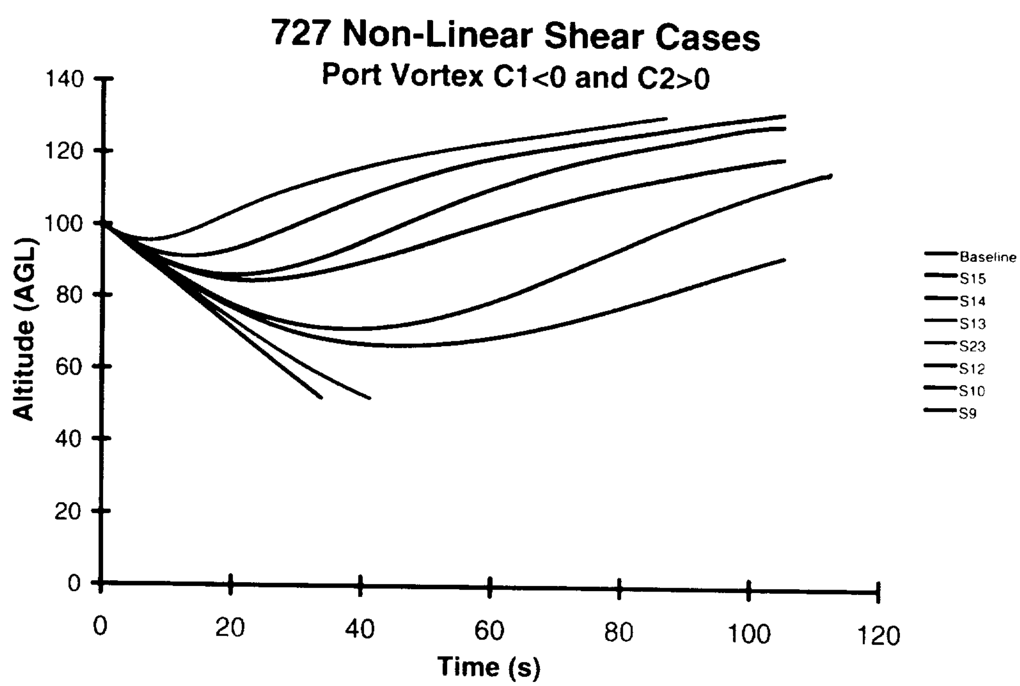
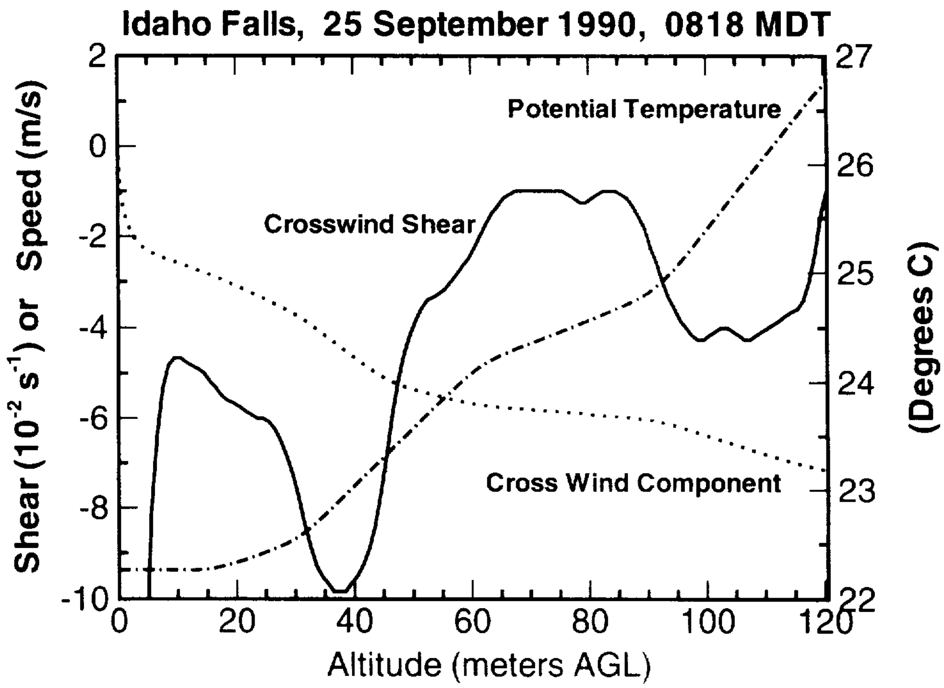

727 Non-Linear Shear Cases
Port Vortex C1<0 and C2>0
Altitude (AGL)
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Time (s)
Baseline
S15
S14
S13
S23
S12
S10
S9

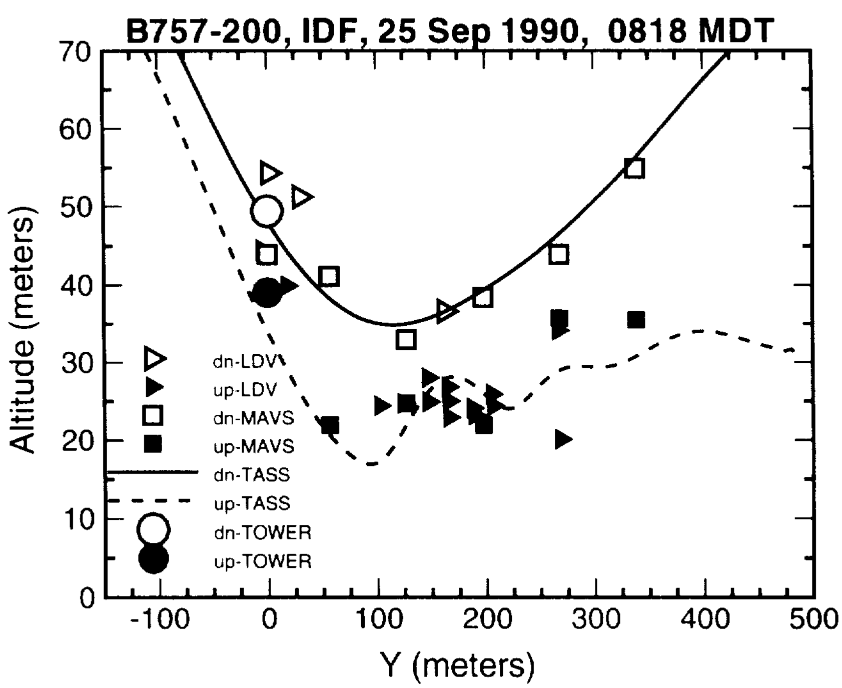
***Table.*** *Sign of crosswind vorticity vs vortex with highest bounce for each experiment.*

| **Crosswind** | **Ambient Vorticity:** $\omega=\partial u/\partial z$ | $\partial\omega/\partial z = \partial^2 u/\partial z^2$ | **Vortex with Highest Bounce** |
|---|---|---|---|
| No Shear | 0 | 0 | Same (no tilting of pair) |
| Linear Shear | + | 0 | Same (no tilting of pair) |
| Nonlinear Shear | 0 | - | Starboard (vortex containing *negative* vorticity† ) |
| Nonlinear Shear | - | - | Starboard (vortex containing *negative* vorticity† ) |
| Nonlinear Shear | + | - | Starboard (vortex containing *negative* vorticity† ) |
| Nonlinear Shear | + | + | Port (vortex containing *positive* vorticity) |

†Vortex with counter-clockwise rotation -- generated on right side of airplane



Idaho Falls, 25 September 1990, 0818 MDT
Potential Temperature
Crosswind Shear
Cross Wind Component
Shear (10^-2 s^-1) or Speed (m/s)
(Degrees C)
Altitude (meters AGL)

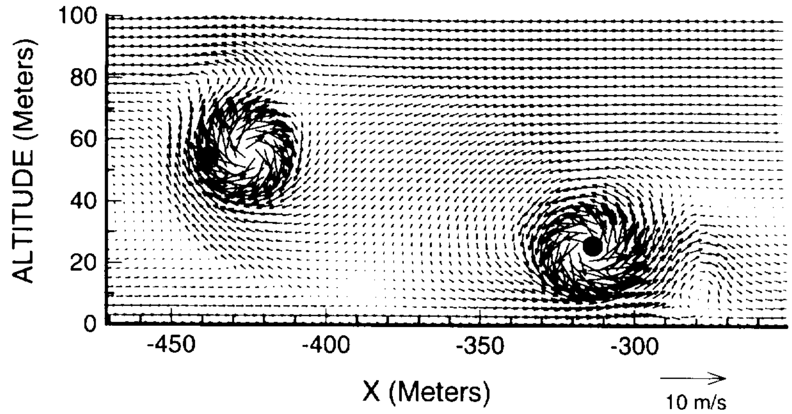
B757-200, IDF, 25 Sep 1990, 0818 MDT
dn-LDV
up-LDV
dn-MAVS
up-MAVS
dn-TASS
up-TASS
dn-TOWER
up-TOWER
Altitude (meters)
Y (meters)

**TASS WAKE VORTEX SIMULATION -- IDF RUN-9**

**RELATIVE WIND VECTORS AT 90 SECONDS**

(horizontal motion of vortex subtracted from flow)

observed vortex locations are denoted by filled circles




## SUMMARY

- Wake Vortex Trajectories are Very Sensitive to Crosswind Flow
- Nonlinear Shear of the Crosswind Component Affects the Vortex Descent Rate and may Result in Vortex Tilting or Rising
- The Member of the Vortex Pair with Same Sign Vorticity as the Vertical Change in Along Track Vorticity Rises Highest
- Zones With Sharp Changes in the Crosswind are Quite Effective in Altering Vortex Trajectories
- Stable Stratification Must be Quite Strong in order to have the Same Effect on Vortex Descent as Nonlinear Crosswind Shear

**Questions and Discussions Following Fred Proctor's Presentation (NASA Langley)**

Unknown
When you have both shear and radiation in shear with vertical distance, if the profile is monotonic, like for example in ones near the ground sometimes, which vortex, the upstream or downstream vortex, bounces higher?

Proctor
The linear shear itself has no effect on bouncing. I can change signs, reverse the mean flow, and the vortex which bounces highest is always based on the second derivative of the cross wing velocity.

Unknown
In neutrally stratisfied atmosphere the Monin-Obukhov Similiarity says that the second derivation of the velocity should go like $1/z^2$ where z is distance from the ground. Under those conditions which vortex would bounce higher?

Proctor
Since $z^2$ is increasing with altitude the one with position vorticity would bounce highest. Normally, that would be the downstream but a profile could be configured to have the upstream have positive vorticity. Normally, near the ground the wind would be such that the downstream vortex would bounce higher. By the way, I am rediscovering this. A paper by Burnham in '72 showed this effect.

S3-02
648 091
318613
22p.

# *Toward Understanding Wake Vortices and Atmospheric Turbulence Interactions using Large-Eddy Simulation*

D. DeCroix, Y.L. Lin, S.P. Arya,
C.T. Kao, S. Shen
North Carolina State University

Scan →

# *Outline*

- Background
- Meteorological considerations
- LES Model
- Results
- Future Work
- Conclusions

Aircraft Wake Vortices and Atmospheric Turbulence
A Large Eddy Simulation Approach to Investigate Their Interaction

by

David S. DeCroix, Y.L. Lin, S.P. Arya, C.T. Kao, S. Shen
North Carolina State University

The vortices produced by an aircraft in flight are a complex phenomena created from a 'sheet of vorticity' leaving the trailing edge of the aircraft surfaces. This sheet tends to roll-up into two counter-rotating vortices. After a few spans downstream of the aircraft, the roll-up process is complete and the vortex pair may be characterized in a simple manner for modeling purposes. Our research will focus on what happens to these post roll-up vortices in the vicinity of an airport terminal.

As the aircraft wake vortices descend, they are transported by the air mass which they are embedded and are decayed by both internal and external processes. In the vicinity of the airport, these external influences are usually due to planetary boundary layer (PBL) turbulence. Using large-eddy simulation (LES), one may simulate a variety of PBL conditions. In the LES method, turbulence is generated in the PBL as a response to surface heat flux, horizontal pressure gradient, wind shear, and/or stratification, and may produce convective or unstably stratified, neutral, or stably stratified PBL's. Each of these PBL types can occur during a typical diurnal cycle of the PBL. Thus it is important to be able to characterize these conditions with the LES method. Once this turbulent environment has been generated, a vortex pair will be introduced and the interactions are observed. The objective is to be able to quantify the PBL turbulence vortex interaction and be able to draw some conclusions of vortex behavior from the various scale interactions.

This research is ongoing, and we will focus on what has been accomplished to date and the future direction of this research. We will discuss the model being used, show results that validate its use in the PBL, and present a nested-grid method proposed to analyze the entire PBL and vortex pair simultaneously.

# Numerical Modeling studies of Wake Vortices in the Planetary Boundary Layer

NASA Cooperative Agreement

Dr. Yuh-Lang Lin, Associate Professor of Atmospheric Science, Numerical Weather Prediction, Mesoscale Analysis and Modeling.
Dr. S. P. S. Arya, Professor of Atmospheric Science, Turbulence and Diffusion
Dr. Michael Kaplan, Visiting Associate Professor, Numerical Weather Prediction, Mesoscale Analysis and Modeling
Dr. Chung-Teh Kao, Scientist, Vortex Dynamics
Dr. Shaohua Shen, Visiting Assistant Professor, Planetary Boundary Layer Turbulence
Mr. David S. DeCroix, Ph.D. Graduate Student
Mr. Jongil (Martin) Han, Ph.D. Graduate Student

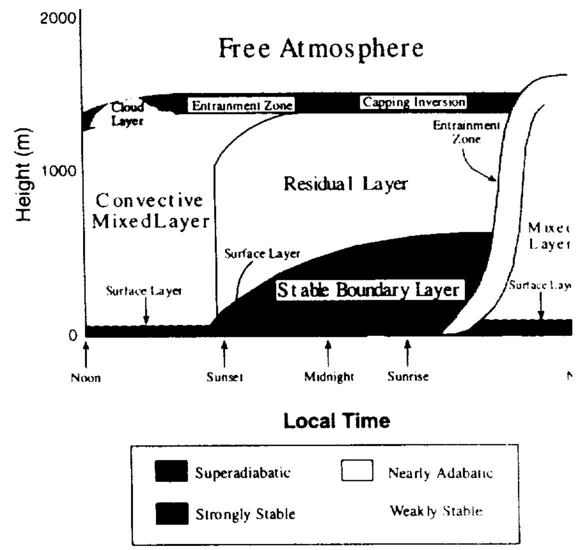
## Two-Pronged Approach

- Adapt TASS to study Atmospheric turbulence (DeCroix)
- Adapt TASS to study 3-D aircraft vortices (Han)
- Combine and get best possible simulation of interactions

## Meteorology

- Meteorological scales
  - Synoptic, meoscale, microscale
- Planetary boundary layer
  - Part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a timescale of about an hour or less (Stull, 1993)

# Typical PBL Evolution




# PBL Classifications

- Convective
  - Unstable stratification
  - Eddies range from km to mm
  - Vigorous turbulence due to
    - buoyancy and shear
    - Ri < 0.25, N is undefined

## *PBL Types*

- Neutral
  - No stratification
  - Turbulence due primarily to shear
    - N=0, Ri=0
- Stable
  - Stable stratification (night-time)
  - N>0, Ri<0.25 for turbulence
  - Low-level Jets

## *Turbulence in the PBL*

- Responds to forcings
  - Surface roughness
  - Surface heat flux
  - Wind Shear
  - Mesoscale effects
    - Fronts, severe storms, etc.
    - Topography

## *Turbulence in the PBL*

- Length scales
  - *O*(1 km) to *O*(1 mm)
    - Integral length scale (Large eddies)
    - Taylor microscale (Small eddies)
    - Kolomgrov microscale (Dissipation scale)
- Time scales
  - *O*(hours) to *O*(seconds)

## *TASS - Terminal Area Simulation System*

- Nonhydrostatic
- Fully compressible
- Large-eddy simulation
  - Smagorinsky type closure
- Microphysical interactions
- 2 or 3 Dimensional simulations

## *Modifications for PBL Simulation*

- Surface heat flux or temperature
  - Spatially uniform
  - Temporally variable
- Pressure gradient via geostrophic wind
  - Variation with height
- Initial random temperature perturbation
- Upper horizontal velocity
  - Time dependent, given by observations

## *Model Initialization*

- Vertical Profile of horizontal winds, temperature, dew point
  - Horizontally homogeneous
- Surface Heat Flux/Temperature
- Geostrophic Wind (pressure gradient)
- At t=0, random temperature perturbation in 1st 3 vertical levels

## *Boundary Conditions*

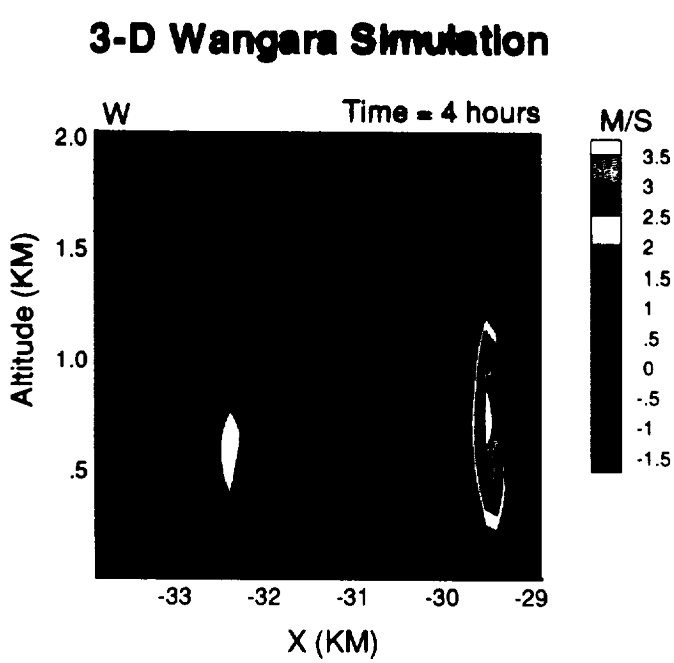
- Periodic in X and Y directions
- Upper BC
  - No vertical motion, sponge
- Lower BC
  - No-slip

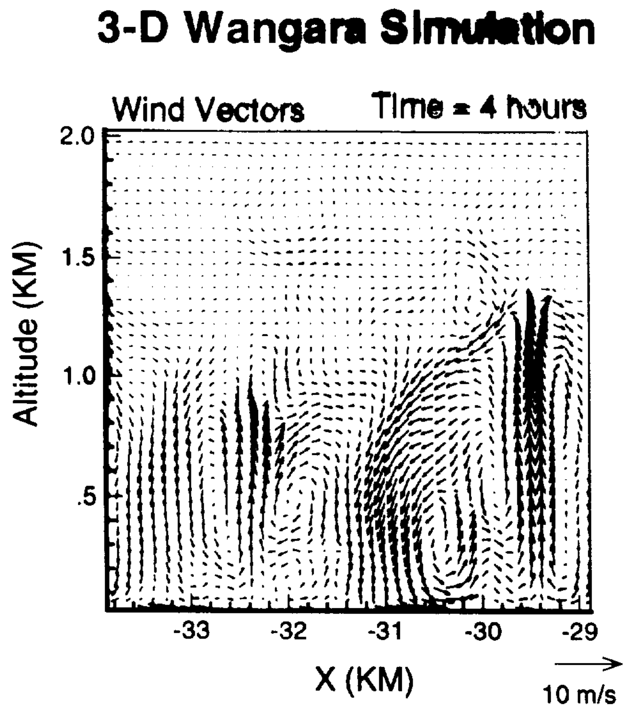
## *TASS Simulation Comparisons*

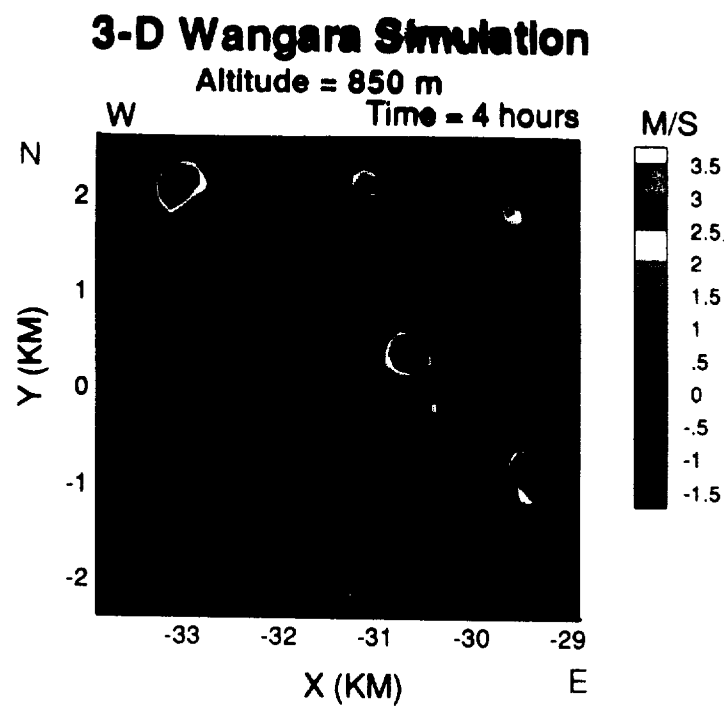
- Instantaneous Fields
- Ensemble Averages
  - Variances, Fluxes, and Spectra
    - Nieuwstadt et. al. convective pbl comparison
    - Andren et. al. neutral pbl comparison
    - Evening Transition to stable pbl

# *Convective PBL simulations*

- Wangara Day 33
  - Deardorff 1973 results
  - Classical case
- 1973 Minnesota Experiment
  - Comparison to other models
  - Comparison to observations
    - Mesoscale influences?
      - Model initialization suspect (?)

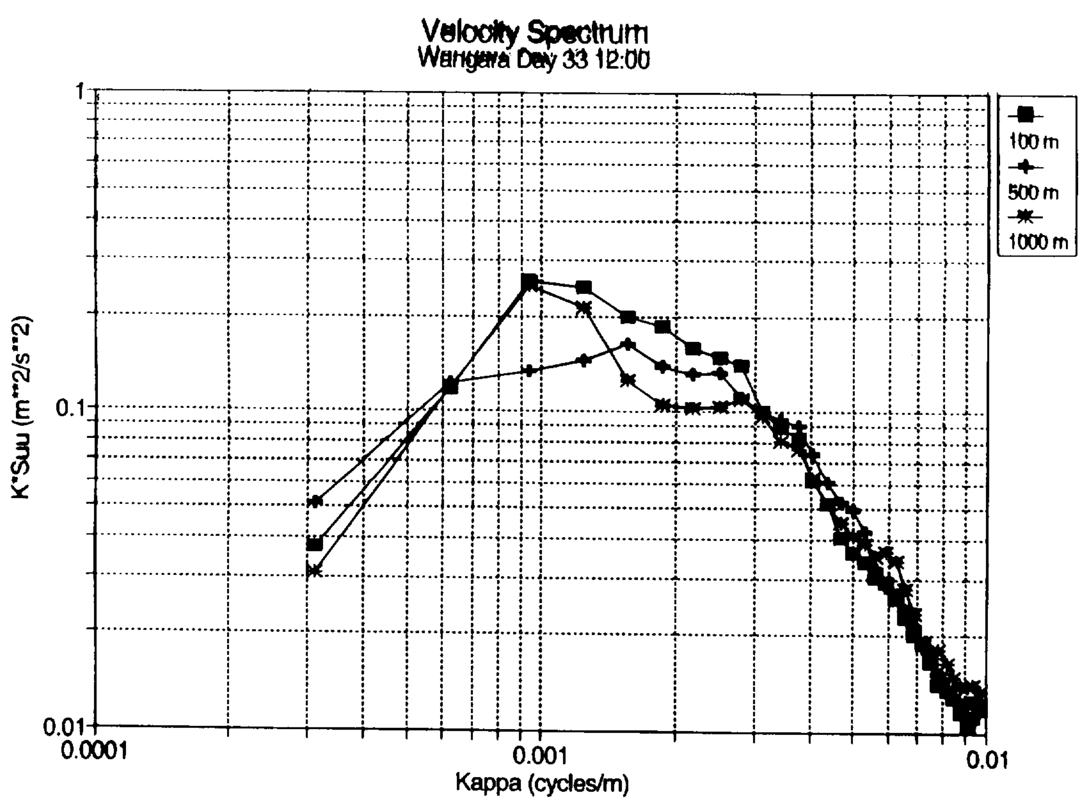



3-D Wangara Simulation
Wind Vectors
Time = 4 hours
2.0
1.5
1.0
.5
Altitude (KM)
-33
-32
-31
-30
-29
X (KM)
10 m/s


3-D Wangara Simulation
Altitude = 850 m
W
Time = 4 hours
M/S
N
2
1
0
-1
-2
Y (KM)
-33
-32
-31
-30
-29
X (KM)
E
3.5
3
2.5
2
1.5
1
.5
0
-.5
-1
-1.5

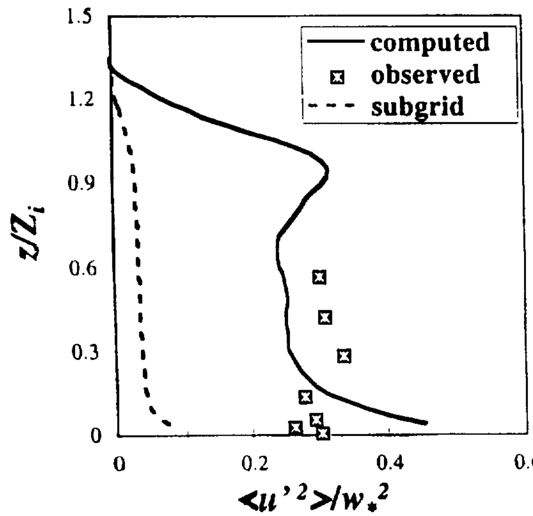
# Spectrum of Turbulence

- Instantaneous fields
- Power spectrum of CBL
  - Significant Peaks
    - 9.3E-4 1075m pbl height
    - 1.6E-3 625m downdrafts
    - 2.6E-3 380m Thermals
    - 4.0E-3 250m begin ISR
  - Dissipation 1.E-3 to 1.E-4 $m^2/s^3$

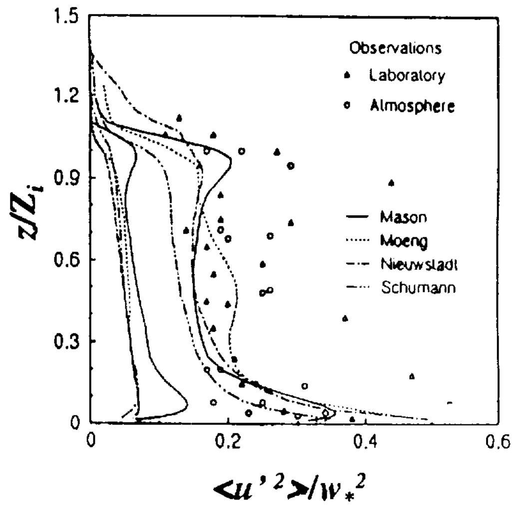


# Horizontal velocity variance

**Minnesota Simulation**

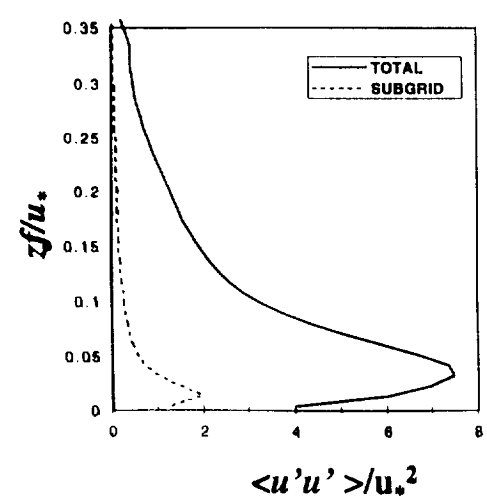



**Nieuwstadt et al.**

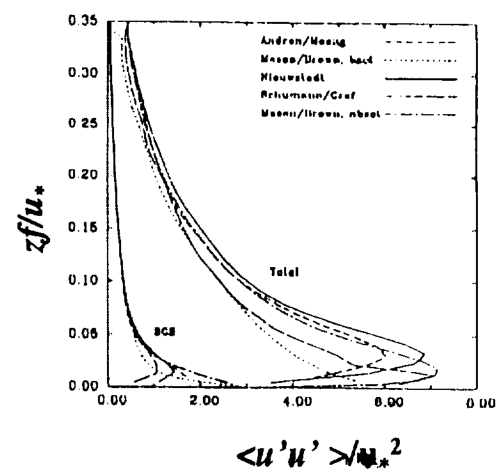



# Longitudinal velocity variances

**TASS**



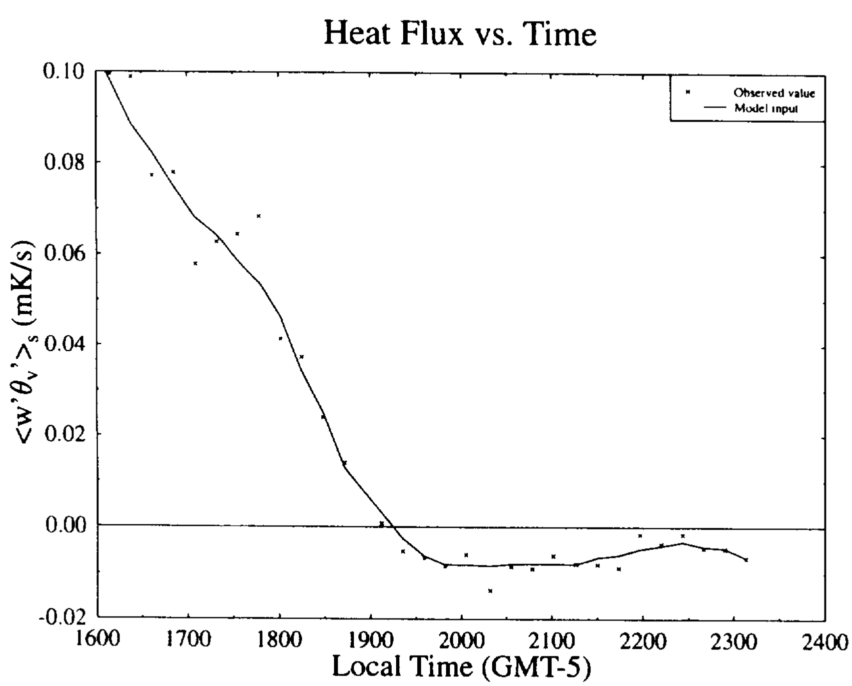

**Andren et al.**



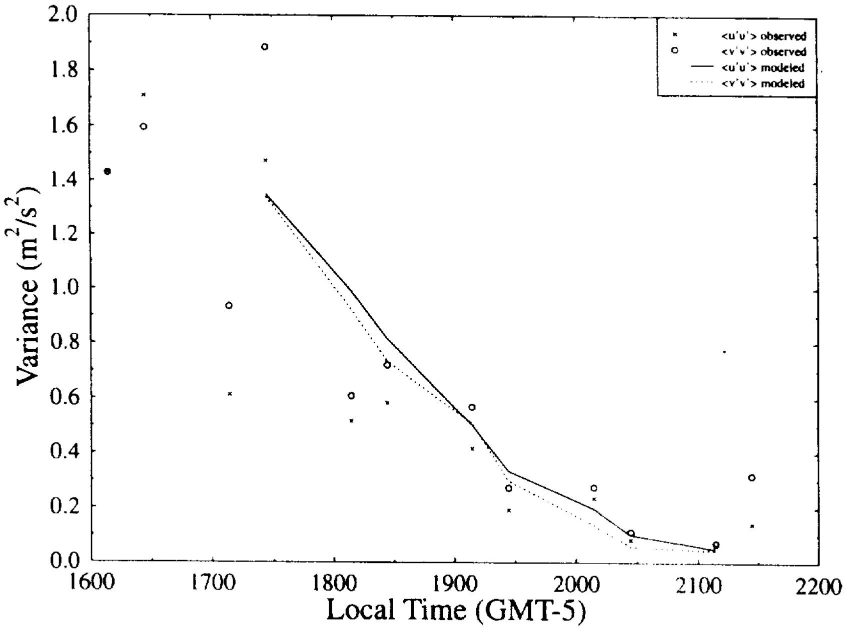

NC State University

# *Transitioning PBL simulation*

- Memphis, Tn. August1995
  - Comparison to observed PBL structure
- 90x90x100 Grid Mesh
- 62m Horizontal Resolution
- 1.6km Initial Inversion height

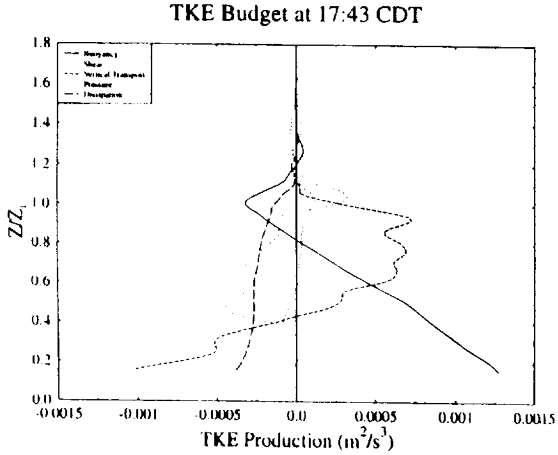


Comparison of Velocity Variance at 40m height

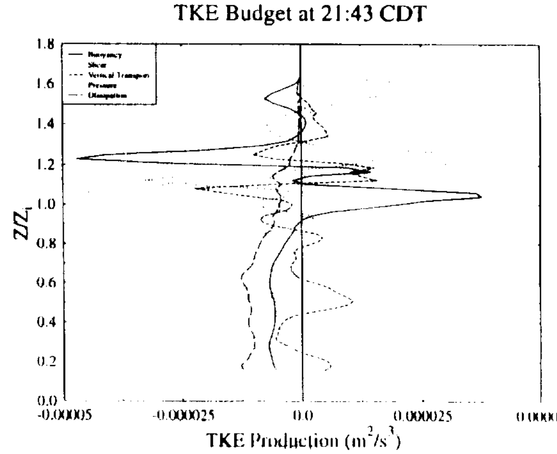



# TKE Budget

TKE Budget at 17:43 CDT




TKE Budget at 21:43 CDT

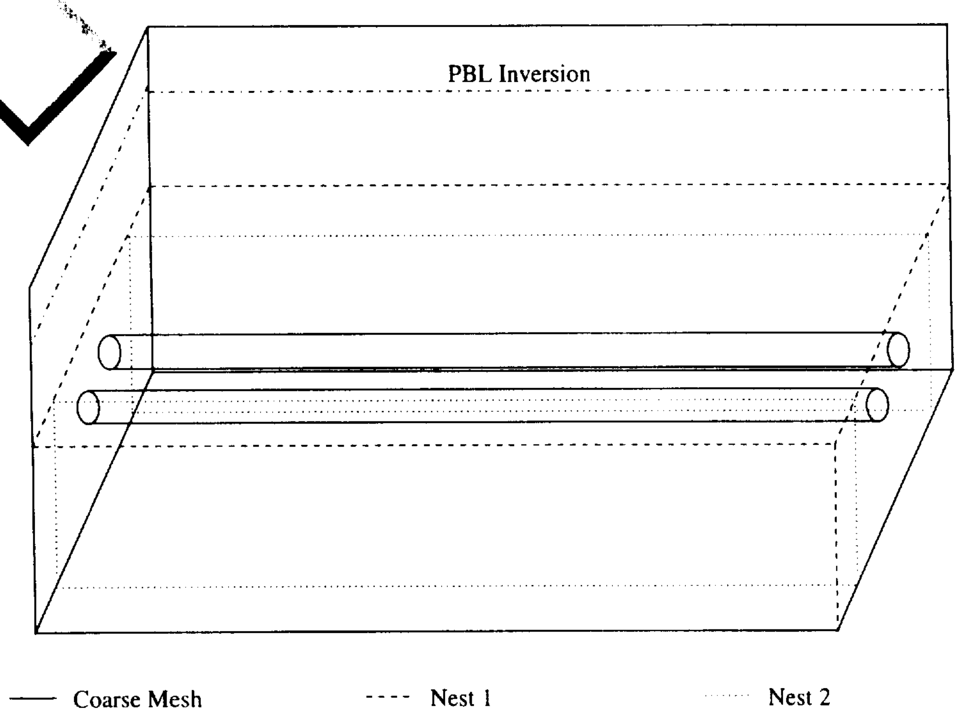


## *Some Deficiencies*

- Insufficient resolution
  - Increase surface layer resolution
- Inaccurate model initialization
  - Need for more 'realistic' mesoscale modeling
- Sub-grid Closure
  - Always a suspect
    - No backscatter, etc.

## *TASS Nested Grid Version*

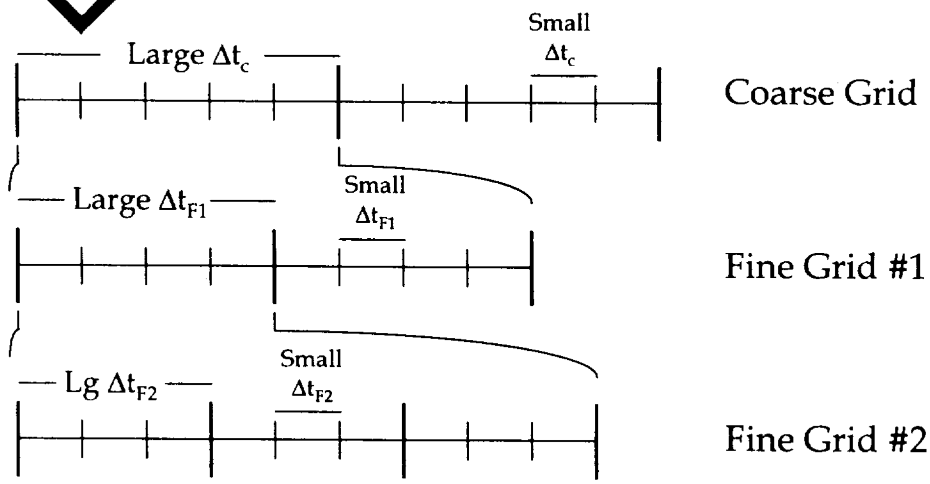
- Allows one to customize domain
  - Model entire PBL
  - Telescope down to vortex scales
  - Allows for interaction between nests




# TASS Implimentation

- Digest additional B.C. info for its nest
- Take time-steps to CM stopping point
- If 1-way nesting
  - Each nest (job) may run simultaneously
- If 2-way nesting,
  - Average its 'fine-grid' fields to parent 'coarse-grid' resolution
  - Pass updated fields to parent

## *Nested Grid Flow*




Pass averaged data back to parent after large $\Delta t$ of parent

## *Boundary Condition Modifications*

- Lateral
  - Periodic (Full domain in X and/or Y)
  - Non-reflecting (Nested)
- Vertical
  - Surface
    - Monin-Obukhov Similarity
    - Non-reflecting (Nested)
  - Top of domain
    - Sponge
    - Non-reflecting (Nested mod. Klemp-Durran)

## *Status of Grid-nesting*

- Implemented and tested interpolation, averaging, and BC's
- Initial test cases
  - Need to modify filters for nested grid
  - Upper BC seems to work for neutral
    - Modifications needed for unstable
  - SGS turbulence of nested mesh
    - 'Blending' procedure needed in vertical
  - Modify mesh communication time?

## *Turbulence Closure*

- Is increasing resolution enough?
- Possible Closures
  - Stochastic Backscatter (Mason)
  - 2-Part model (Sullivan)
  - 3-Part model
    - 2-part plus vortex core treatment?

## Future Investigations

- CBL surface layer
  - Nesting to resolve detailed structure
  - Vortex pair in ground effect
    - Compare to neutral stratification
    - Compare to specified turbulence level
- CBL Mixed Layer
  - Vortex behavior aloft

## Future Investigations (cont)

- Stable PBL
  - Vortex bouncing
  - What range of conditions produce bouncing?
    - Effect of stratification
    - Effect of wind shear
    - Combination
- Is there a range of $R_i$ or $R_f$?

## Future Investigations (cont)

- Model initialization
  - Vertical sounding
  - Mesoscale model (eg. MASS)
    - Interpolate fields and BC's for TASS
      - Run 5-6 nested domains?
      - Meso Beta to vortex scales
      - i.e. 1km to 1m resolution

## Conclusions

- Importance of Meteorology
  - PBL turbulence greatly varies
    - Convective, neutral, and stable conditions
    - Wind shears and jets
- TASS simulates PBL turbulence
  - Can analyze particular conditions
  - Characterize effects individually
  - Provide more realistic spectra

## *Conclusions (cont)*

- Nesting strategy
  - Allow greater resolution within larger domain
  - Embed vortices in PBL
- Continue PBL and vortex-only simulations
- Combine PBL/vortex simulations using grid-nesting technique


## *Acknowledgements*

- Super-Computer time from
  - North Carolina Supercomputer Center
  - NASA Langley
  - NASA Ames
- This research is sponsored by NASA Langley Research Center

**Questions and Discussions Following Dave DeCroix's Presentation (North Carolina State University)**

Unknown
How close to the ground do you plan to approach before you rely on Monin-Obukhov itself to do parameterization of turbulence?

DeCroix
That is a good question. That is something we need to investigate. As we increase the resolution we are obviously going to be resolving finer scales and it is not clear what the threshold is. It is something we plan to look at.

# Large Eddy Simulation of Aircraft Wake Vortices: Atmospheric Turbulence Effects

J. Han, Y. -L. Lin, S. P. Arya, and C. -T. Kao

North Carolina State University

## Ambient Atmospheric Turbulence Effects

* Initiate three-dimensional instability such as Crow instability and vortex bursting

* Increase vortex decay by three-dimensional vorticity stretching

* Strong and large turbulent eddy motion can transport wake vortices significantly

* Dimensionless measure of turbulence

$$\eta = (\varepsilon b_o)^{1/3} / (\Gamma_o / 2\pi b_o)$$

$\varepsilon$: TKE dissipation rate, $\Gamma_0$: circulation, $b_0$: vortex pair spacing

$V_0 = \Gamma_0/(2\pi b_0)$ : Descent speed of vortex pair in inviscid fluid

$T = V_0 t/b_0$ : Dimensionless time

* In the middle of Atmospheric Convective Boundary Layer (CBL)

$1.0\times10^{-4}$ ($m^2/s^3$) $\leq \varepsilon \leq$ $1.0\times10^{-3}$ ($m^2/s^3$) (from LES results)

From Idaho Falls and Memphis observation data (Proctor, 1996)

| | $\Gamma_0$ ($m^2/s$) | $b_0$ (m) | $\eta$ |
|---|---|---|---|
| IDF/B727 | 300 | 26 | 0.075 ~ 0.161 |
| IDF/B757 | 360 | 30 | 0.075 ~ 0.163 |
| IDF/B767 | 375 | 38 | 0.099 ~ 0.214 |
| MEM/DC-9 | 215 | 23 | 0.089 ~ 0.191 |
| MEM/DC-10 | 480 | 37 | 0.075 ~ 0.162 |
| MEM/MD-11 | 560 | 41 | 0.074 ~ 0.159 |

## Previous Studies

* Atmospheric observations (Tombach, 1973)

- The vortices are never observed to decay away due to viscous or turbulent dissipation, but are always destroyed by some form of instability
- Crow instability appears at all levels of turbulence except a very calm and stable atmosphere
- Vortex bursting is the dominant mode

* Water tank experiments (Sarpkaya and Daly, 1987)

- Crow instability in weak turbulence ($\eta<0.1$)
- Vortex bursting in medium to stronger turbulence($\eta>0.1$)

* Direct Numerical Simulation (DNS)

- Spalart and Wray (1996)
  - * Crow instability in weak turbulence ($\eta<0.1$)
  - * Chaotic deformations in stronger turbulence ($\eta>0.1$)
- Corjon et al. (1996)
  - * The stretching exerted by the vortices create tubes of intense vorticity rolling up the vortices and produces strong axial velocity

# The model

* Terminal Area Simulation System (TASS) LES model

* Domain size: $20b_0 \times 5b_0 \times 5b_0$ =324m×84m×84m ($b_0$ = 16 m)
  Grid points: 324×112×112, Grid size: $\Delta x$ = 1 m, $\Delta y = \Delta z$ = 0.75 m
  Periodic boundary condition is applied at all boundaries

* Vortex system: Burnham-Hallock (1982) model

$$V(r) = \frac{\Gamma_o}{2\pi} \frac{r}{r_c^2 + r^2}$$

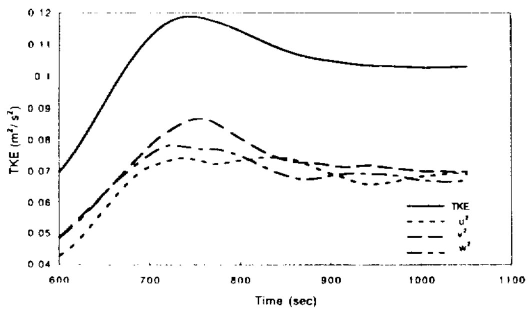
$V$ : vortex tangential velocity, $r$ : radius, $r_c$ : core radius (= 2 m)
$\Gamma_0$: circulation at $r >> r_c$

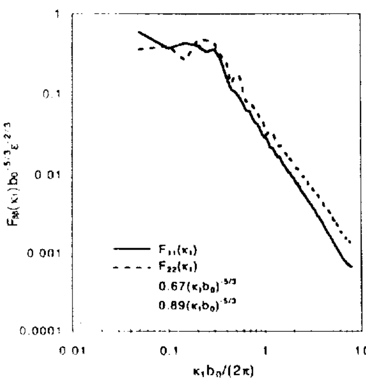
# Ambient atmospheric turbulence initialization

$$\frac{\partial u_i}{\partial t} + \frac{H}{\rho_o} \frac{\partial p}{\partial x_i} = -\frac{\partial u_i u_j}{\partial x_j} + u_i \frac{\partial u_j}{\partial x_j} + g(H-1)\delta_{i3} + \frac{1}{\rho_o} \frac{\partial \tau_{ij}}{\partial x_j} + f(\vec{\kappa})$$

$$where \qquad H = \frac{\rho_o}{\rho}$$

A constant amplitude forcing is added every time step in the range of $\kappa = |\vec{\kappa}| \le 3.0$ using three-dimensional Fast Fourier Transform




* Integral length scale: $L_{11} \equiv \int_0^\infty \langle u(x)u(x+r)\rangle / \langle u'^2\rangle dr \approx$ 13.5 m

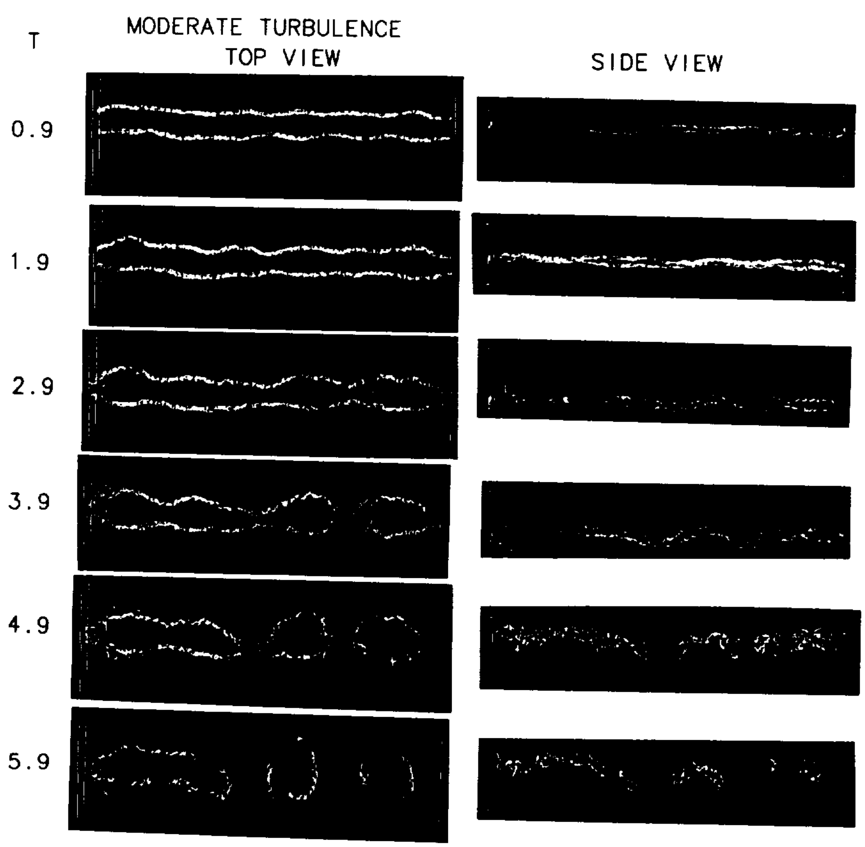
* Large eddy turnover time: $t_e = L_{11}/\langle u'^2\rangle^{1/2} \approx$ 50.2 seconds

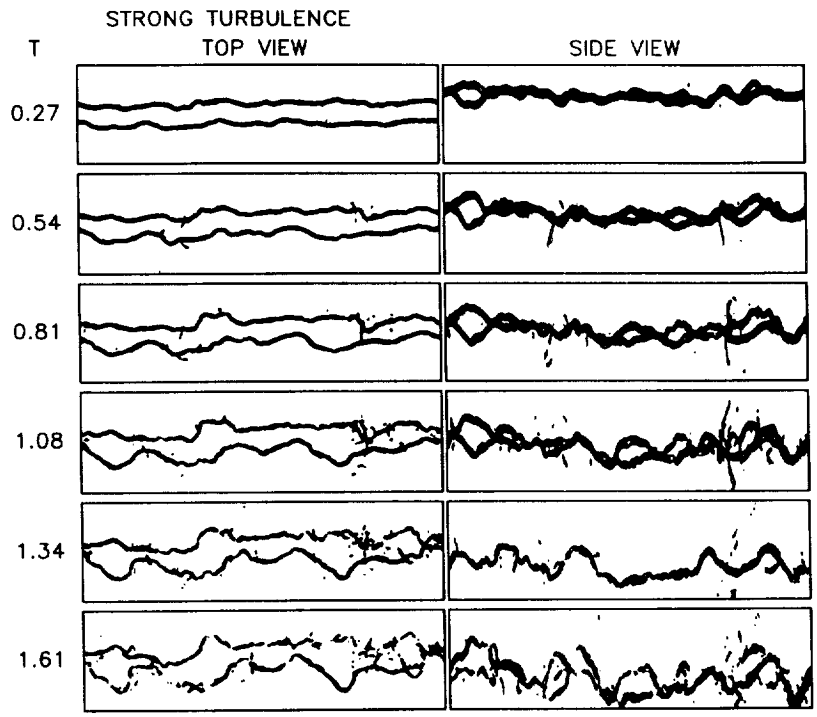
* Isotropy: $I \equiv [\langle u'^2\rangle/\langle v'^2\rangle]^{1/2} \approx 0.93$

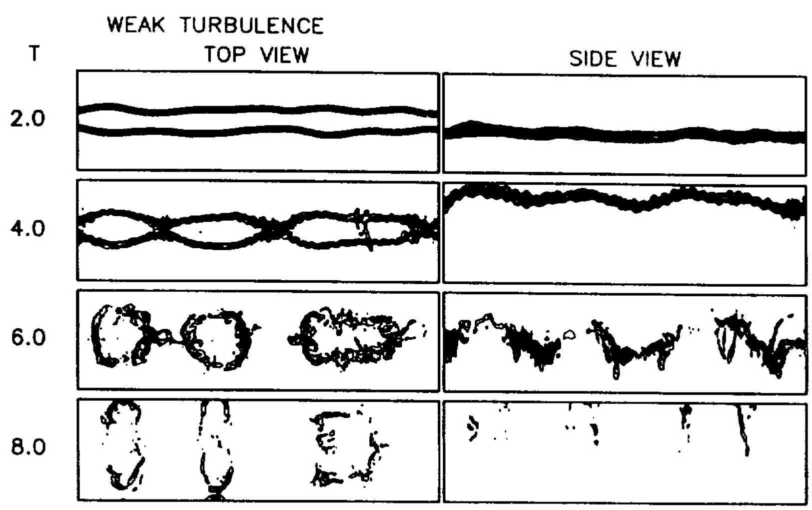
* TKE dissipation rate: $<\varepsilon>=<K_m D_{ij}> \approx 7.43\times10^{-4}$ ($m^2/s^3$)

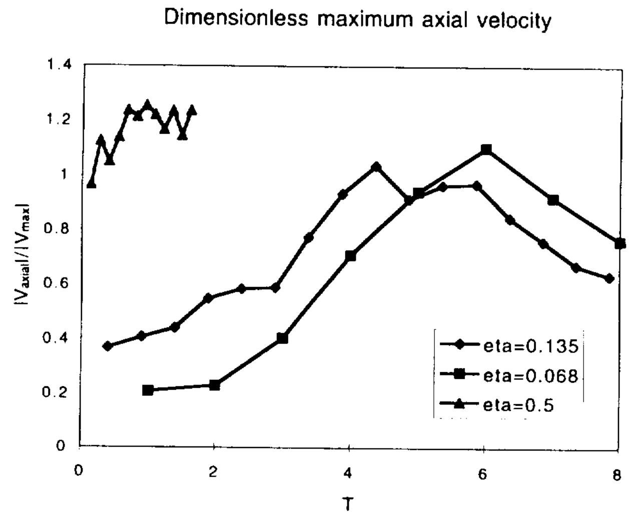
# Numerical experiments

| Dimensionless turbulence level | $\eta$ | $\Gamma_0$ ($m^2/s$) | $V_0$ (m/s) |
|---|---|---|---|
| Moderate | 0.143 | 160.0 | 1.59 |
| Strong | 0.5 | 43.2 | 0.43 |
| Weak | 0.068 | 320.0 | 3.20 |

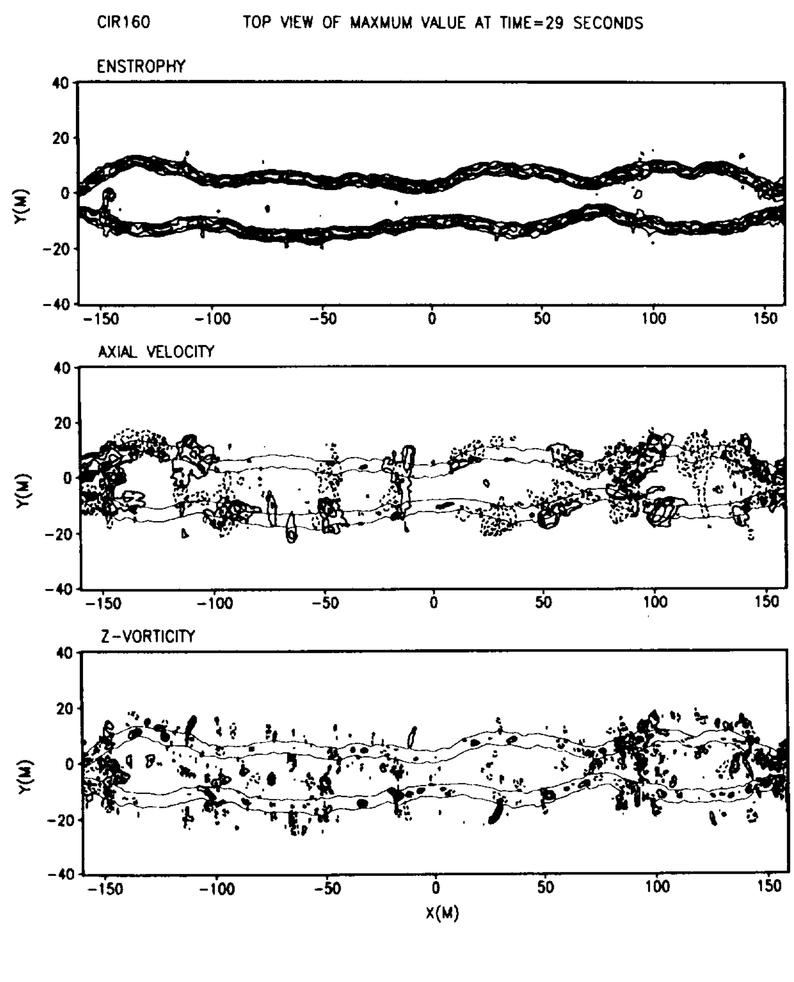



STRONG TURBULENCE
T
TOP VIEW
SIDE VIEW
0.27
0.54
0.81
1.08
1.34
1.61

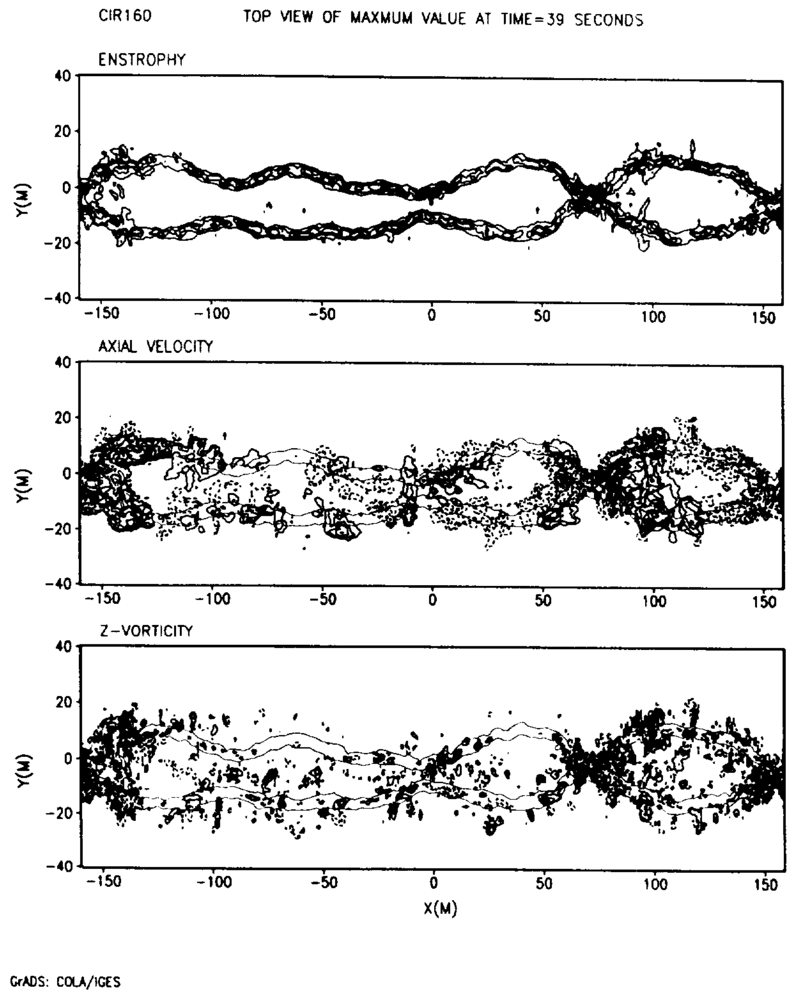

WEAK TURBULENCE
T
TOP VIEW
SIDE VIEW
2.0
4.0
6.0
8.0



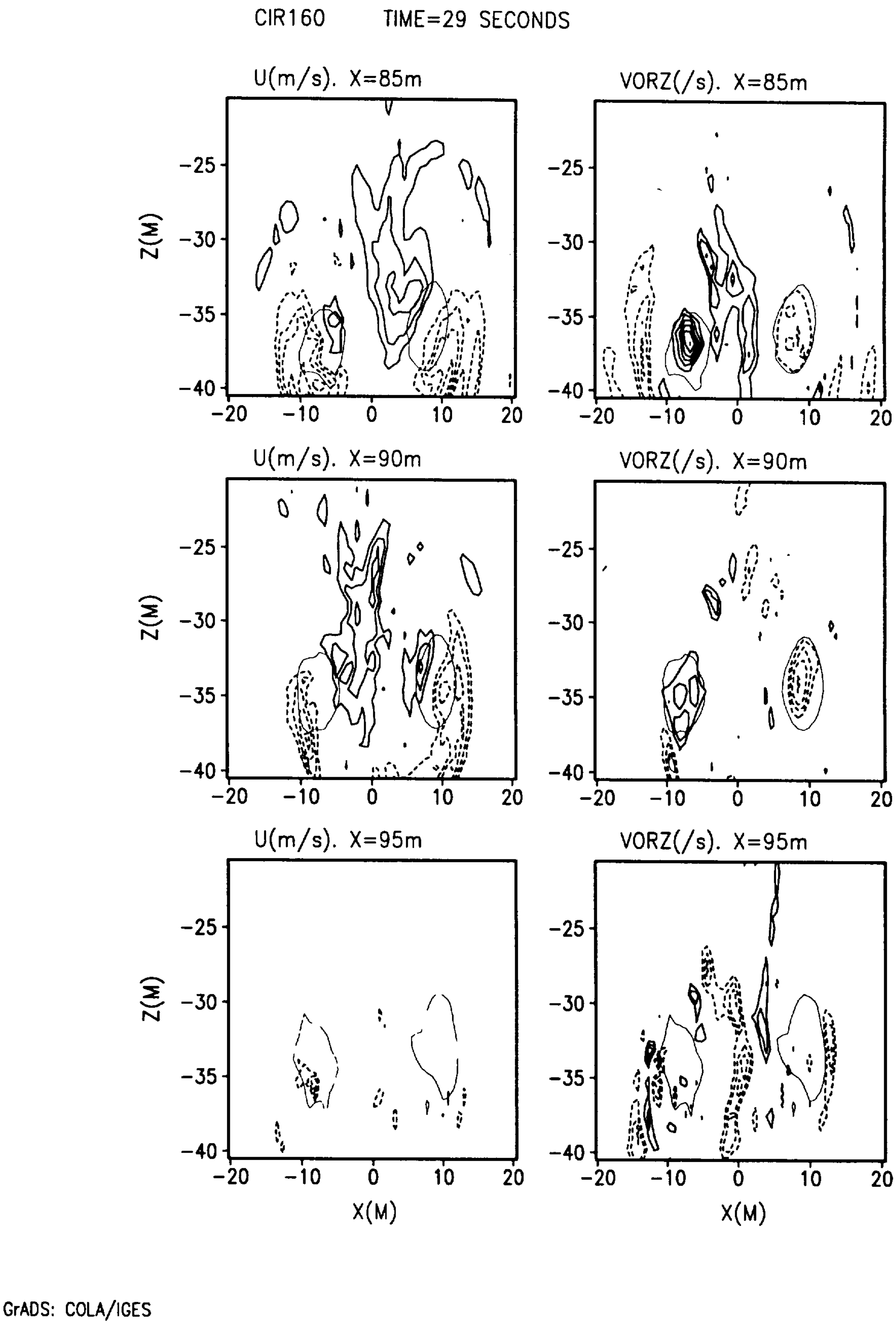
Dimensionless maximum axial velocity
|V_axial|/|V_max|
T
eta=0.135
eta=0.068
eta=0.5

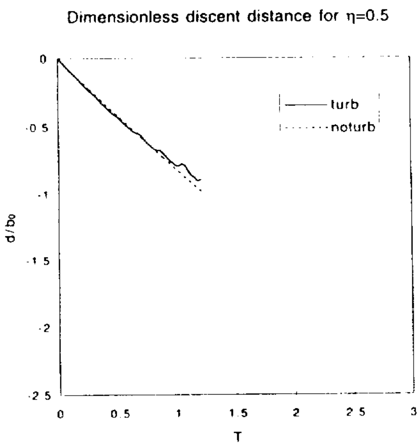



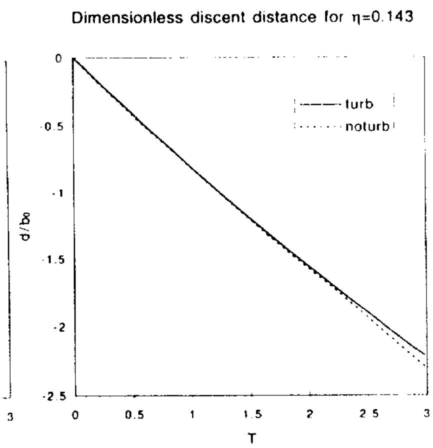
CIR160
TOP VIEW OF MAXMUM VALUE AT TIME=29 SECONDS
ENSTROPHY
AXIAL VELOCITY
Z-VORTICITY
Y(M)
X(M)
GrADS: COLA/IGES

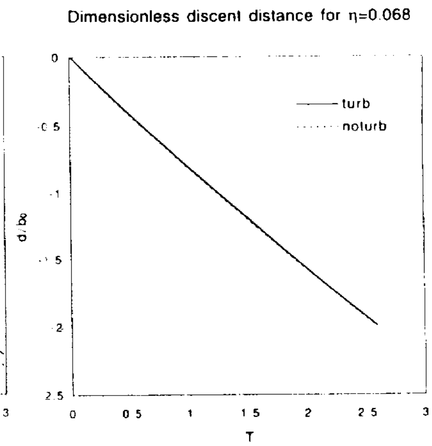


CIR160
TOP VIEW OF MAXMUM VALUE AT TIME=39 SECONDS
ENSTROPHY
AXIAL VELOCITY
Z-VORTICITY
Y(M)
X(M)
40
20
0
-20
-40
-150
-100
-50
0
50
100
150
GrADS: COLA/IGES


CIR160 TIME=29 SECONDS
U(m/s). X=85m
VORZ(/s). X=85m
U(m/s). X=90m
VORZ(/s). X=90m
U(m/s). X=95m
VORZ(/s). X=95m
Z(M)
X(M)
-25
-30
-35
-40
-20
-10
0
10
20
GrADS: COLA/IGES


Dimensionless discent distance for η=0.5
turb
noturb
d/bo
T
0
-0.5
-1
-1.5
-2
-2.5
0
0.5
1
1.5
2
2.5
3


Dimensionless discent distance for η=0.143
turb
noturb
d/bo
T
0
-0.5
-1
-1.5
-2
-2.5
0
0.5
1
1.5
2
2.5
3


Dimensionless discent distance for η=0.068
turb
noturb
d/bo
T
0
0.5
1
1.5
2
2.5
3

# Summary and Conclusion

* Crow instability can develop in most of atmospheric turbulence level, however, the ring vortices may not form in extremely strong turbulence case due to strong dissipation of the vortices
* It appears that a strong turbulence tends to accelerate the occurence of Crow instability
* The wavelength of the most unstable mode is estimated to be about $5b_0$, which is less than the theoretical value of $8.6b_0$ (Crow, 1970) and may be due to limited domain size and highly nonlinear turbulent flow characteristics.

* Three-dimensional turbulence can decay wake vortices more rapidly.

* Axial velocity may be developed by vertical distortion of a vortex pair due to Crow instability or large turbulent eddy motion.

* More experiments with various non-dimensional turbulence levels are necessary to get a useful statistics of wake vortex behavior due to turbulence.

* Need to investigate larger turbulence length scale effects by enlarging domain size or using grid nesting.

## *Acknowledgements*

- Super-Computer time from
  - North Carolina Supercomputer Center
  - NASA Langley
  - NASA Ames
- This research is sponsored by NASA Langley Research Center

**Questions and Discussions Following Martin Han's Presentation (North Carolina State University)**

Fred Proctor (NASA Langley)
In your plots of vortex decay of circulation, it seems you were seeing more of a linear decay rather than a sudden transitioning decay.

Han
I averaged along direction. The individual vortices may be more random.

Philippe Spalart (Boeing)
Do the left and right vortex touch on the centerline?

Han
They do.

Spalart
What was the circulation Reynolds number?

Han
Reynolds numbers were quite high. Order of about $10^7$.

Spalart
You were plotting average circulation. Can you explain what that is?

Proctor
Isn't it a 10 meter circulation you are plotting?

Han
I averaged along axel direction. This is at 10 meters radius. This one is at 5 meters.

Spalart
Since your vortices are developing waves, and your average circulation is dropping, the true circulation around the vortex is not.

Han
I find the location over every vortex, then at some radius average slice of vortex along the vortex axis.

Spalart
If you were to draw a contour around the vortex, with contour coming down the centerline and if you took circulation around that large contour, would that circulation decay or not?

Han
Yes, if you took large radius, I think I would be no different from 2D simulation. I think

atmospheric turbulence diffuses vortex strength.

Proctor
Does core size change much with time?

Han
Yes, I think core size changes and becomes larger. I need to look at this in more detail.

510-02

048093

318616

24p

# 1st NASA Wake Vortex Dynamic Spacing Workshop

## *Large Eddy Simulations of Rebound and Aging of Three-Dimensional Wake Vortices Within the Atmospheric Boundary Layer*

**Alexandre CORJON, Denis DARRACQ**
**and**
**Frédéric DUCROS**

**NASA LaRC, Hampton (VA)**

**May 13, 1997**

MFLAME project BE-1541

CERFACS

# OUTLINE

- **MFLAME Project**
- **Real test-cases**
  - ✓ **Idaho Falls experimental data**
  - ✓ **Increase or decrease of the descent velocity**
- **Idealized test-cases**
  - ✓ **Aging due to turbulence**
  - ✓ **Ground effect with 3D wind**
  - ✓ **Crow instability near the ground**
- **Theoretical modelling**
- **Lidar Simulation**
- **Concluding remarks**

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# MFLAME PROJECT

MFLAME: Multifunction Future Laser Atmospheric Measurement Equipment (Industrial and Materials Technologies – Brite/Euram III)

- Task objectives:
  - ✓ wake vortex, dry windshear, clear air turbulence, volcanic ash, gust alleviation, mountain rotors and dry hail predictive detection.
  - ✓ Demonstrate wake vortex detection by means of a series of ground and flight tests of a 2μm LIDAR system.
  - ✓ Improve the techniques and technologies for a cost effective equipment .
  - ✓ Investigate operational aspects (integration, certification,...).
- Consortium comprises:

SEXTANT Avionique and GEC Marconi Avionics, SOFREAVIA, CERFACS, DLR, University College of Galway, University of Hamburg, INESC

and a "User Club" attached to the project as "associated partners" (Airliners, aircraft manufactures, airports, and official authorities).

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# COMPLEX MODELLING

- Decay due to atmospheric turbulence
  - Donaldson and Bilanin 1975

    $\Gamma(t)=f(u',d_0,\Gamma)$
- New model by means of complex modelling and experiments
  - DNS too viscous flow but no approximation
  - LES more realistic flow conditions
- Two types of problems
  - Convective boundary layer: turbulence effects
  - Stable boundary layer: rebound effect

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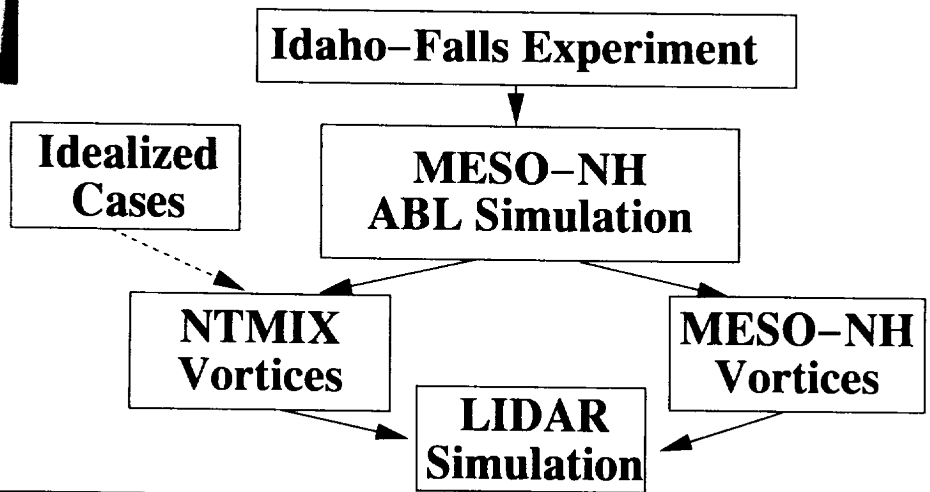
## SIMULATION PROCESS

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## LAMB OSEEN VORTEX

- Lamb–Oseen Vortex (Lamb, 1932)
  - ✓ Core radius $r_c$
  - ✓ Maximal velocity $V_o$

$$U_\theta(r)/V_o=\alpha\,(r_c/r)(1-e^{-\beta(r/r_c)^2})$$

- Q–Vortex (Lessen & Paillet, 1974)
  - ✓ Lamb–Oseen
  - ✓ Axial velocity $W_o$

$$U_z(r)/W_o=e^{-\beta(r/r_c)^2} \text{ and } W_o=\alpha\sqrt{\beta}/q\,V_o$$

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# MESO-NH

- Amospheric Simulation System (CNRM and LA)
  - ✓ large meso-alpha scale down to micro-scale
  - ✓ flexible file manager
  - ✓ facilities to prepare initial states (idealized or interpolated)
  - ✓ post-processing and graphical facility

- Hypothesis
  - ✓ Reynolds system with anelastic and Boussinesq approximations

    $d\rho / dt = 0$ and $w\, d\rho / dz = 0$
  - ✓ Wall function

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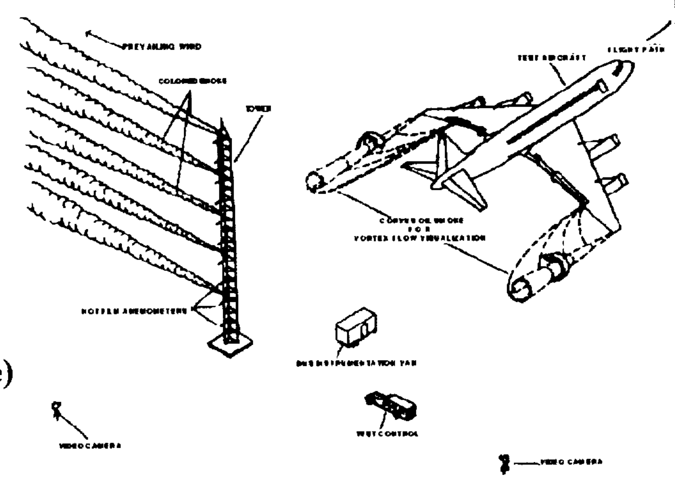
# IDAHO FALLS

Vortex measurements:
- ✓ LDV and MAVSS
- ✓ anemometers

Meteorological data:
- ✓ anemometers
- ✓ thermometers (tower & tethersonde)

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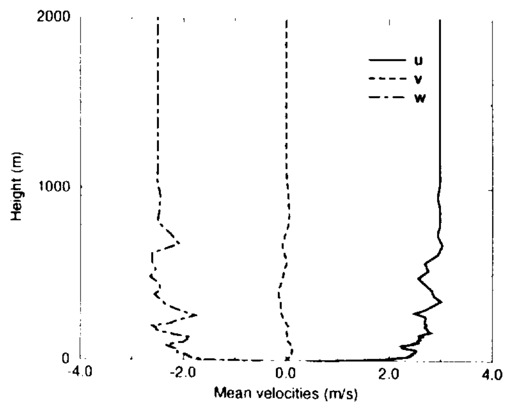
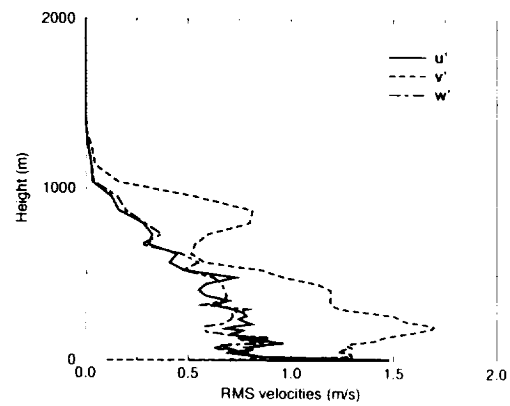
# BOEING 757 – RUN 30: ABL SIMULATION

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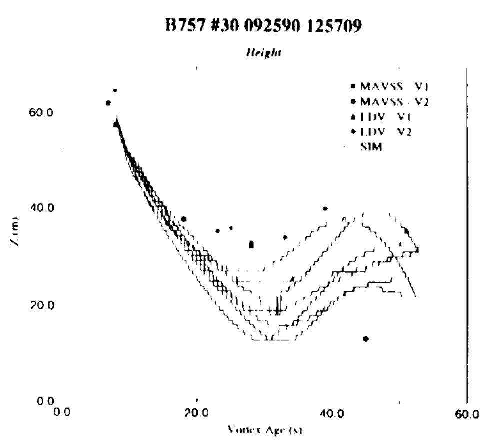
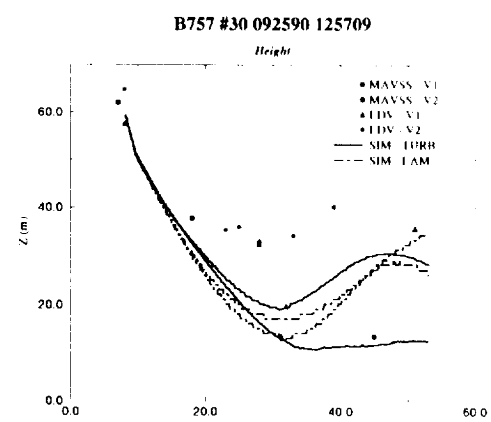
# RUN 30: 2D TURBULENCE EFFECTS

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# RUN 30: 3D SIMULATIONS

t=15s (23s)

t=30s (38s)

MFLAME project

BE–1541

# RUN 30: Iso–Surface of $\lambda_2$

t=15s (23s)

MFLAME project

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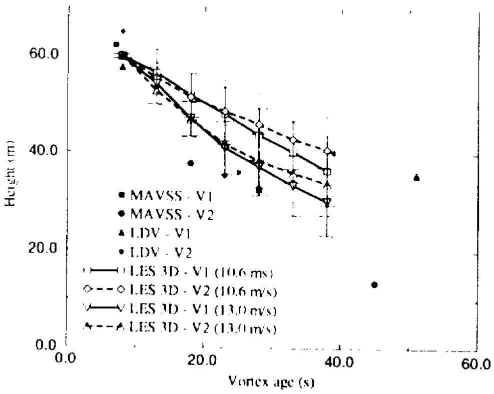
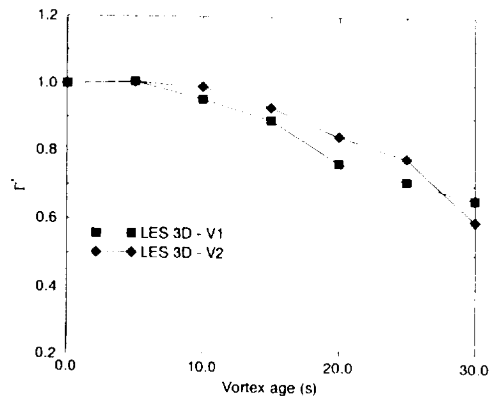
# RUN 30: TRAJECTORIES and DECAY

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# NTMIX3D

- Fully compressible 3D Navier–Stokes
- High–order compact scheme (Lele 92)
- Third order Runge–Kutta
- New way to define boundary conditions
  - ✓ NSCBC (Poinsot–Lele 92)
  - ✓ Periodic assumption no more required

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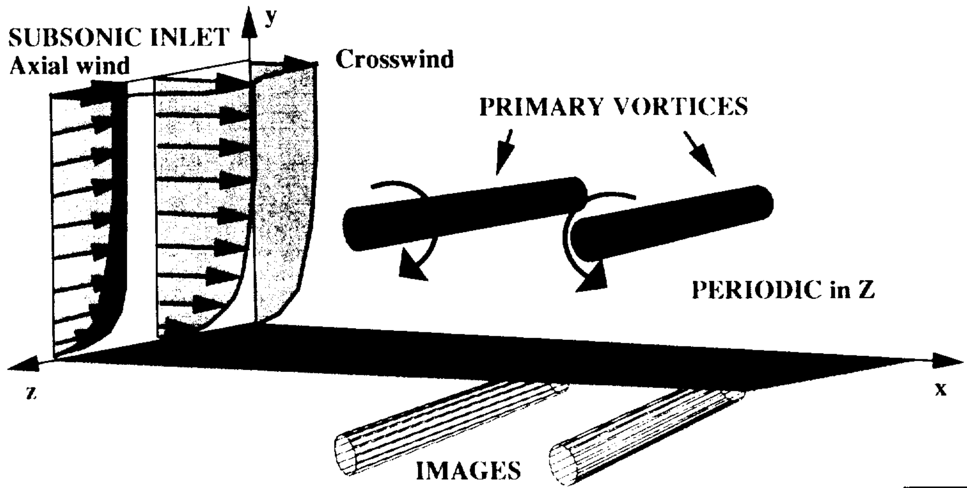
# COMPUTATIONAL DOMAIN

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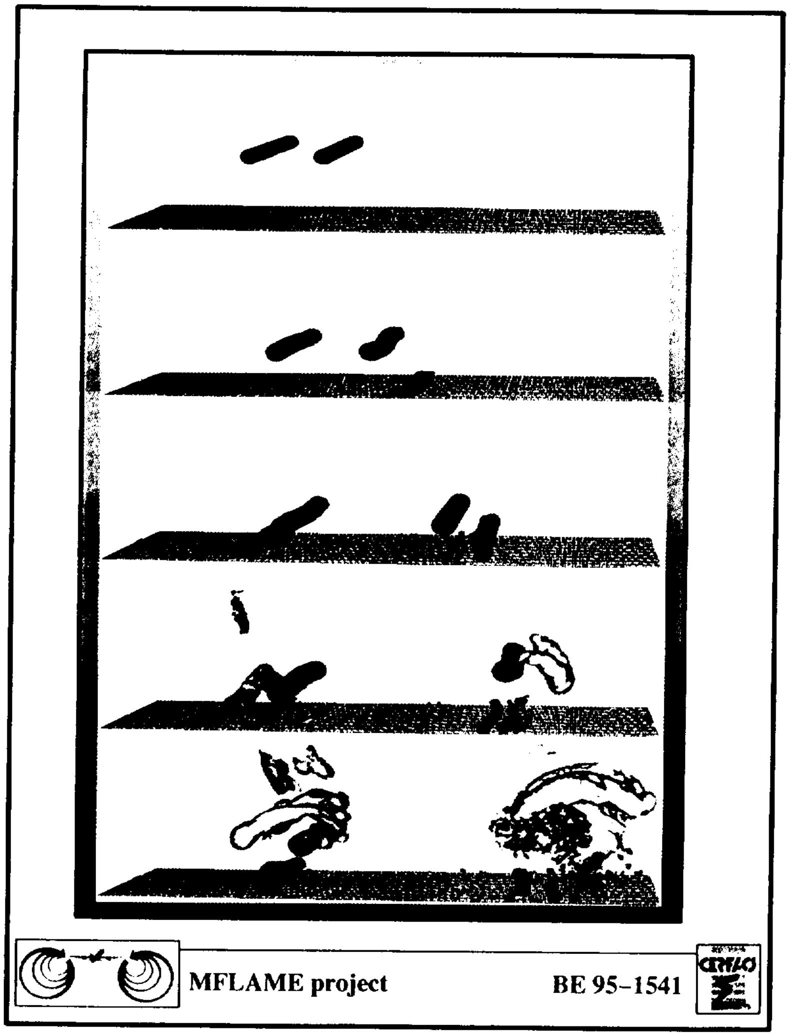
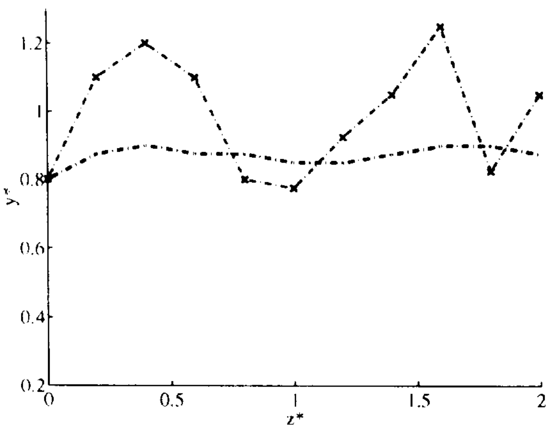
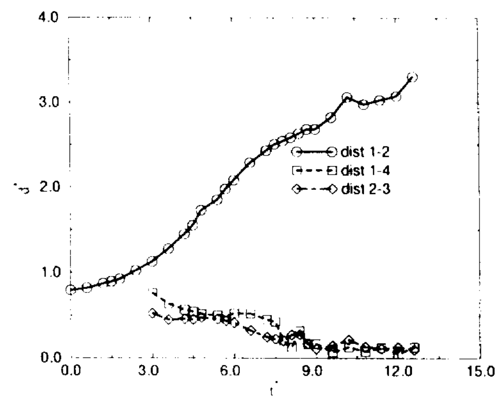

MFLAME project
BE 95-1541

# THREE-DIMENSIONAL REBOUND

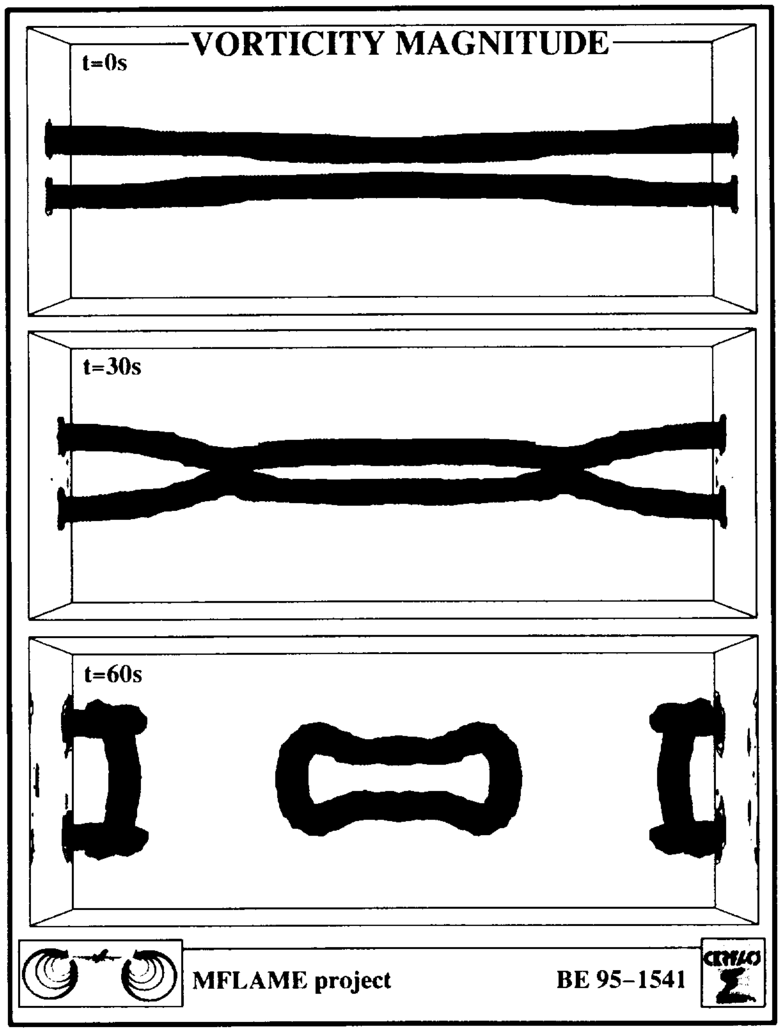
## $\alpha_{wind}$=45°

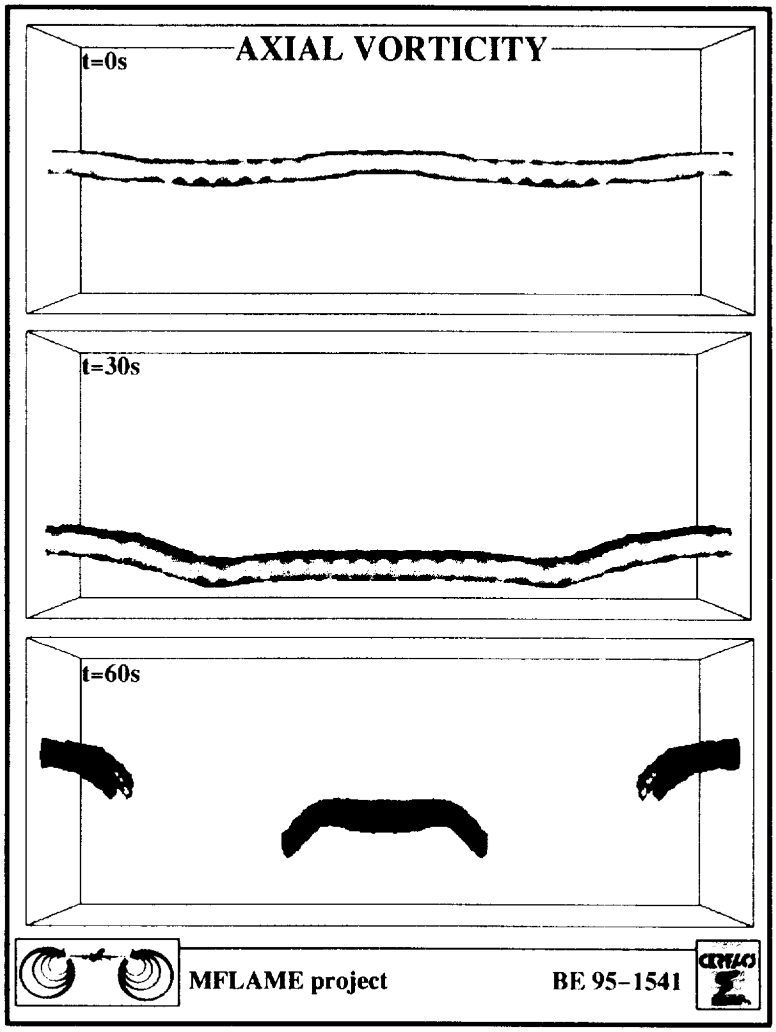


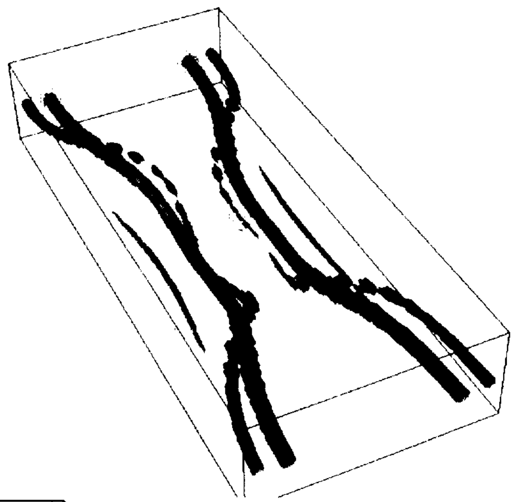

MFLAME project

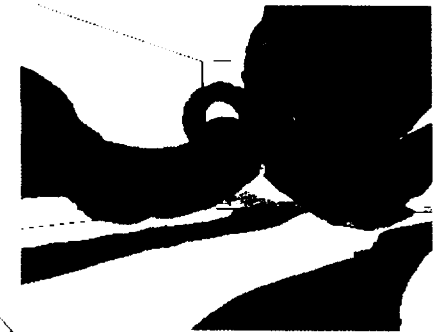
BE-1541


VORTICITY MAGNITUDE
t=0s
t=30s
t=60s
MFLAME project
BE 95-1541


AXIAL VORTICITY
t=0s
t=30s
t=60s
MFLAME project
BE 95-1541

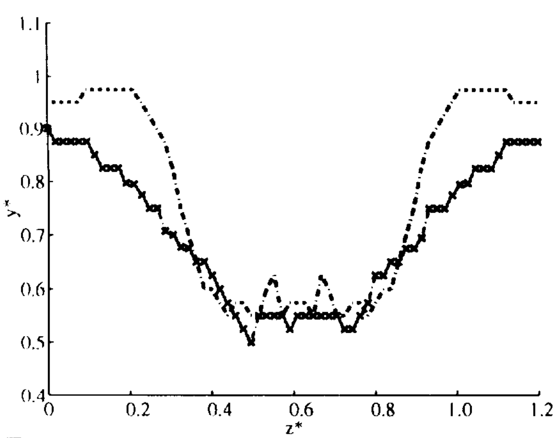
# CROW INSTABILITIES NEAR GROUND

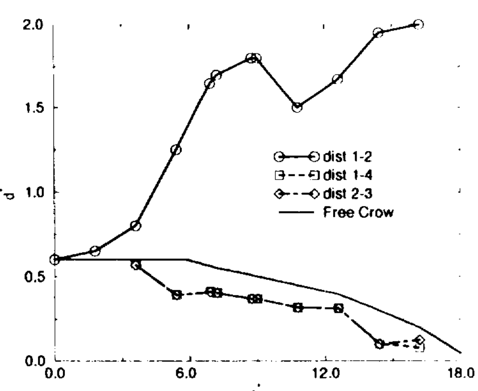




MFLAME project BE-1541

# CROW INSTABILITIES NEAR GROUND



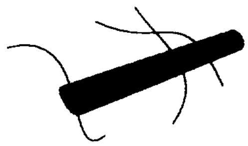




MFLAME project BE-1541

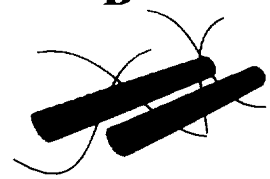
# NEW THEORETICAL MODEL

- **Principles of the simulations**

**A**

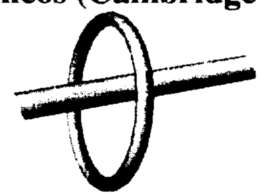


**B**



- **New model developed with C. Vassilicos (Cambridge Univ.)**

$\Gamma(t)=f(u',\Lambda,\Omega_0,r_c,d_0,\Gamma)$



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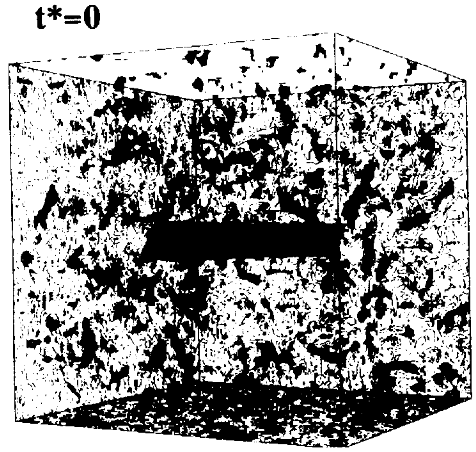
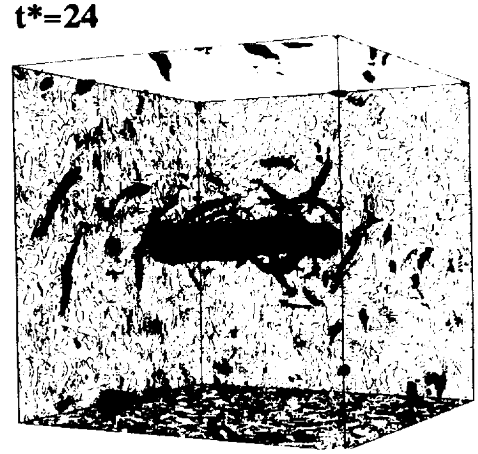
# SINGLE VORTEX

**t*=0**



**t*=24**



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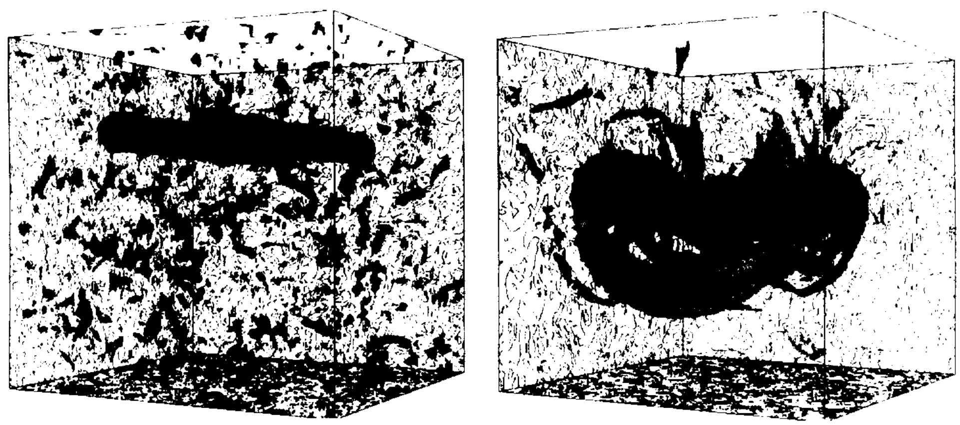
# VORTEX PAIR




MFLAME project

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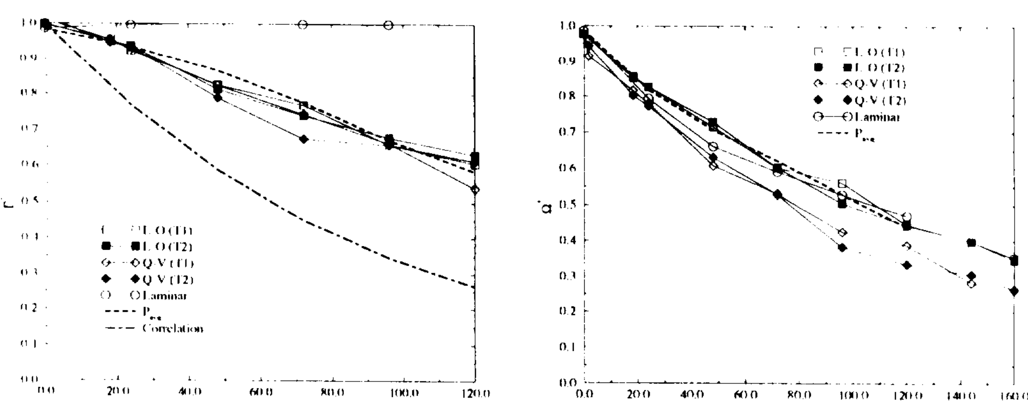
# STATISTICS




MFLAME project

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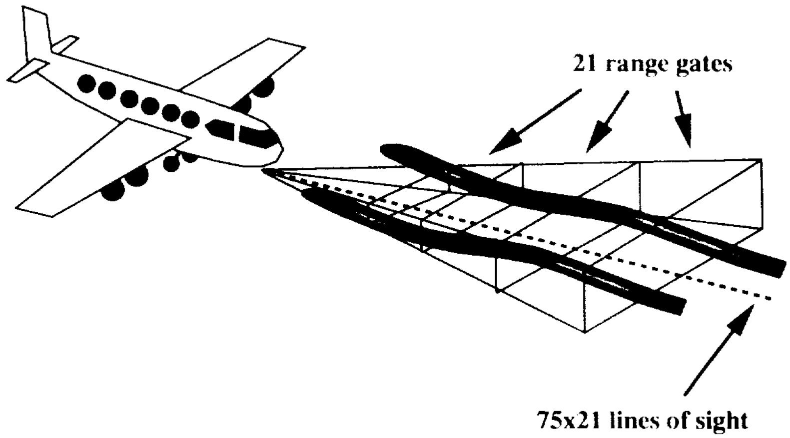
# LIDAR SIMULATION

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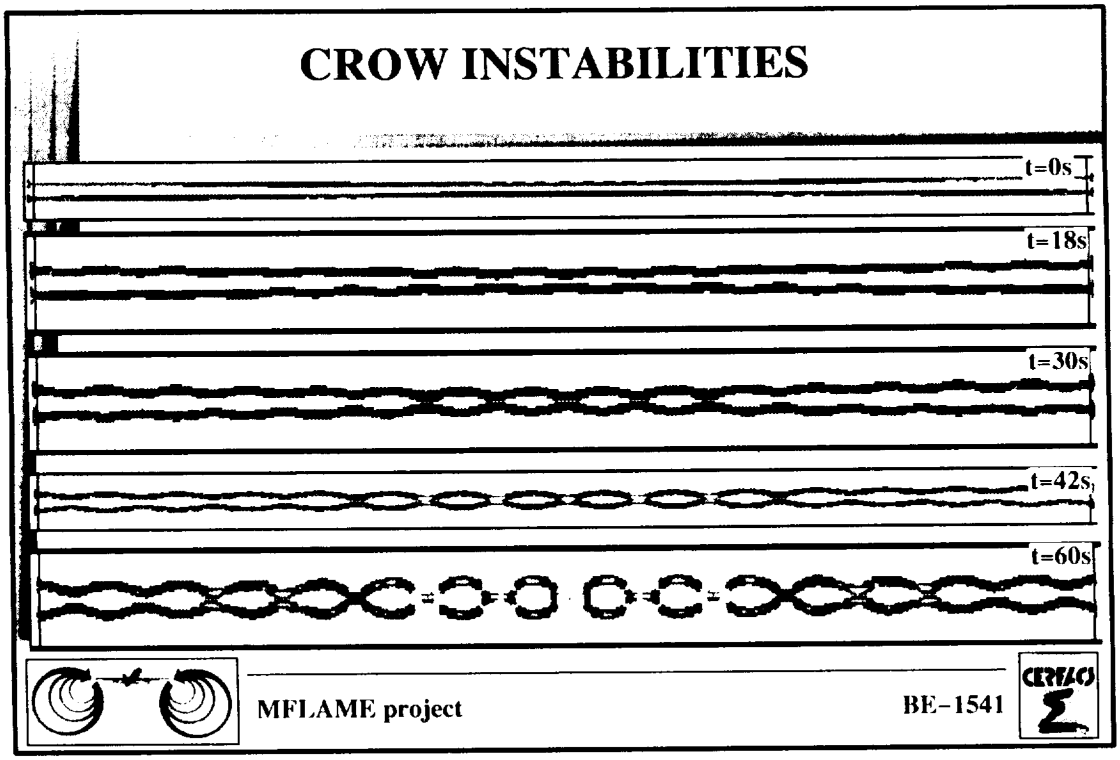
# RUN 30: LIDAR SIMULATIONS

t=15s (23s)

t=30s (38s)

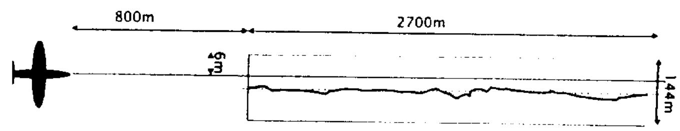
MFLAME project BE-1541


CROW INSTABILITIES
t=0s
t=18s
t=30s
t=42s
t=60s
MFLAME project
BE-1541

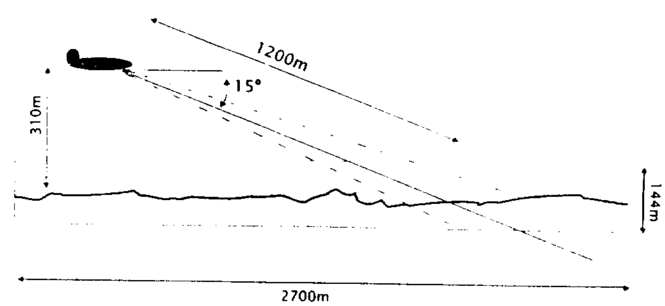
**SIMULATION OF PULSED LIDAR**

*University College Galway (IRL)*

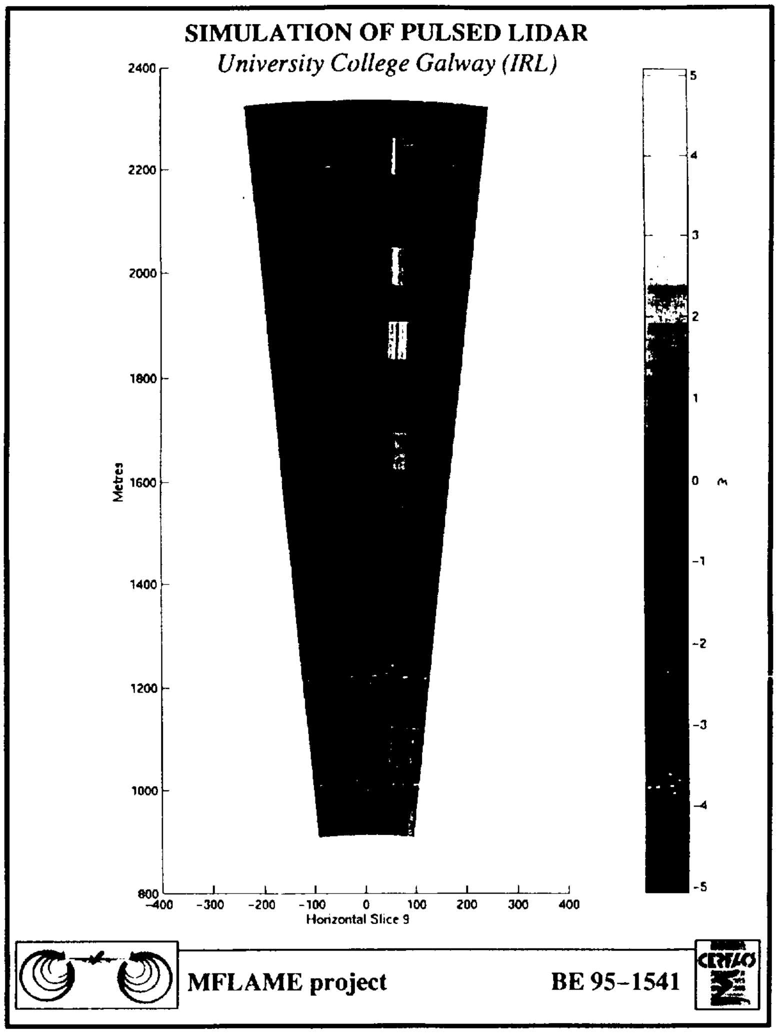
Case 1: Head on Vortex Encounter (plan view)

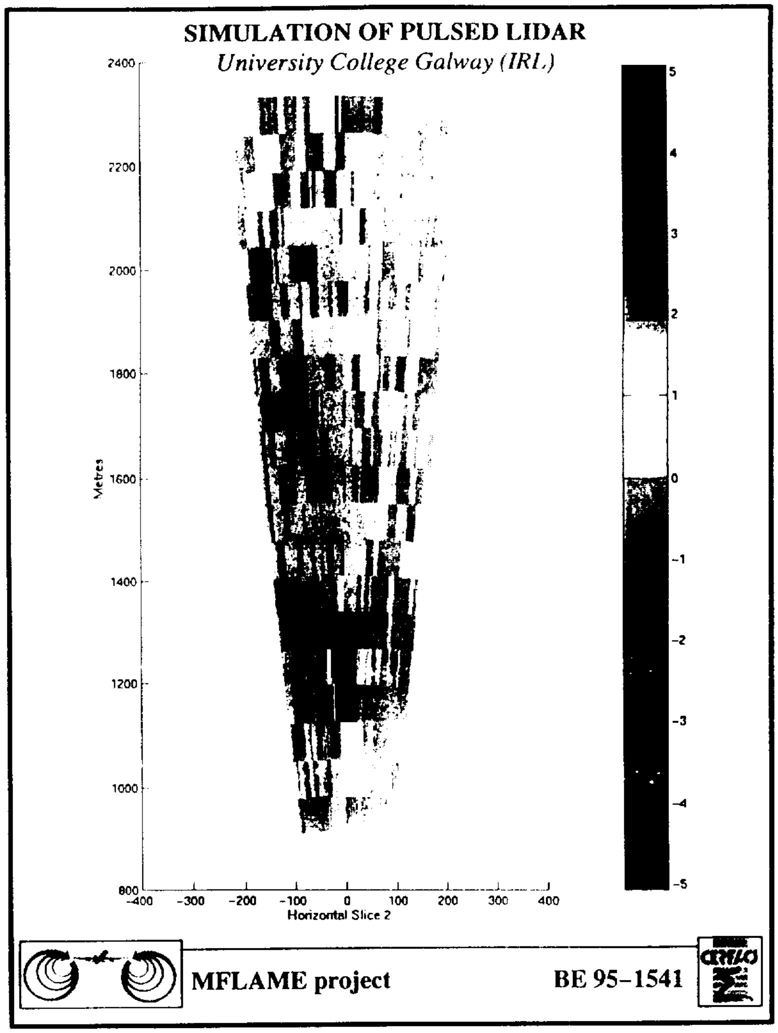



Case 2: Proposed Flight Test Scenario (side view)




**MFLAME project** **BE 95-1541**


SIMULATION OF PULSED LIDAR
University College Galway (IRL)
Metres
Horizontal Slice 9
MFLAME project
BE 95-1541


SIMULATION OF PULSED LIDAR
University College Galway (IRL)
2400
2200
2000
1800
1600
1400
1200
1000
800
Metres
-400 -300 -200 -100 0 100 200 300 400
Horizontal Slice 2
5
4
3
2
1
0
-1
-2
-3
-4
-5
MFLAME project
BE 95-1541

## CONCLUDING REMARKS

- Development of a new aging model
- 2D simulations => 3D mandatory
- 3D simulations compared to experimental cases
  - ✓ Convective ABL: completed, two aircraft types
  - ✓ Stable ABL: in progress
- 3D simulations in idealized cases
  - ✓ Atmospheric turbulence effects
  - ✓ Effects of ground and wind
  - ✓ Crow instability near the ground
- New theoretical model of turbulent aging in development
- LIDAR simulations: up to 21 range gates (≅ 2.7km)

MFLAME project BE-1541

## CONCLUDING REMARKS

- Participation to EUROWAKE (Brite/Euram III - basic research program for the near field wake)
- Thematic Networks "Wake Vortex"
- New proposal "WAVENC"

  WAke Vortex Evolution in the far wake region and
  WAke Vortex ENCounter
  (NLR, AS, RED Scientific, DLR, ONERA, CERFACS, IST, TsAGI)
- European Commission is waiting for a letter of FAA

  "Wake Vortex" could be selected as a US-CEE common research project

MFLAME project BE-1541

**Alexandre Corjon (CERFACS)**

Leo Staton (Research Triangle Inst.)
Can you go back up to the slide you showed of lidar simulation, what are we seeing?

There is a lack of velocity in the core.

**Questions and Discussions Following Alexandre Corjon's Presentation (CERFACS)**

Leo Staton (Research Triangle Institute)
Could you go back to the color slide you showed of lidar simulation, and describe what lidar target is? What are we seeing on this chart? Is that a chart of intensity returned to lidar?

Corjon
It is velocity measured by lidar. What you see is absence of velocity in core of vortex. In doing simulation we assume there is no velocity in core and all the velocity we find is between the vortices.

Staton
So these are axial velocities we are looking at?

Corjon
Axial velocities is between two vortices. We think that is due to the eddies that surround primary vortices and create axial velocity. Also, there is axial velocity due to curvature of vortices.

Greg Winckelmans (GSW Consulting Services)
In 3-D computation near the ground that you showed, is there a no-slip ground or is it a slip ground?

Corjon
No-slip ground.

Winckelmans
So the computation is not periodic with respect to ground?

Corjon
Not periodic. There is only one direction periodic, the axial direction.

Winckelmans
Why do you have images then?

Corjon
Only at initiation. I always put image vortices because you have to pay attention near the ground to properly initialize vortices to put slip conditions of the world and put damping functions on velocity.

Winckelman
If you are interested, I can show you a numerical way of putting proper vortex sheet on the ground that will ensure no slip without funny games of image. There is a way of doing it exactly, analytically.

Alexander Praskovsky (National Center for Atmospheric Research)
Again the same color slides of what lidar sees. This is continuation of the previous question about lidar. How did you simulate? Did you take into account moving aircraft? What was your scanning pattern, speed of lidar scanning, and so on? How can you produce such a nice picture?

Corjon
I don't do this job. It was the University of Gerwach. I did the 3-D simulation of wake vorticity. There is no effect of speed of aircraft. We do not move grid like Fred Proctor. We look at two vortices that descent at us. We look at constant age vortex.

Praskovsky
How does the lidar look? This is an extermely important question.

Corjon
This one looks in the actual direction in the axis of vortices.

Praskovsky
But lidar can only see radical not normal velocity component.

Corjon
We have profile and afterward we compute the radial velocity and the velocity of sight along lidar.

Klaus Sievers (Germans Pilot Association)
You work seems to consist of two parts. First, a big part is simulation and the second part is development of something airborne. I would like to know something of the time scale. When can I expect to have something in the aircraft? What warning time will it be able to provide to me in the cockpit? Will it be able to look through haze?

Corjon
You want the official time scale. The project will end in 1999. I don't think airborne systems will be available then. There are also problems of certification of this type of system which takes a long time.

# AIRCRAFT WAKE VORTICES IN THE ATMOSPHERE



Thomas Gerz, Frank Holzäpfel
Institute of Atmospheric Physics
DLR, Germany

Abstract

By means of large-eddy simulations dynamics are discussed which control the decay of the wake vortices of a subsonic aircraft under cruising conditions. The period between 1s and several minutes of wake age is considered. The method is briefly introduced. Emphasis is put on the effect of turbulence on the decay process of the wingtip vortices; thereby it is distinguished between background atmospheric turbulence and turbulence stemming from the boundary layer of the aircraft.

To introduce ongoing work at the Institute of Atmospheric Physics related to the current topic, some results of wake vortices measured during flight campaigns as well as results of large-eddy simulations of the convective atmospheric boundary layer are presented.

**Deutsche Forschungsanstalt für Luft- und Raumfahrt** e.V.

# AIRCRAFT WAKE VORTICES IN THE ATMOSPHERE

Thomas Gerz, Frank Holzäpfel

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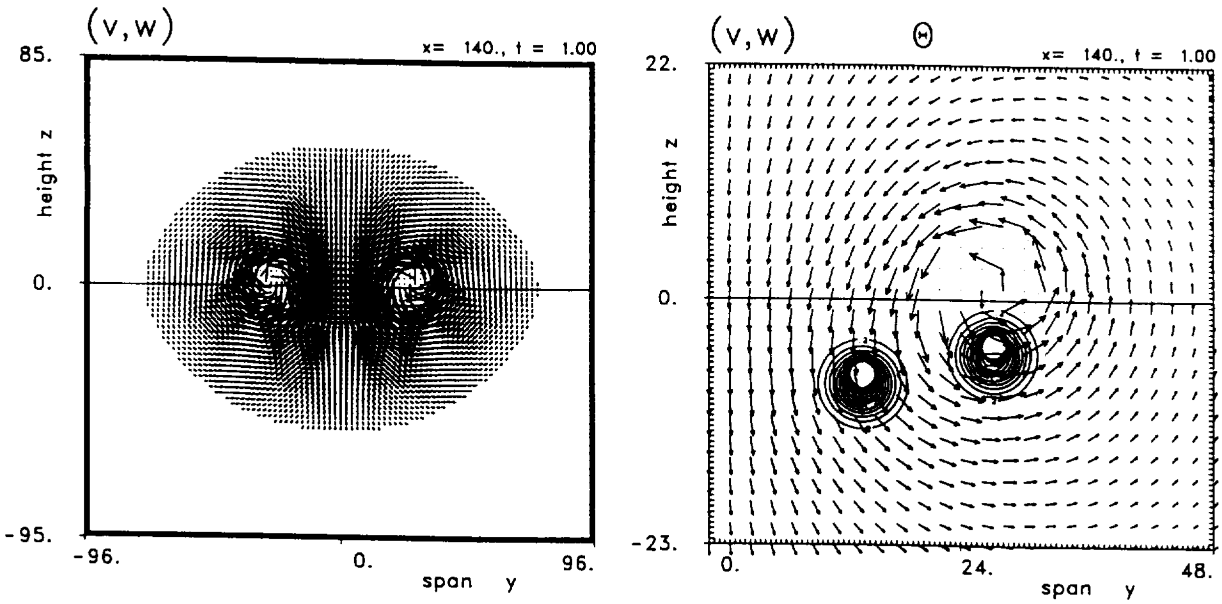
DLR Oberpfaffenhofen, Germany

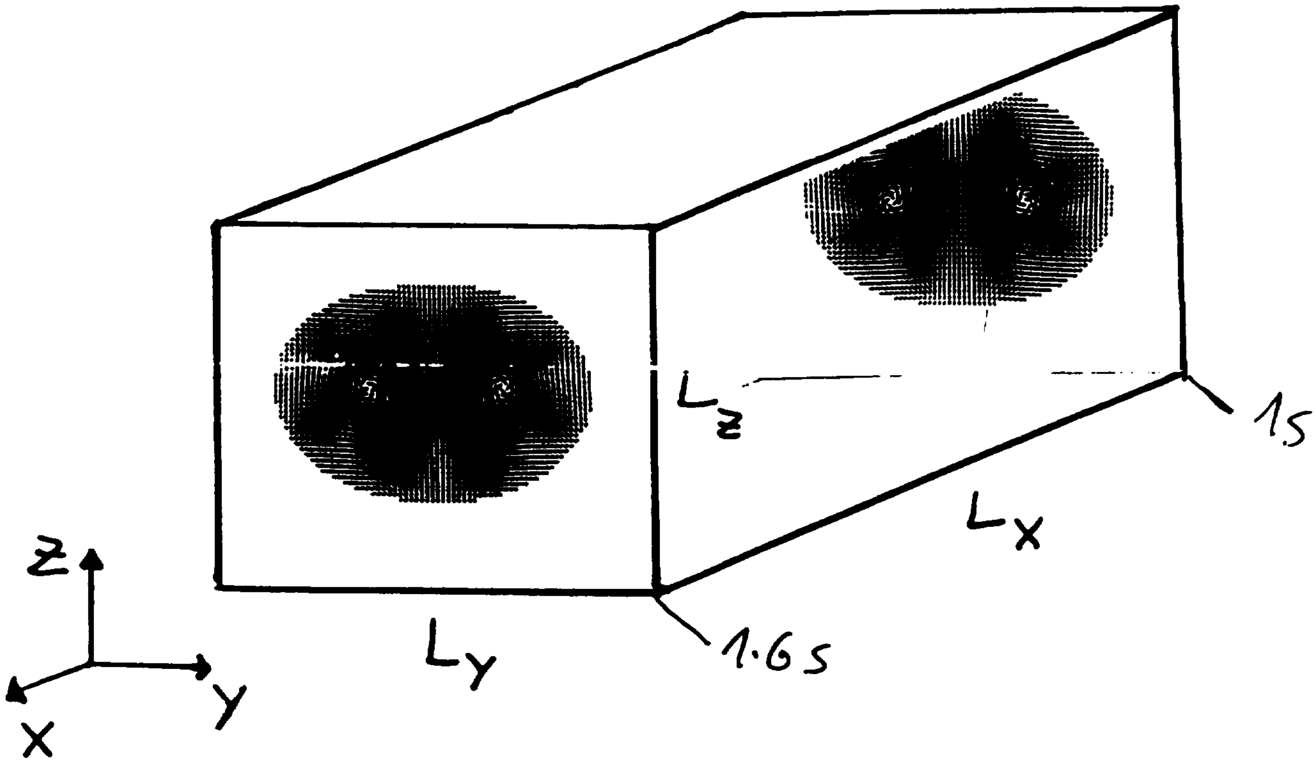
- The new wake vortex group
- Motivation
- Methods and Initialization
- Jet Regime
- Vortex Regime
- Flight Measurements
- Convective Planetary Boundary Layer
- Conclusions

DLR




The wake of a B-747 aircraft after 1s (initial fields for LES) in terms of swirl-velocity components $(v, w)$ (left, full domain) and potential temperature excess $\theta$ of the exhaust jets (right, close-up ) in span-height cross-sections. Vectors are displayed every fourth gridpoint between 1 and 13m/s. The black contours of $\theta$ range from 0.2 to 3K with increment of 0.2K and can be attributed to the bypass region; the white kernels inside approximately mark the jet cores with $\theta$ between 3 and 15K. The horizontal line represents the flight level. The Figure labels are in units of m and s for length and time.

# LES domains:




| | 1-7 sec | 7-157 sec |
|---|---|---|
| $L_x$ [m] | 160 | 408 |
| $L_y$ [m] | 192 | 256 |
| $L_z$ [m] | 180 | 540 |

| | 1-7 sec | 7-157 sec |
|---|---|---|
| $\Delta x$ [m] | 2.5 | 6.4 |
| $\Delta y$ [m] | 0.5 | 1.0 |
| $\Delta z$ [m] | 0.5 | 1.0 |
| $\Delta t$ [s] | 0.004 | 0.024 |

CPU time and memory on CRAY-J916:
70 hours and 1 GByte (for 1 simulation)

## Initialization of LES (after 1s):

### Aircraft–Induced Flow (from VFT)

| | | 1 sec | | 3 sec | | 6 sec | |
|---|---|---|---|---|---|---|---|
| | | VFT | LES | VFT | LES | VFT | LES |
| Vortex separation | [m] | 53 | 53 | 49 | 49 | 47 = $\frac{\pi}{4}B$ = | 47 |
| Core radius $R_C$ | [m] | 4.0 | 4.0 | 4.0 | 4.0 | 3.5 | 3.5 |
| Swirl velocity $V_C$ | [m/s] | 8.4 | 8.4 | 10.3 | 10.7 | 9.8 | 10.4 |
| Downwash velocity | [m/s] | -11.6 | -11.6 | -11.8 | -12.2 | -11.5 | -12.1 |

### Boundary-Layer Turbulence   cases B, A

$$(\mathrm{v_R}, \mathrm{w_R})(x, y, z) = 0.16\, \mathrm{V_C} \exp\left[-(1 - \frac{r}{\mathrm{R_C}})^2\right] \times \mathrm{ranf}(x, y, z)$$

Max = 16% $V_C$

### Atmospheric Conditions (POLINAT case)

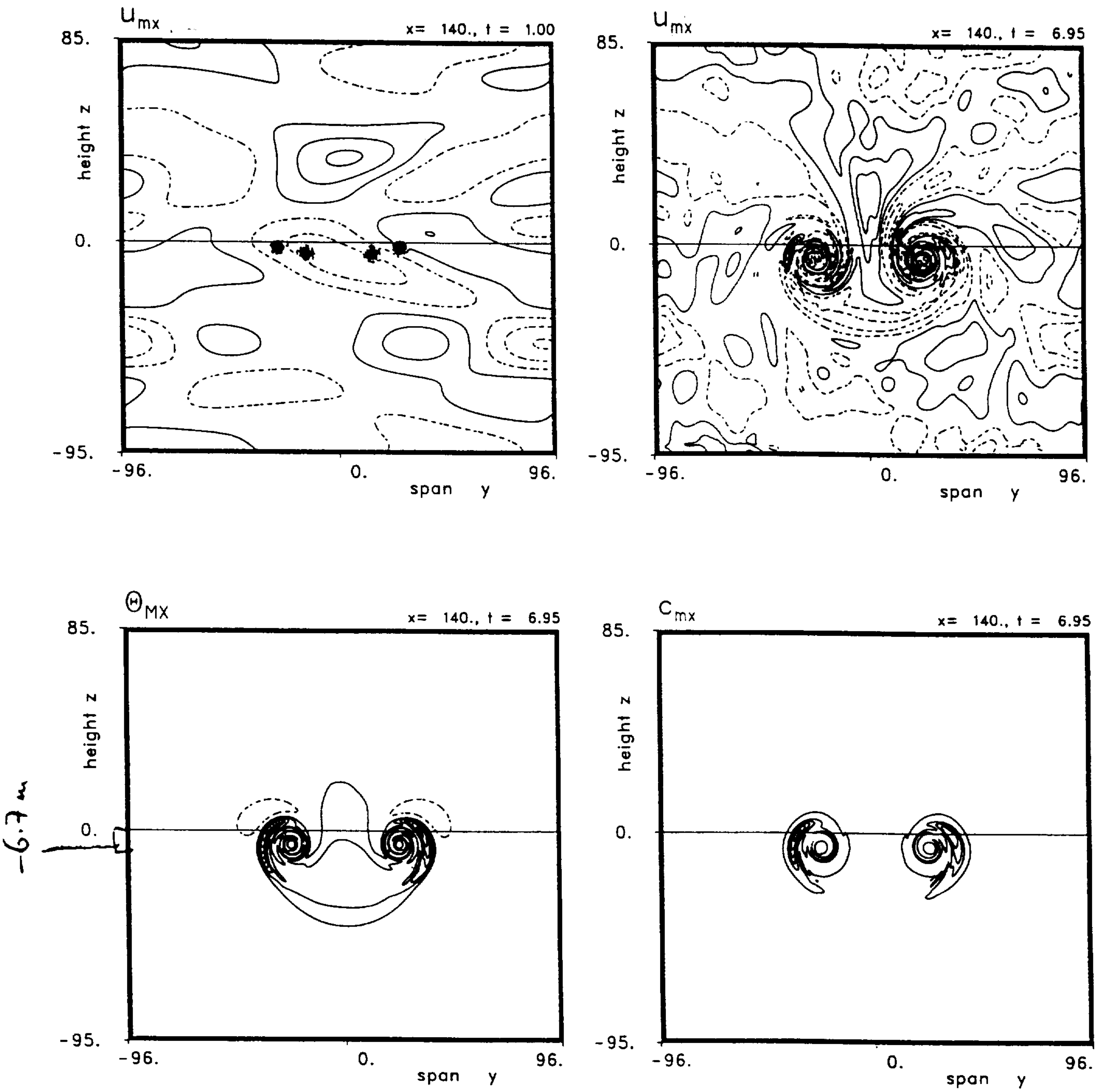
| | | |
|---|---|---|
| Height | [km] | 11.3 |
| Pressure | [hPa] | 216 |
| Density | [kg/m$^3$] | 0.35 |
| Temperature | [K] | 214.3 |
| Pot. Temperature | [K] | 332.1 |
| Stratification | [1/s] | 0.014 — cases N, B, A |
| Turbulence h/v | [m/s] | 0.38/0.21 → 0.03/0.017 $V_c$ } A |
| Eddy size | [m] | 50 ... 100 |

$\tau_{BV}$ = 7,5 minutes

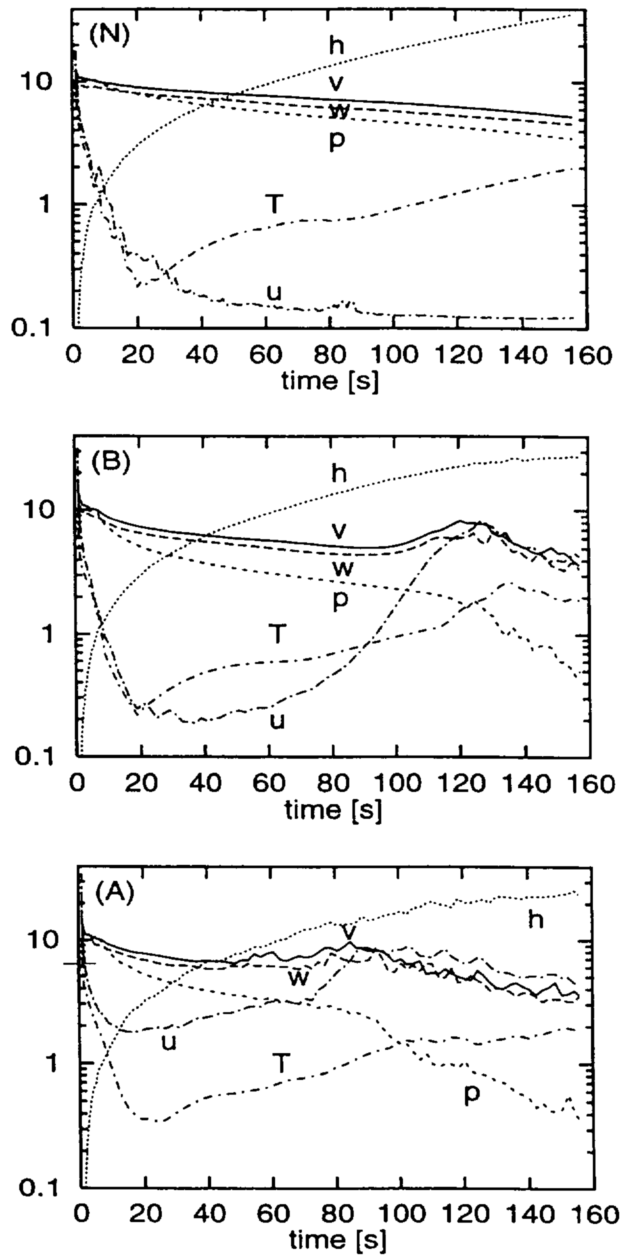
$\tau_{BV}/4 \simeq 112s$

$$Re := \frac{\Gamma}{\nu} = \infty$$

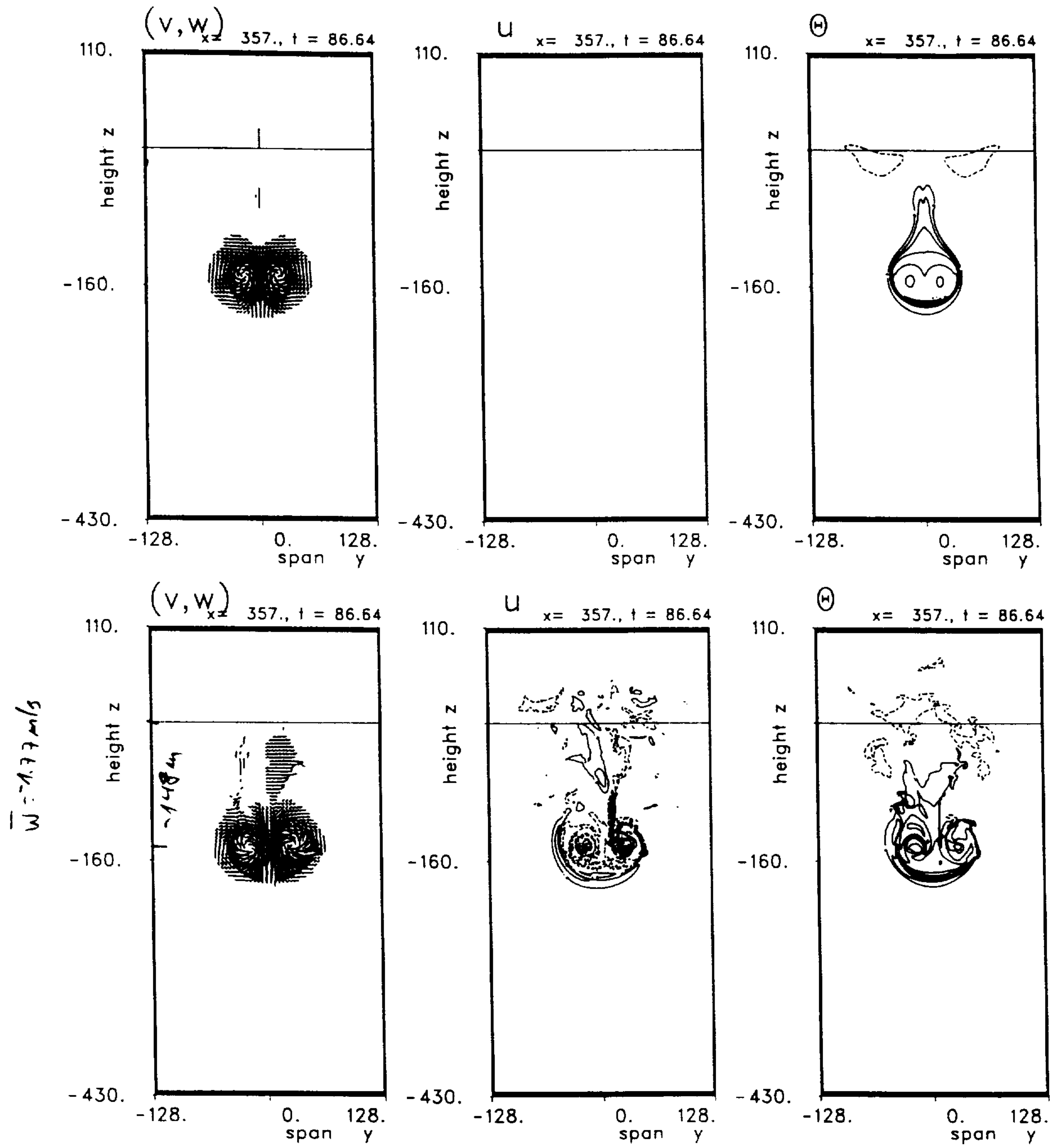
$$Re_{eff} = \frac{\Gamma}{\nu_t} \begin{cases} 700.000 & (N) \\ 70.000 & (A) \end{cases}$$



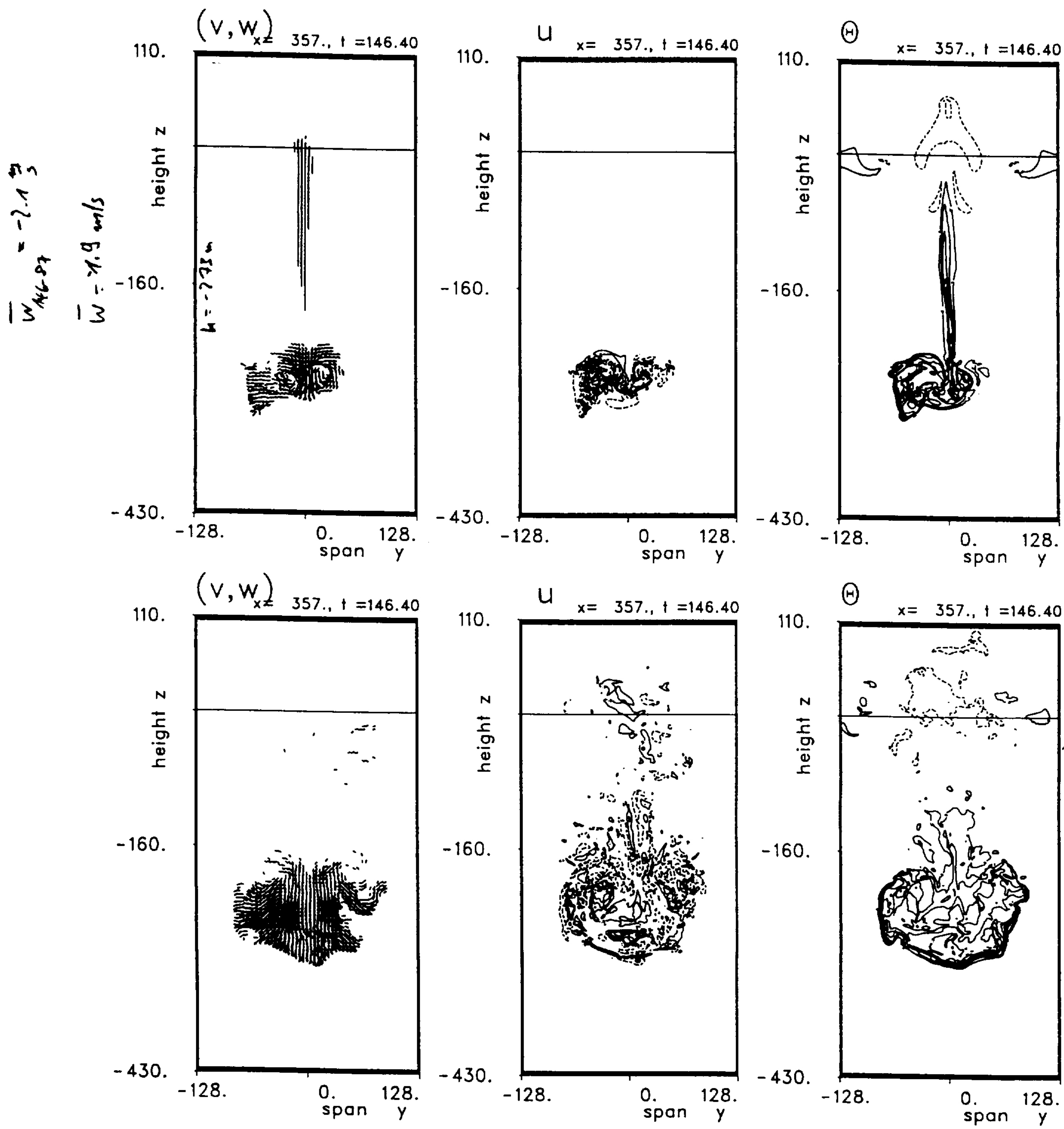

The early wake of case A in span-height cross-sections in terms of $u$ after 1 and 7s (top); $\theta$ and $c$ after 7s (bottom). All quantities are averaged over meshes in axial (flight) direction $x$. Contour increments: 0.1 m/s starting at $\pm$ 0.05 m/s for $u$; 0.1K starting at $\pm$0.1 K for $\theta$; $2 \times 10^{-4}$ starting at $0.05 \times 10^{-4}$ for $c$. Negative values are marked by dashed lines.



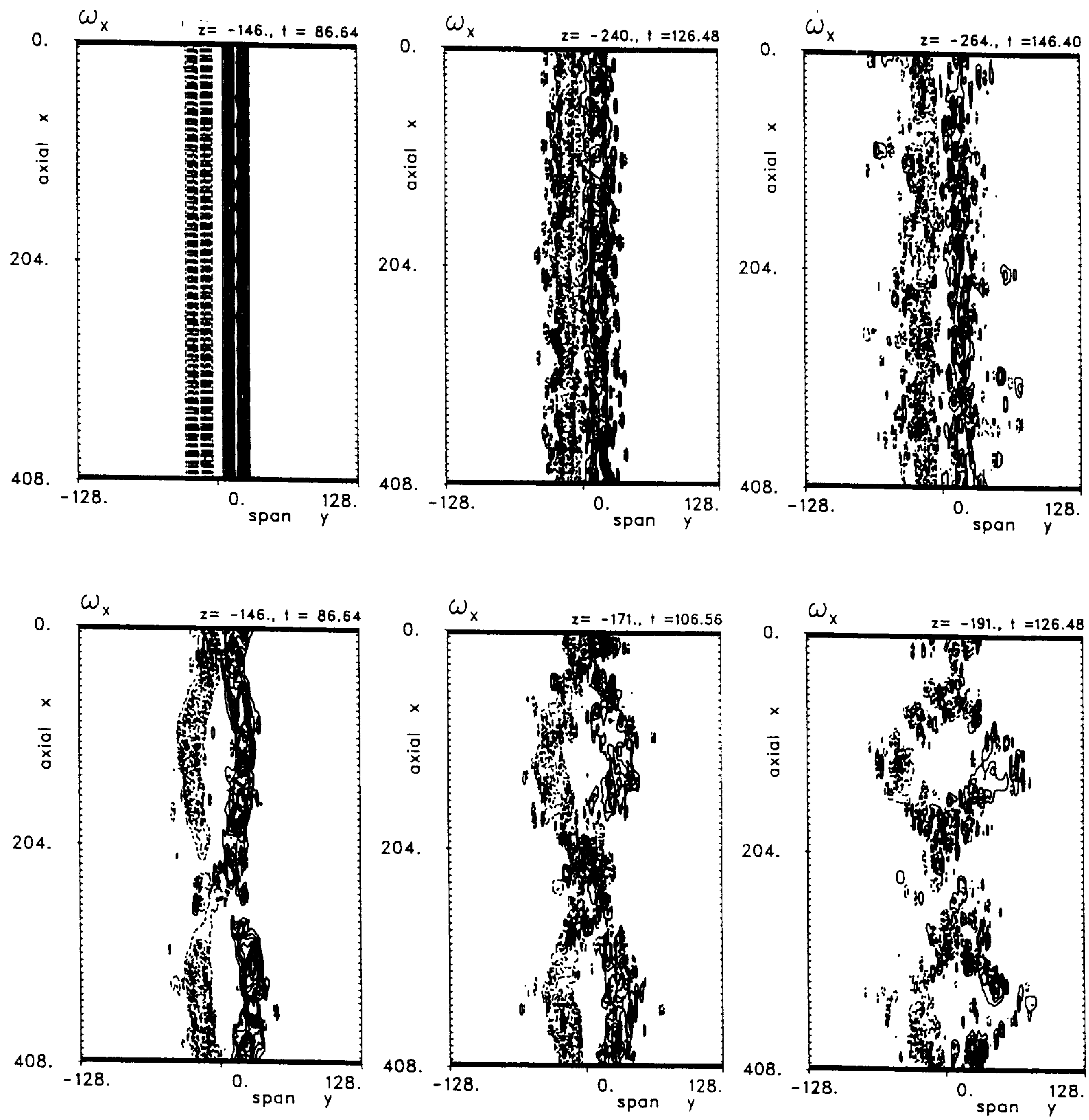

Timeseries of wake and jet flow quantities in a stably stratified atmosphere. N: no turbulence; B: aircraft boundary-layer turbulence; A: boundary-layer and atmospheric turbulence. Velocity maxima v, w [m/s]; pressure deviation minimum p (< 0) [dPa]; downward travelled distance h [dm]; velocity maximum u [m/s]; maximum of absolute temperature deviation T [K].



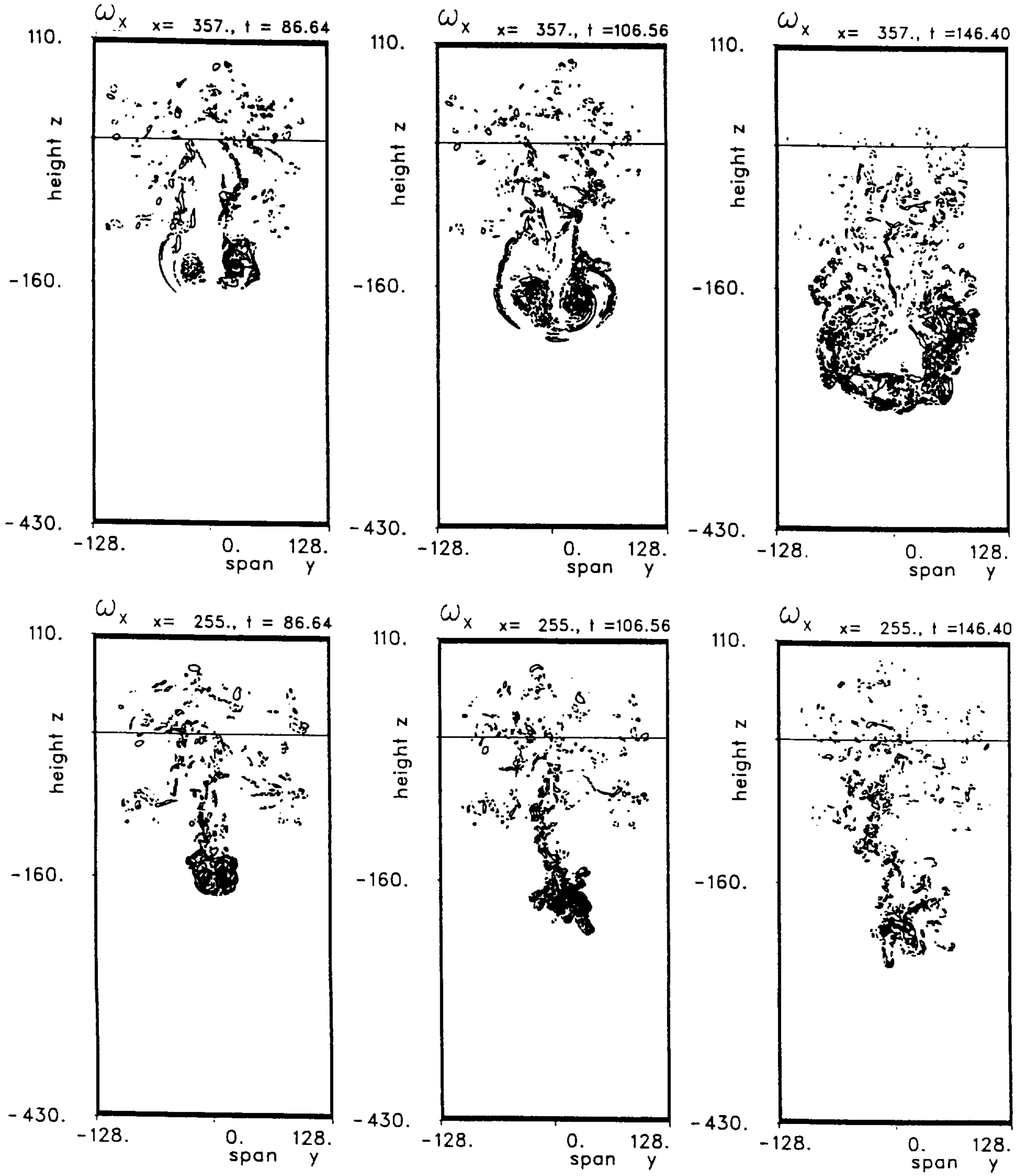

The instantaneous non-averaged wakes of case B (top) and A (bottom) after 87s in span–height cross-sections in terms of swirl velocity $(v, w)$ with magnitude $\geq 1\,\mathrm{m/s}$; axial velocity $u$ with increment $0.5\,\mathrm{m/s}$; and temperature deviation $\theta$ with increment 0.2K. Negative values are marked by dashed lines. The horizontal line represents the flight level. The Figure labels are in units of m and s for length and time.



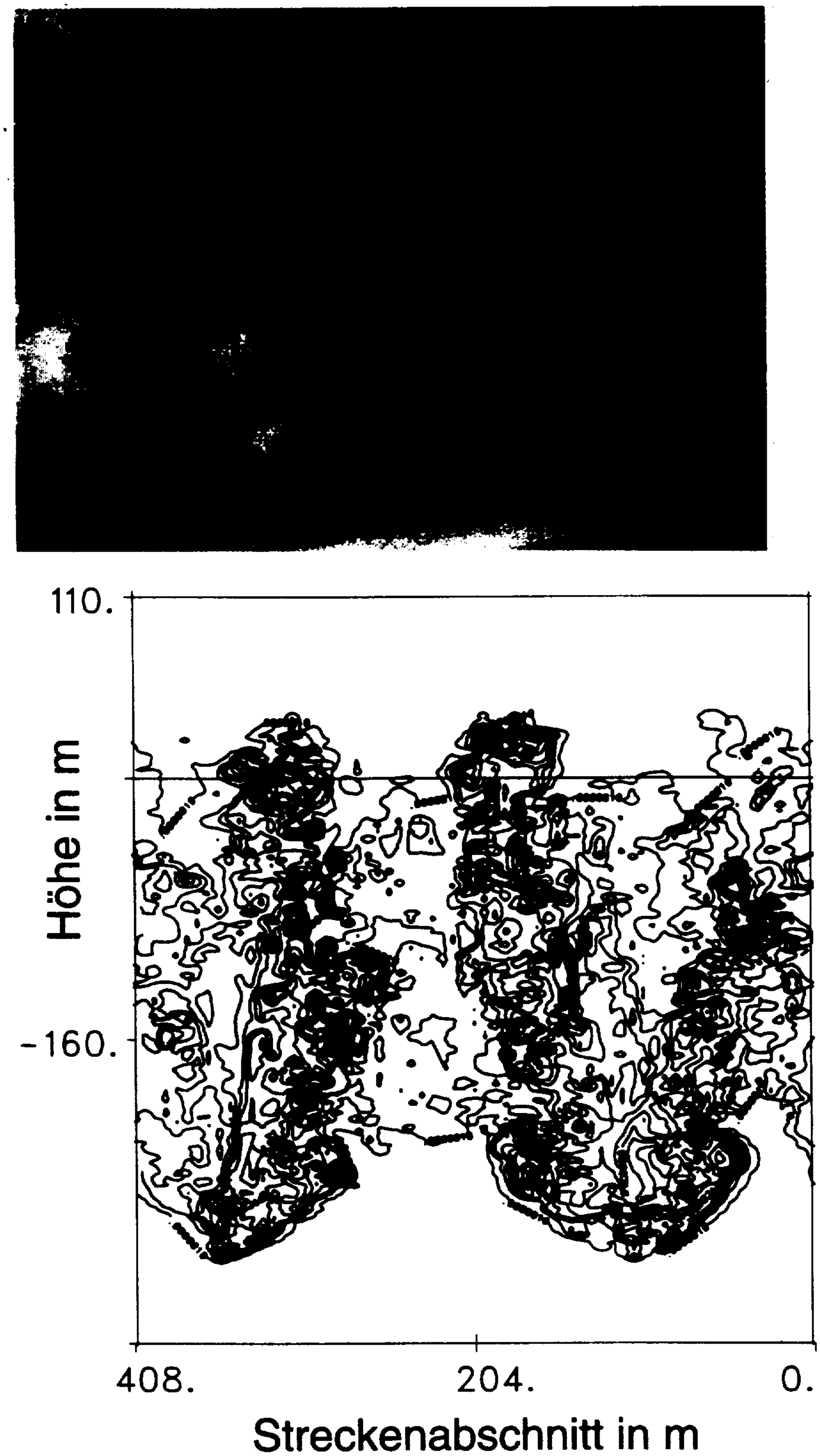

The wakes of case B (top) and A (bottom) after 146s. Legend as in the previous Figure.




Span–axial cross-sections of axial vorticity $\omega_x$ for wakes B (top) and A (bottom) for several instants of time and vertical positions. Contour interval is $1s^{-1}$. The left vortex (dashed contours) rotates clockwise.



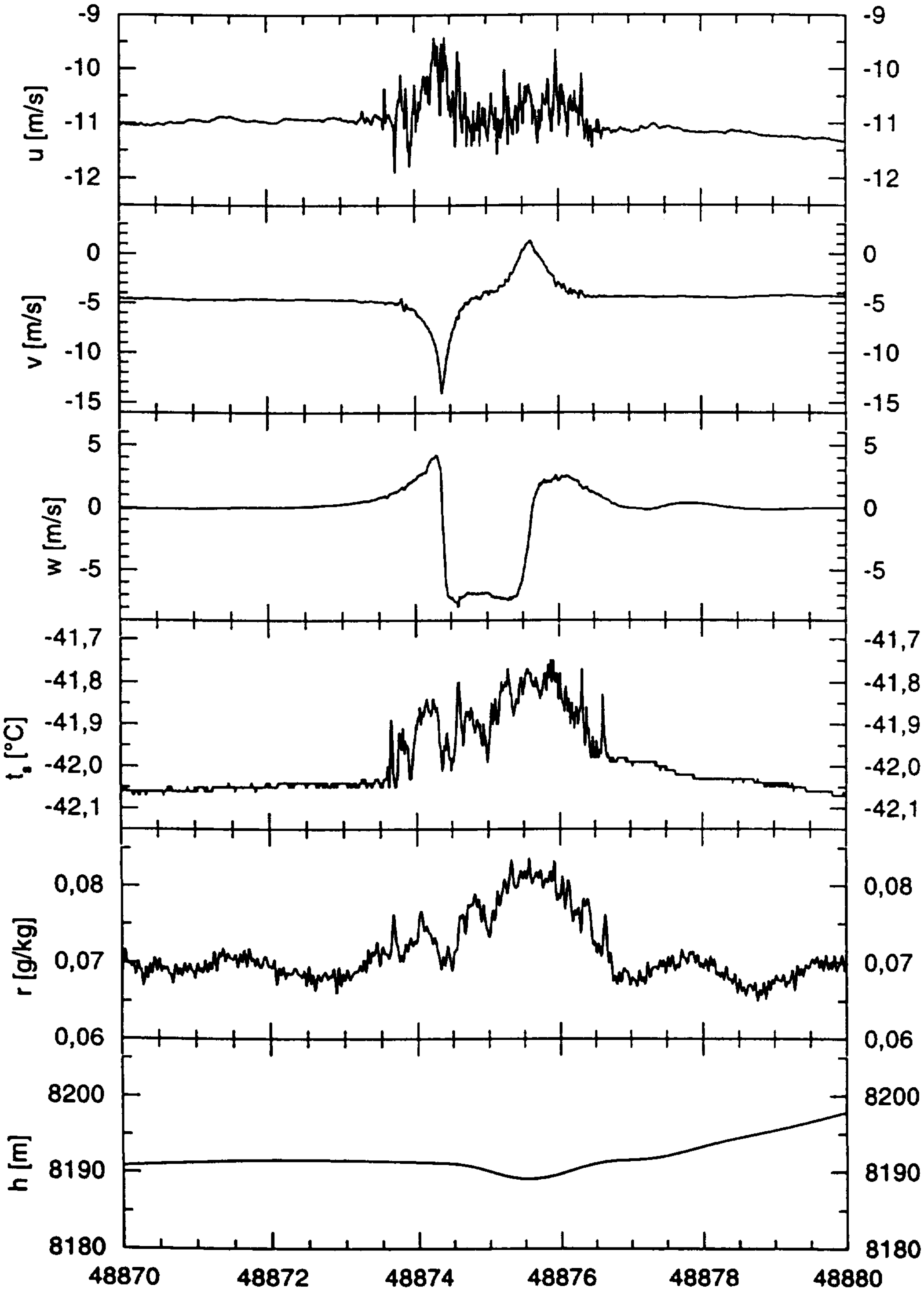

Span–height cross-sections of axial vorticity $\omega_x$ for wake A at different times. Contour interval is $1s^{-1}$ starting from $\pm 0.5s^{-1}$.



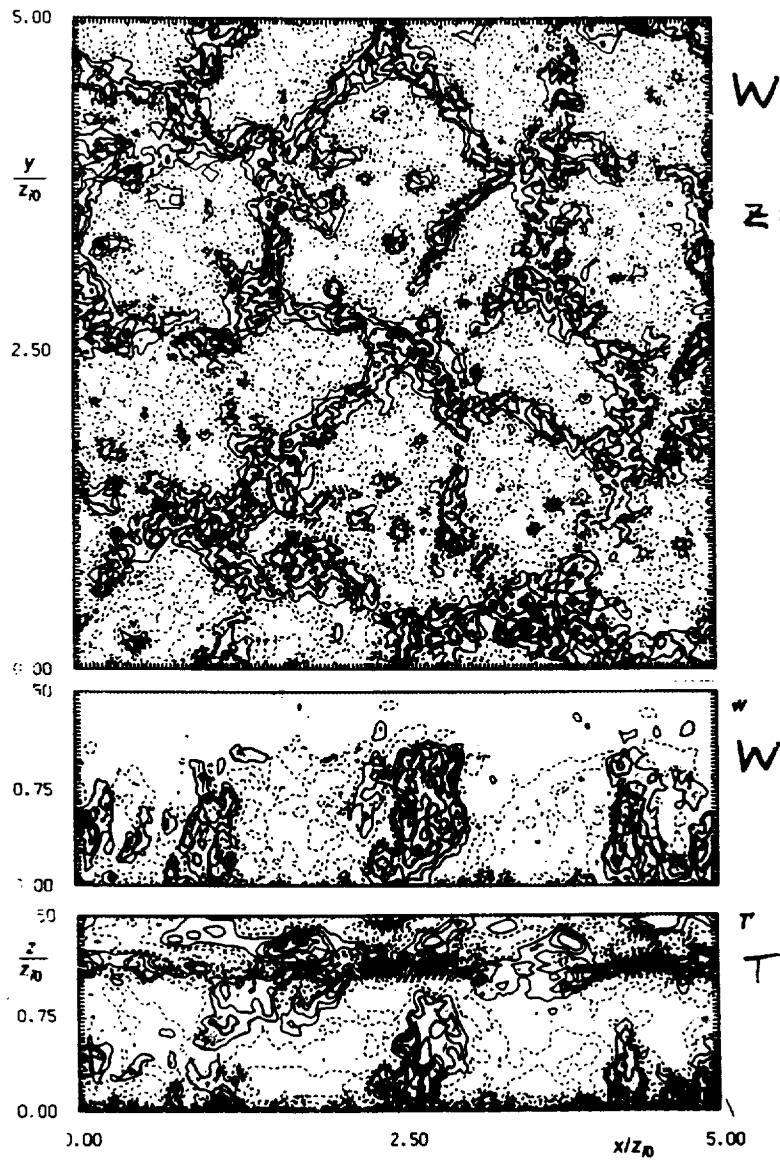

Exhaust distribution of a B–747 in side view. Top: Foto of a contrail. Bottom: Axial–height cross-sections of the simulated exhaust concentration after 146s in the symmetry line of the aircraft.

## SULFUR 4, March 15, 1996 (Falcon Flight #2829), ATTAS case
## 2 NM distance, 13:34:30-13:34:40

wind components transformed to coordinate system with u parallel to mean heading



LES der konvektiven Grenzschicht
of the Convective Boundary Layer (CBL)




z.B. 0 8 km

$z_i$ = 1.6 km

$\Delta x$ = 50 m 160 · 160 · 48 Maschen

$w_*$ = 1.5 m/s , N = 0.01 $s^{-1}$ $t_* = t w_* / z_i = 7 \hat{=} 2h$

$T_*$ = 0.04 K , $z_0$ = 0.16 m

Schmidt + Schumann (1989)

## Conclusions

- LESs of the vortex wake dynamics were performed
- Boundary layer turbulence can not be neclected
- Weak atmospheric turbulence has the strongest capabilities to destroy the wake structure

DLR

**Questions and Discussions Following Frank Holzapfel's Presentation (DLR)**

Turgut Sarpkaya ( Naval Postgraduate School)
Just a suggestion that in the future, not only in your case, but in all LES studies, when one concludes that weak atmospheric turbulence has such and such effect, I believe that one should show graphs of the intensity and integral length scale of the turbulence so one knows what is the quote "weak" atmospheric turbulence. Otherwise, it can be very low intensity large scale or the other way around. I believe neither boundary in particular, whether it is length scale or intensity, or combination thereof will have far reaching consequences.

Holzapfel
The length scale of the most energetic eddies was 50 to about 100 meters and you had impression of the actual velocity when we started the calculations at one second.

Fred Proctor (NASA Langley)
Did you notice any added buoyancy effects from the heat of the jet engines?

Holzapfel
Yes, of course, the distance between the cores decreased and in the core without turbulence, the descent velocity was accelerated. There was an acceleration of the descent.

Proctor
By how much? Significant? Minor?

Holzapfel
I don't really know since these are not really any results.

# Effects of Stratification on 3-D Trailing Vortex Evolution

Robert E. Robins

Donald P. Delisi

NASA Langley Research Center

5/-02
048 075
17P.
38618

May 13, 1997

# Abstract

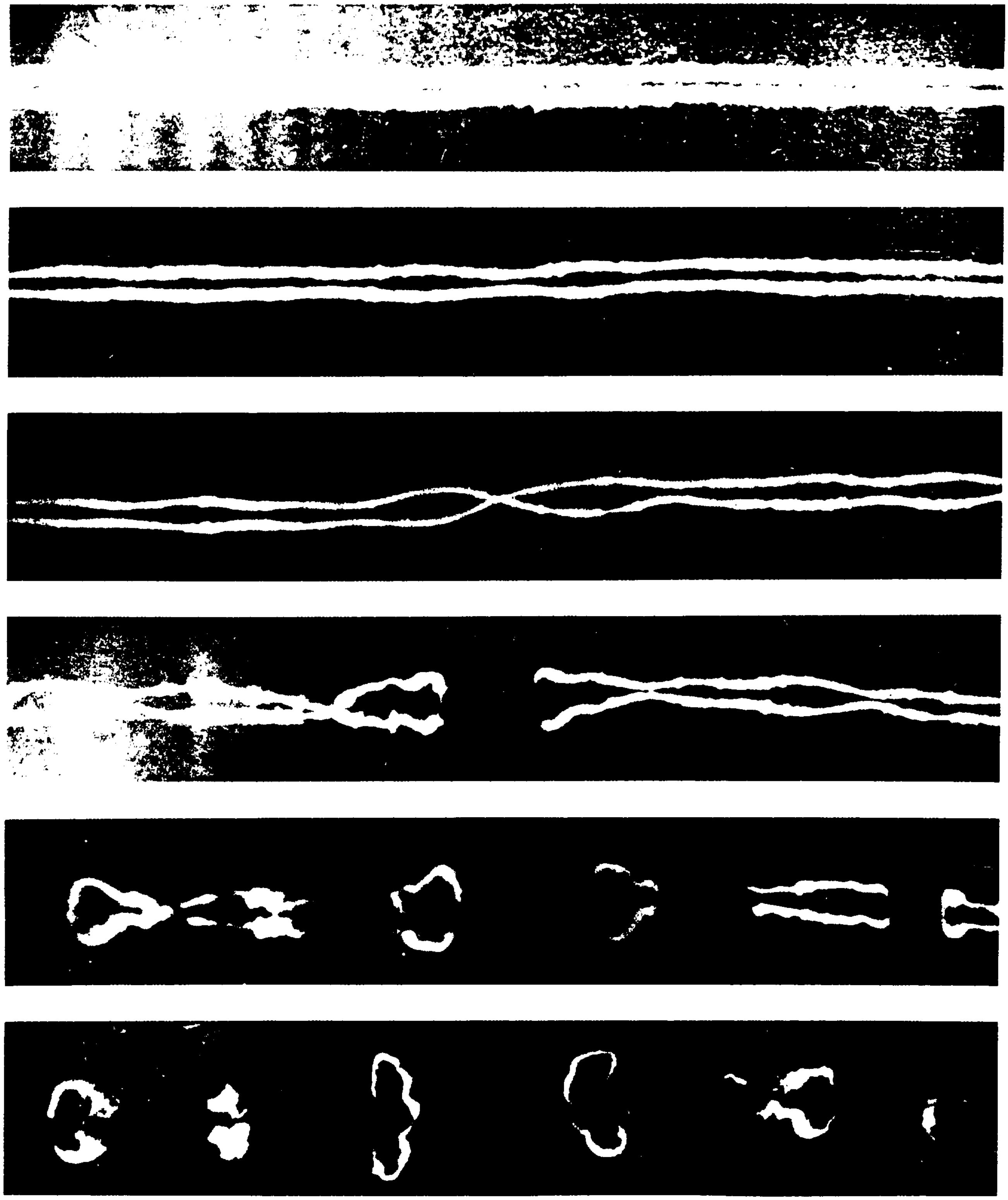
Two studies are presented. First, the effects of stratification on Crow instability are examined numerically. Results from calculations for Froude number, F, equal to 2, 4, and 8, are shown at non-dimensional times of 4, 6, 8, and 10. Stratification is seen to accelerate the onset of linking due to Crow instability and to suppress the downward migration of the vortices. It is also seen that for low stratification, such that F > ~8, Crow instability results in the formation of downward propagating vortex rings. For higher stratification, such that F < ~4, the ring formation is suppressed. In a second study, laboratory and numerical results, in good agreement, show the occurrence of a small-scale instability for strong stratification, such that F < ~2. These results may be relevant to airport operations because of the possibility that stratification effects and small-scale instabilities may result in trailing vortices remaining near the flight path of following aircraft.

# Outline

- Effect of stratification on Crow instability
  - Numerical study

- Small-scale instability in high stratification
  - Laboratory results
  - Numerical results

- Conclusions

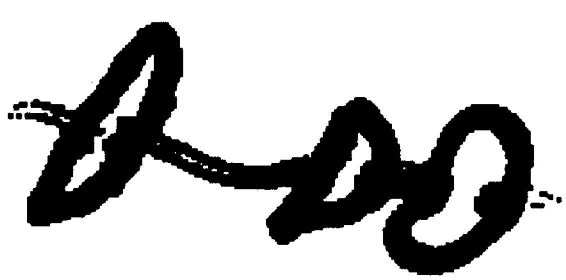


**116. Instability of a pair of trailing vortices.** The vortex trail of a B-47 aircraft was photographed directly overhead at intervals of 15 s after its passage. The vortex cores are made visible by condensation of moisture. They slowly recede and draw together in a symmetrical nearly sinusoidal pattern until they connect to form a train of vortex rings. The wake then quickly disintegrates. This is commonly called Crow instability after the researcher who explained its early stages analytically. *Crow 1970, courtesy of Meteorology Research Inc.*

T = 0.0, H = 0.0

T = 7.5, H = 7.0

T = 10.0, H = 9.1



T = 12.5, H = 10.7

# Froude Number

- $F = V_0 / N\, b_0$

  where $V_0 = \Gamma_0 / 2\pi\, b_0$ and

  $$N^2 = (g/\Theta_0) / (d\Theta/dz)$$

- Example: B-747 in inversion (or stratosphere)

  $b_0 = 50$ m, $V_0 = 2$ m/sec,
  $d\Theta/dz = 1^\circ C / 100$ m  ($N = 0.02$ rad/sec)

  ➡ $F = 2$

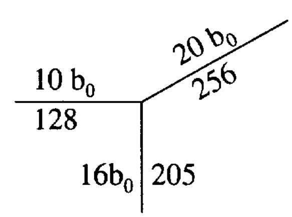
# Numerical Approach

- Solve 3-D N-S equations (Boussinesq)

- Projection method for time stepping

- Pseudo-spectral and compact methods for spatial derivatives

- Computational domain:

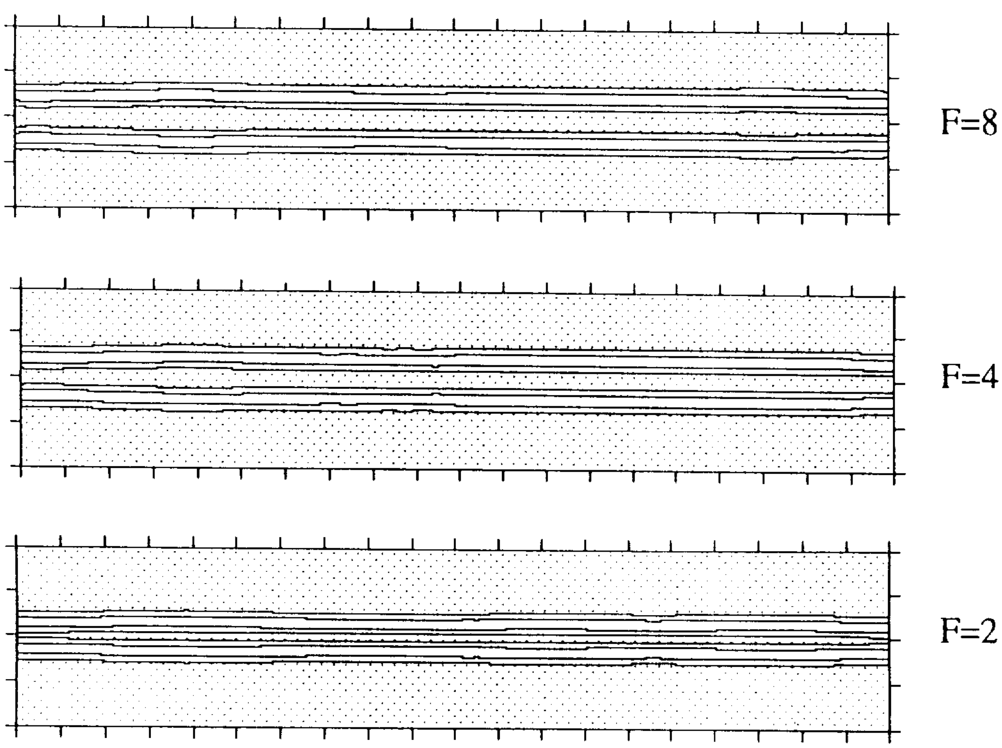


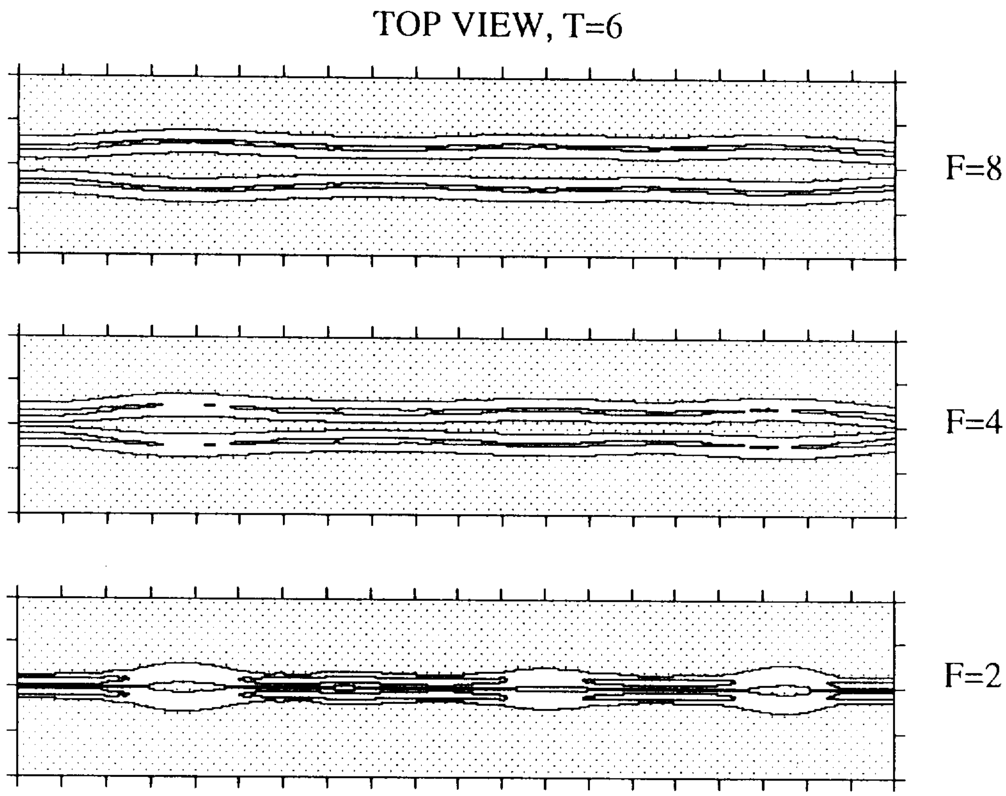

- Initial vortices composed of a spectrum of slightly perturbed vortex components

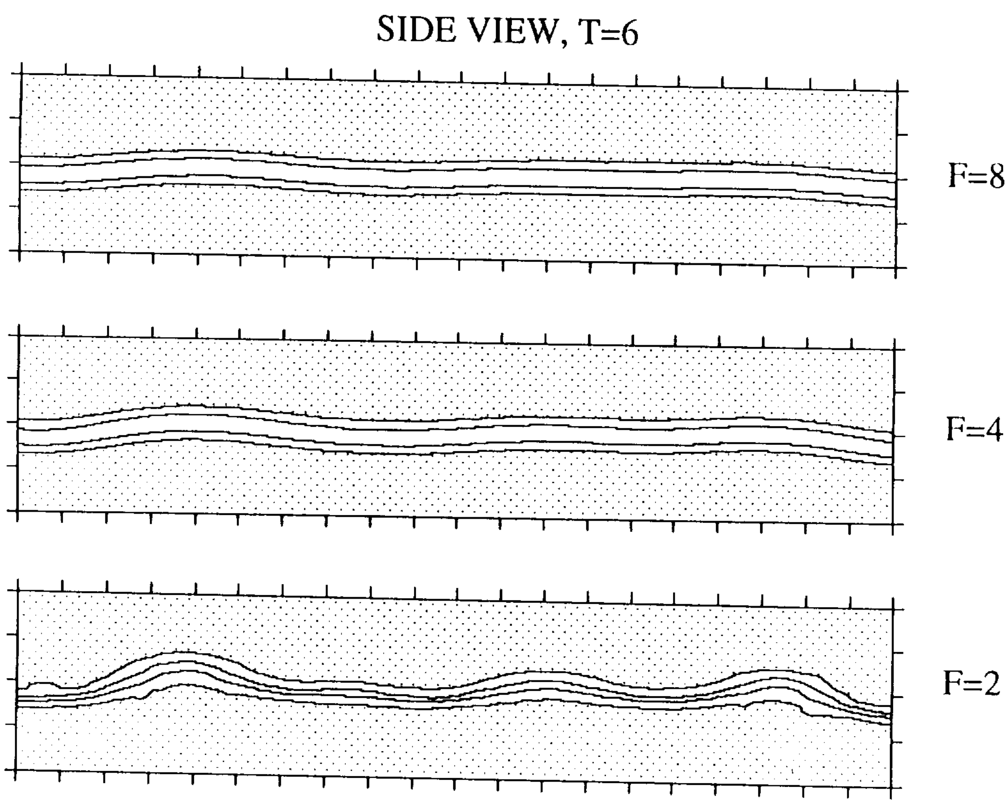
# Numerical Study of Stratification Effects on Crow Instability

- F = 2, 4, 8
- T = 4, 6, 8, 10

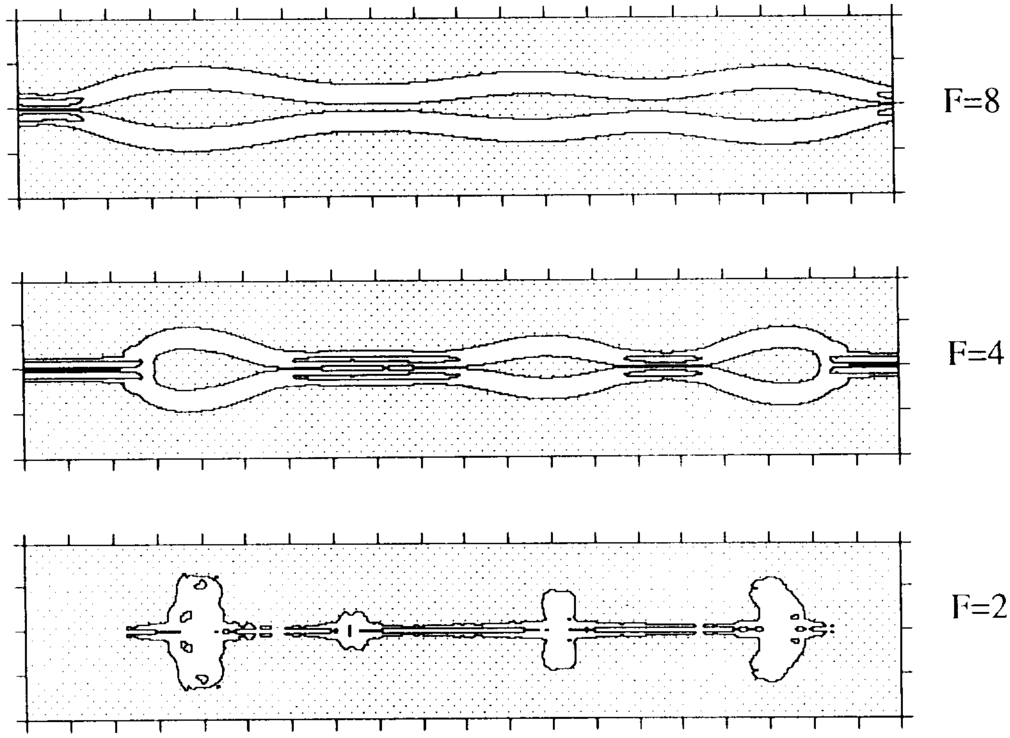
TOP VIEW, T=4



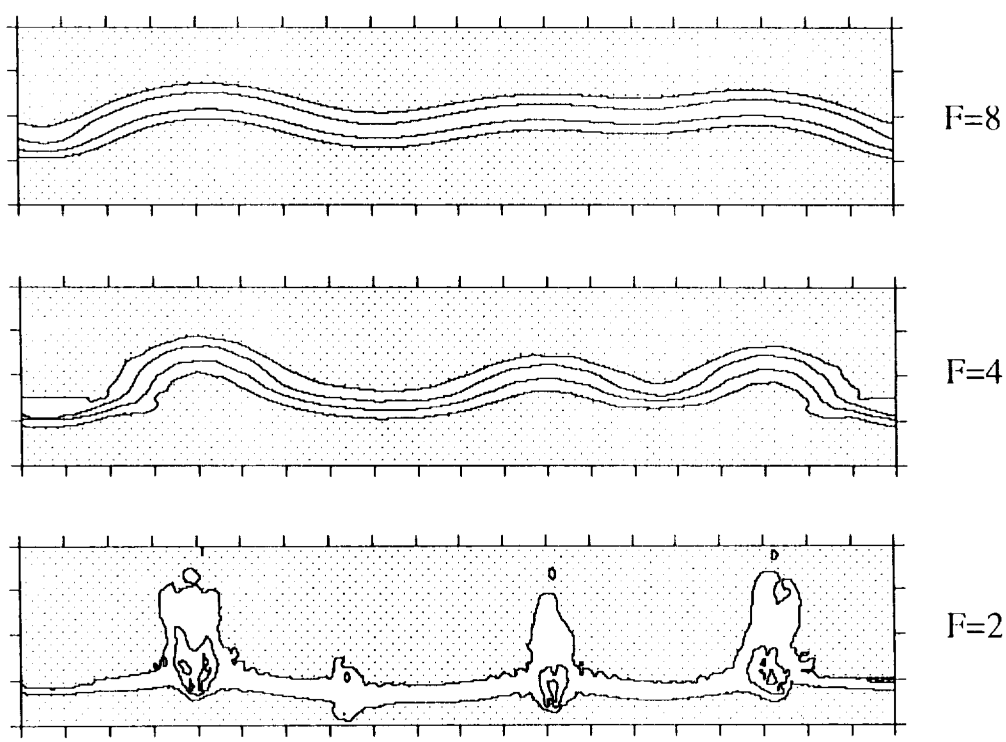

TOP VIEW, T=6
F=8
F=4
F=2


SIDE VIEW, T=6
F=8
F=4
F=2

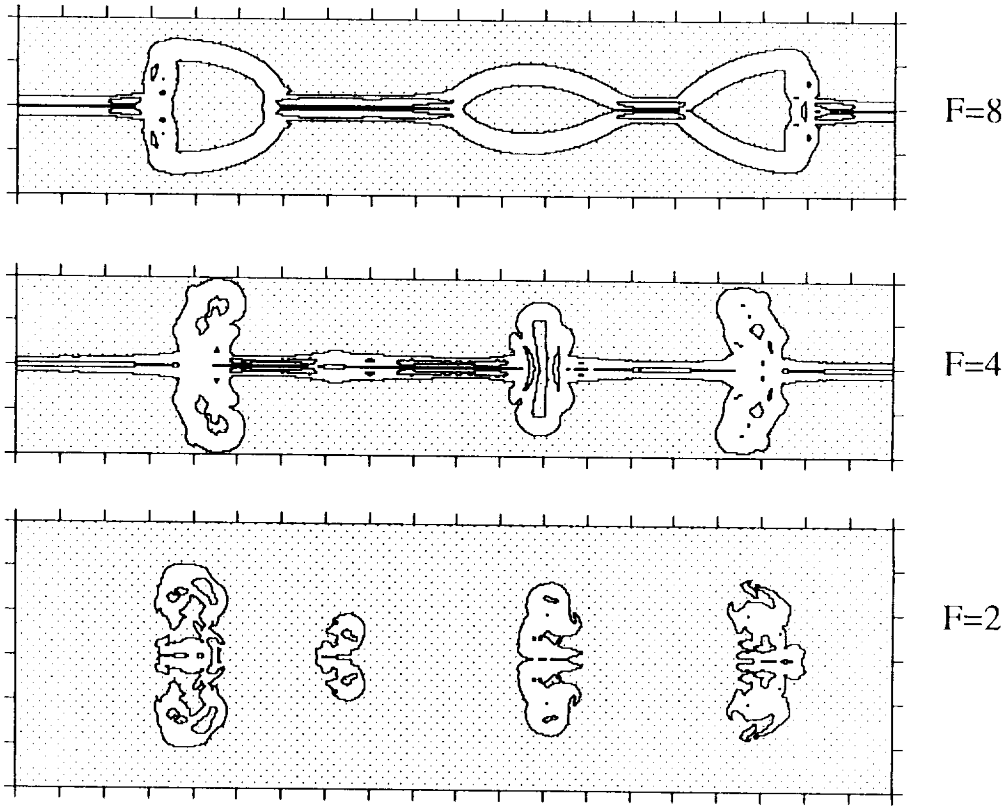
TOP VIEW, T=8



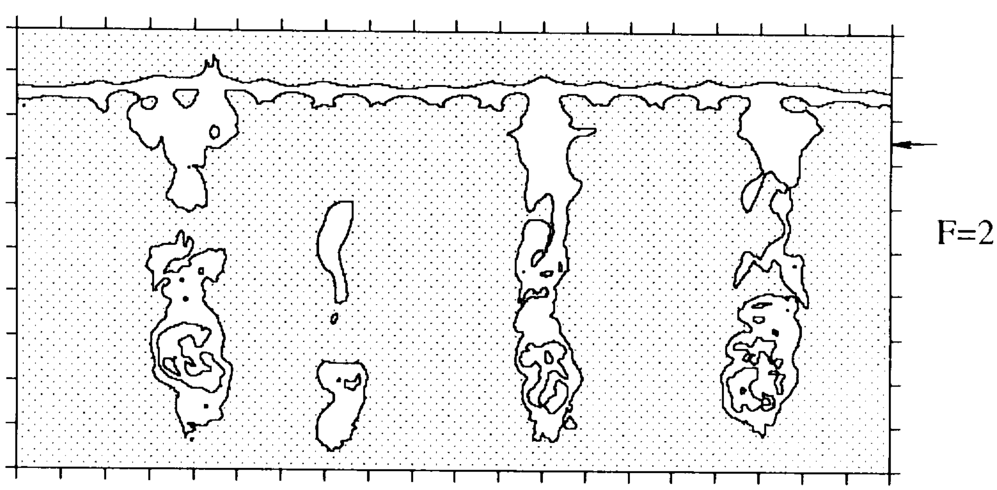

SIDE VIEW, T=8



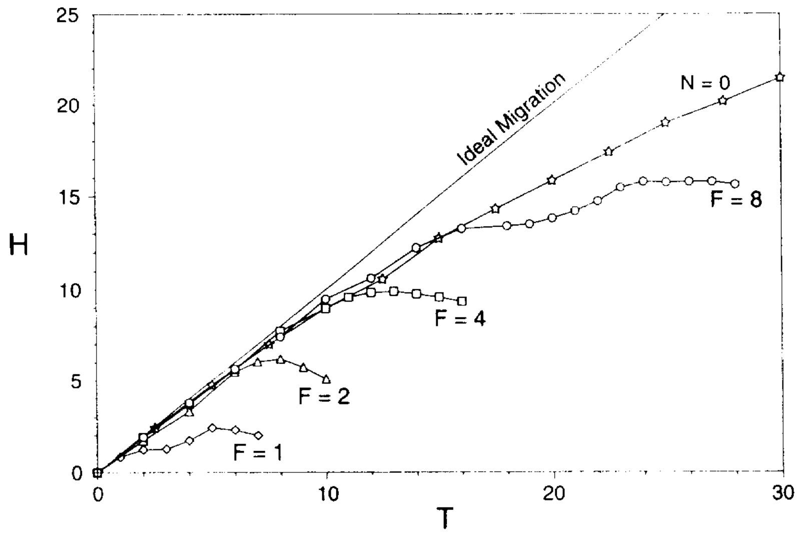
TOP VIEW, T=10




SIDE VIEW, T=10



**Stratification Effects on Vortex Migration**




# Summary

- Stratification causes faster linking and suppression of vertical propagation
- Low (or no) stratification (F > ~8) results in formation and propagation of vortex rings
- Moderate stratification (F < ~4) results in suppression of ring formation

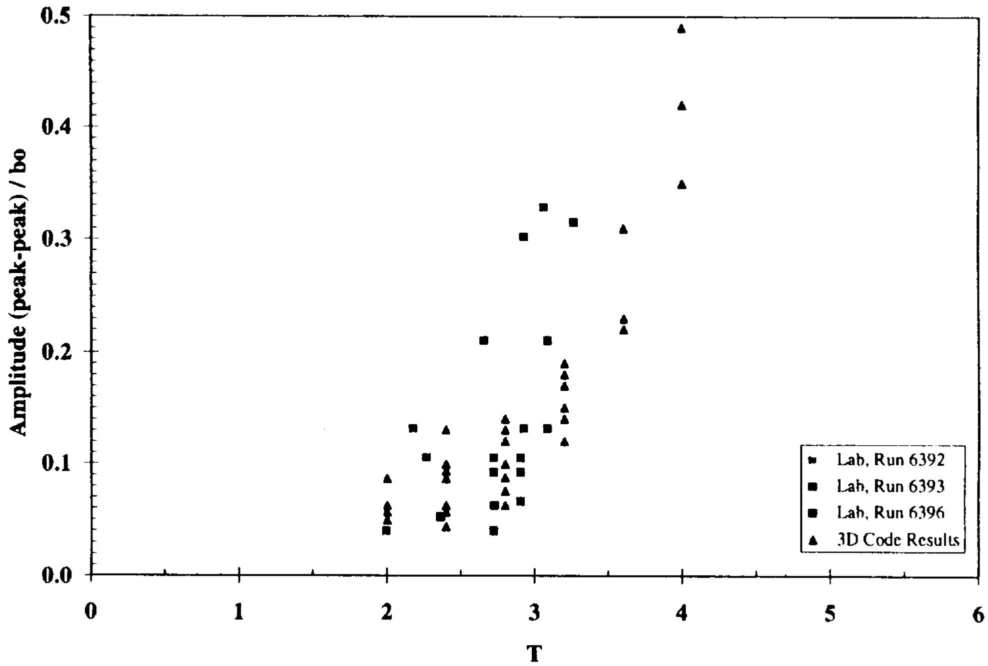
# Small-Scale Instability in High Stratification

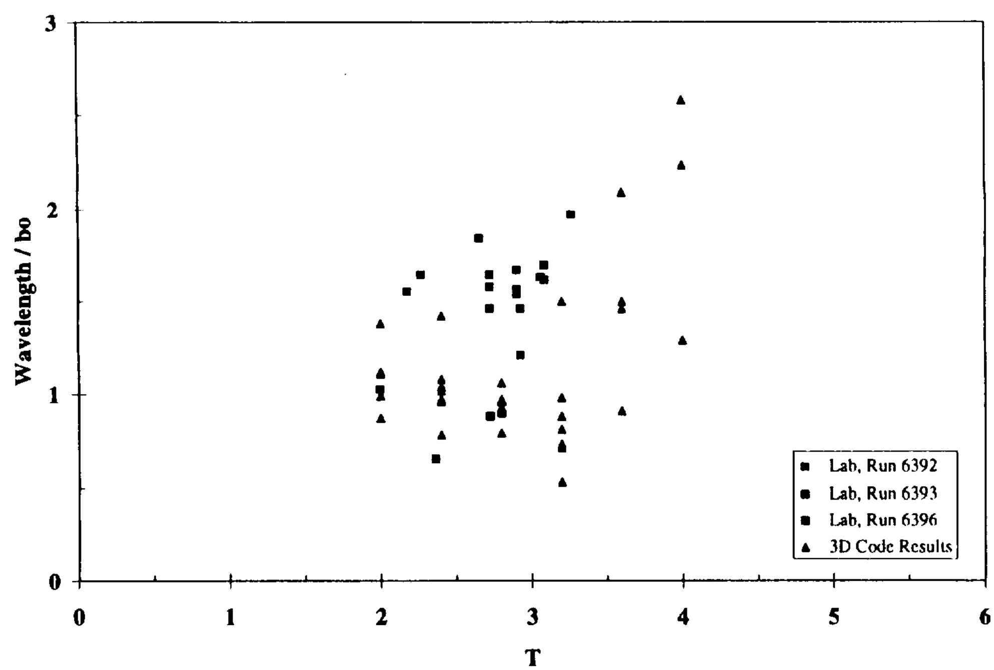
- Laboratory visualizations
- Numerical visualizations

T = 2.4

T = 3.2

T = 4.0


0.5
0.4
0.3
0.2
0.1
0.0
Amplitude (peak-peak) / bo
0
1
2
3
4
5
6
T
Lab, Run 6392
Lab, Run 6393
Lab, Run 6396
3D Code Results


3
2
1
0
Wavelength / bo
0
1
2
3
4
5
6
T
Lab, Run 6392
Lab, Run 6393
Lab, Run 6396
3D Code Results

# Conclusions

- Stratification causes faster linking and suppression of vertical propagation
- Low (or no) stratification ($F > \sim 8$) results in formation and propagation of vortex rings
- Moderate stratification ($F < \sim 4$) results in suppression of ring formation
- High stratification ($F < \sim 2$) results in small-scale instability

**Questions and Discussions Following Bob Robbins' Presentation (Northwest Research Assoc.)**

Philippe Spalart (Boeing)
I think we have a great controversy here. We are all getting a reduction in spacing in stable stratification. I don't think any experiment has shown that. What do you think of it?

Robbins
One point which I didn't make, which I should have made while talking and I'll get to what you said to, is that what we have seen for some of the two-dimensional results is that the vortices come together and they sometimes accelerate and they sometimes oscillate. We presented four different phenomena. What is looking from these results is that when you include the third dimension you get instabilities that supress the vertical motion and maybe give you a supression of what you see in 2-D. It looks like 3-D effects might give you a different phenomena from what you are observing in 2-D. Could you repeat your question?

Spalart
Has anyone in the audience seen vortices come together?

Robbins
No one is jumping up.

Tim Dasey (Lincoln Labs) - I am not going to volunteer that I have seen it. But operationally and in field measurement it is difficult to separate the influences of stratification from those near the ground. I am assuming in these cases there is no discontinuity in the level of stratification. In other words it is uniform stratification.

Robbins
It is idealized uniform stratification case.

Dasey
Which you hardly ever see in atmosphere, at least in the ranges where people have gone to airports and measured vortices, there is generally the top of an inversion or strong discontinuity and also happens fairly close to ground. I think that there is room for field data in that area.

Robert Neece (NASA Langley)
I have some video tape of an experiment where we had smokers on a C-130. I believe we observed as the Crow instability developed, as the vortices came together they did dip down. I'll try and look at the tape and we can show it tomorrow if people are interested.

Robbins
I think what has also been observed in that experiment are the kind of vertical oscillations that we see in small scale instabilities as well. Some of these cases should also be looked at.

Neece
I might add I have copies of those video tapes that I could make available if people are interested.

Pal Arya (North Carolina State University)
I have a question about what kind of simulation did you use. Is it large eddie simulation or DNS?

Robbins
There was no turbulence, no formal LES assumption made. I used the smallest possible viscosity I can to get the simulation on the machine. The actual Reynolds number was about 3,000. I have also run 4,000 and 6,000. It turns out once you get to 3,000 because you are maintaining vorticity in respected cores, you don't get much different results from going higher. Although the Reynolds number sounds low, you are getting behavior much like what you would see at higher Reynolds number.

Arya
You don't have any shear, you have uniform flow?

Robbins
Well it is just 0. I have actually done a few preliminary shear calculations that show some very interesting effects, but I am not ready to present that yet.

Arya
Somewhat inconsistent. The atmosphere with stable stratification will always have strong shear you know.

Robbins
That's true, the intent was to focus on the stratification physics and isolate on that and learn as much as we can. The next step is to include more realism.

George Greene (NASA Langley)
Can you comment, sort of as a follow-up to Philippe's question, on what sort of percentage reduction in spacing are we talking about? Did they decrease their spacing by a factor of 2, or just 10 percent?

Robbins
You should be able to see it. Let's go back. Each of these tic marks is equal to separation. The separation here at Froude number 2 at time 4 is probably between 3/4 and 1/2 of $B_0$ before they link. I am not sure that answers your question.

Greene
I think people have seen numbers of about 10 percent at low Reynolds number. If it is about 1/3 we should be able to pick that up in a flight test.

Robbins
It would be interesting to see, for example, in the Wallops Island tape if that can be observed.

# Initialization and Computation of 3-D Wake Vortices

Z. C. Zheng
University of South Alabama
Mobile, Alabama



## Outline

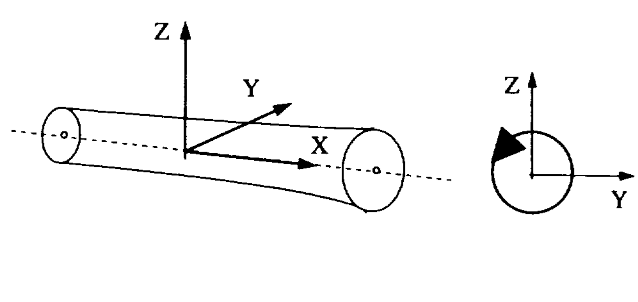
- Axial velocity effects on 3-D vortices
- Initial 3-D computational simulation with axial flow
- Zonal computational method
- Conclusions

## Three-Dimensional Vortex Characterization

- Vortex stretching effects
- Axial velocity profiles
- Stability and breakdown
- Turbulence

## Coordinate System for a 3-D Vortex

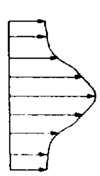
(fixed with flying speed)



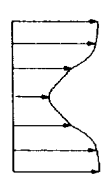
## Axial Vorticity Transport

$$(1+u')\frac{\partial \zeta_x}{\partial x} + \frac{1}{U_o}\left(\frac{\partial (V\zeta_x)}{\partial y} + \frac{\partial (W\zeta_x)}{\partial z}\right)$$
$$= -\frac{\partial W}{\partial x}\frac{\partial u'}{\partial y} + \frac{\partial V}{\partial x}\frac{\partial u'}{\partial z} + \frac{\nu}{U_o}\nabla^2\zeta_x \,.$$

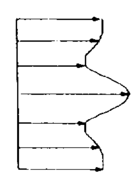
## Axial Velocity Profiles



(1) Jet type



(2) Wake type



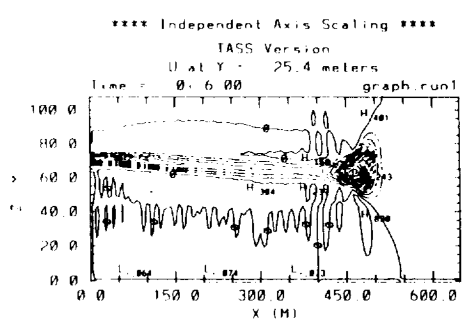
(3) Combined

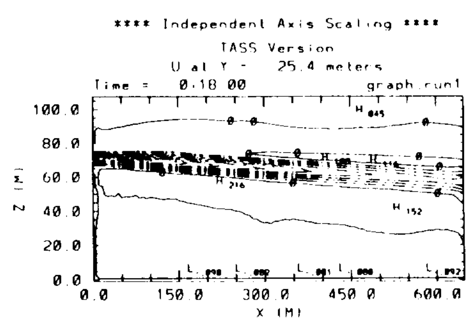
# Influence of Axial Velocity Profiles

Table 1: Change of vortex strength with downstream growth vortex core (under the influence of small $u'$)

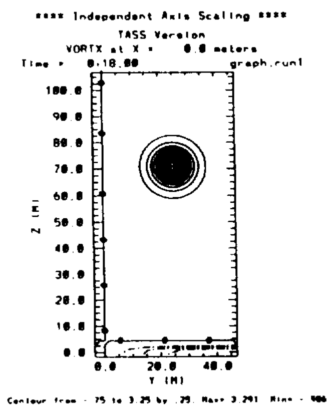
| Axial velocity type | Total circulation | Tangential velocity | Axial vorticity |
|---|---|---|---|
| Uniform | Unchanged | Decrease | Decrease |
| Jet | Decrease | Decrease | Decrease |
| Wake | Increase | Decrease | Decrease |

# Axial Velocity Propagation ($U_0 = 60$ m/s)

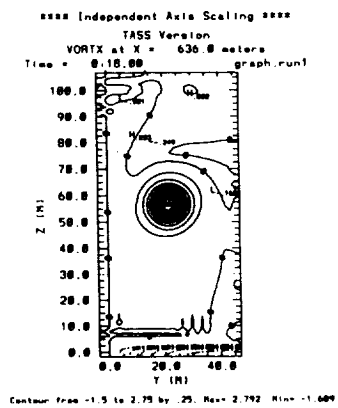


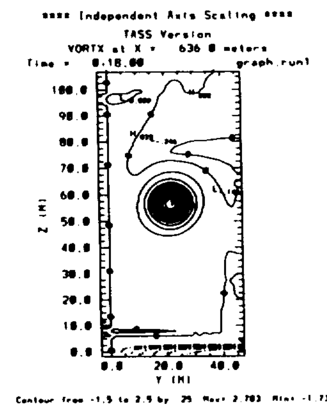
# Axial Vorticity Distribution



(1) At x = 0



(2) At x = 638m with wake



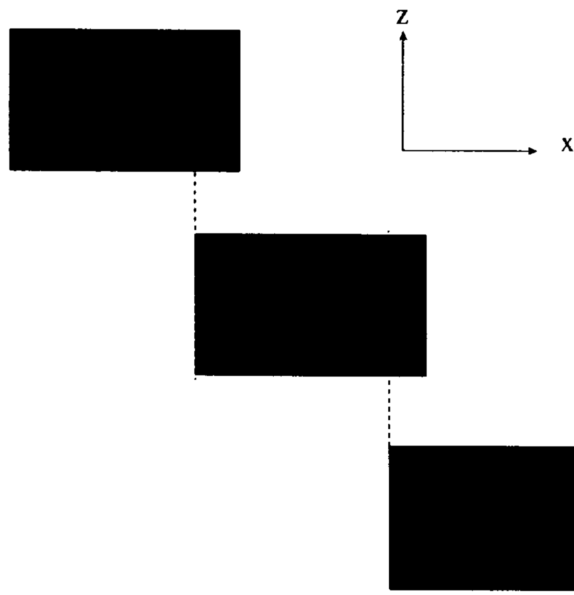
(3) At x = 638m with jet

# Core Increase vs. Vorticity Decrease

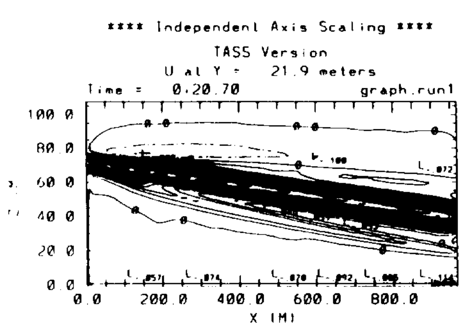
- Wake: core increase 13.3%, vorticity decrease 15.2%
- Jet: core increase 6.7%, vorticity decrease 17.9%
- For Rankine vortex:

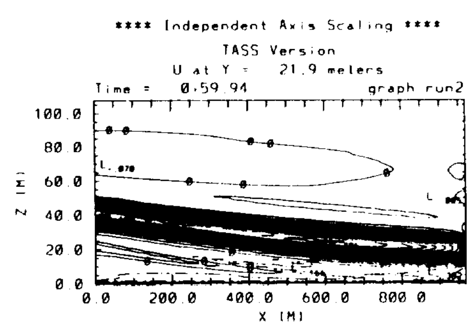
$$\frac{d\zeta_x}{dx} = -\frac{2\zeta_x}{r_c}\left(\frac{1}{1-\frac{2}{r_c^2}\int_0^{r_c} u' r dr}\right)\frac{dr_c}{dx}$$

## Zonal Grid

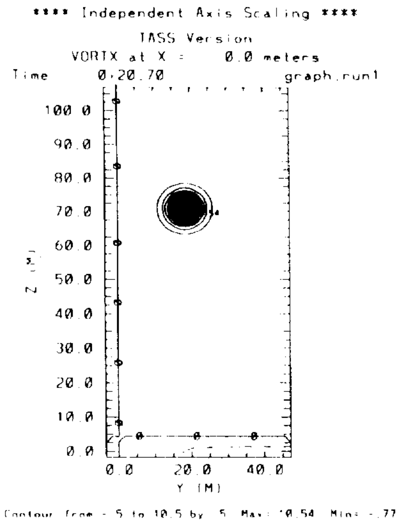


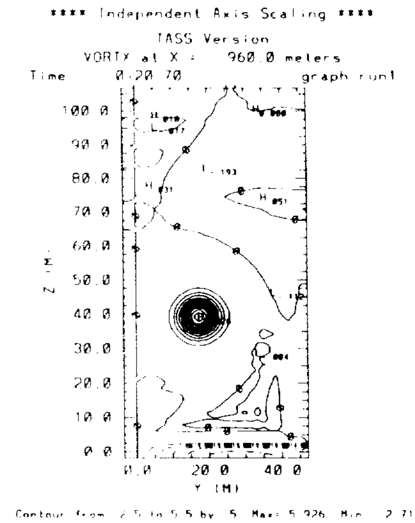

## Axial Velocity in Two Zones



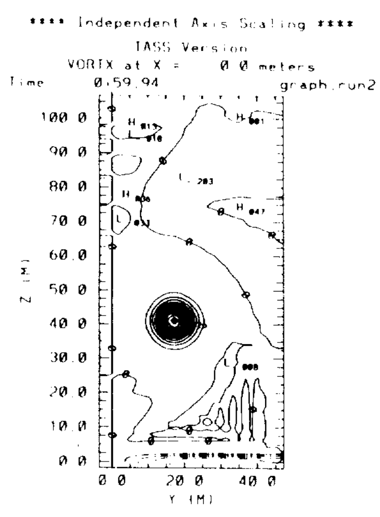



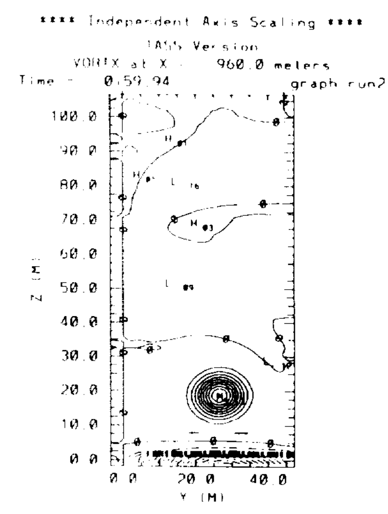
# Axial Vorticity Contours in Zone I




# Axial Vorticity Contours in Zone II



## Conclusions

- Initial axial velocity profiles influence the 3-D vortex decay behavior
- Axial velocity deviation can change the effects of vortex core growth on total circulation, axial vorticity and maximum tangential velocity
- Computational results are in agreement with the trend predicted in the analytical study
- The zonal method can be utilized to extend far downstream 3-D simulation

**Questions and Discussions Following Charlie Zheng's Presentation (University of South Alabama)**

Steve Lewellen (West Virginia University)
You can't handle atmospheric turbulence in this frame of reference. Is that true?

Zheng
Do you mean it can't be included in computational models?

Lewellen
Yes

Zheng
Yes it can. It is in test code. It is large eddie simulation. We used the same code as Fred used and large eddie simulation is in that code.

Lewellen
The turbulence will have to move through your frame at the speed of the aircraft.

Fred Proctor (NASA LaRC)
Yes, we can do this through a nesting procedure or specifying at the boundary, some way. It is a little difficult.

Lewellen
I am concerned with the speed at which the turbulence will have to move through your frame.

Zheng
You mean the turbulence when you move your computational domain with the airplane, the turbulence is no longer steady state?

Lewellen
Turbulence is in the frame of the atmosphere. So you have got the speed of the airplane between the two.

Proctor
If you have got good numerical techniques what difference does it make? It is a lot more expensive.

Zheng
Yes, we are thinking about this.

Proctor
Have you looked at change in circulation along the vortex?

Zheng
For the total circulation in the simulation, I used two vortices along with the ground effect so the total circulation doesn't mean anything. Because you have two vortices if you calculated total circulation of whole domain that came out to be zero. So the only "circulation" that is meaningful for wake vortex is average circulation which you mentioned in an earlier paper in Reno. I have not done that. Get the average circulation based on the 3 dimensional calculation.

# TWO-DIMENSIONAL SIMULATION OF WAKE VORTEX INTERACTION FROM MULTIPLE AIRCRAFT

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George Switzer*

* Research Triangle Institute

NASA First Wake Vortex Dynamic Spacing Workshop May 13, 1997

## Abstract

This numerical experiment investigates the significance of wake interaction from multiple aircraft in the region of the runway threshold. The study is chosen from the 1995 Memphis observations of cases 1493 to 1496 because of close spacing and varied strengths of the wake vortex systems. The observed environmental input conditions are of weak crosswinds winds with a mean value of 1 m/s. The model vortex systems are injected at times and altitudes corresponding to that of the actual aircraft. A video of potential temperature and vorticity shows the dynamics of the vortex interaction. The observations from the video are that vortex movement may change direction from downwind to upwind due to influence of other vortex systems and vortices from different aircraft may couple to produce new vortex systems. However, the interaction from multiple vortex systems did not create significant departures from what was predicted with an isolated vortex system. Finally the trajectory of altitude and lateral position is compared for Memphis case 1494 and 1496 showing good agreement.

# OUTLINE

- Purpose
- Description of study
- Results
- Summary

# PURPOSE

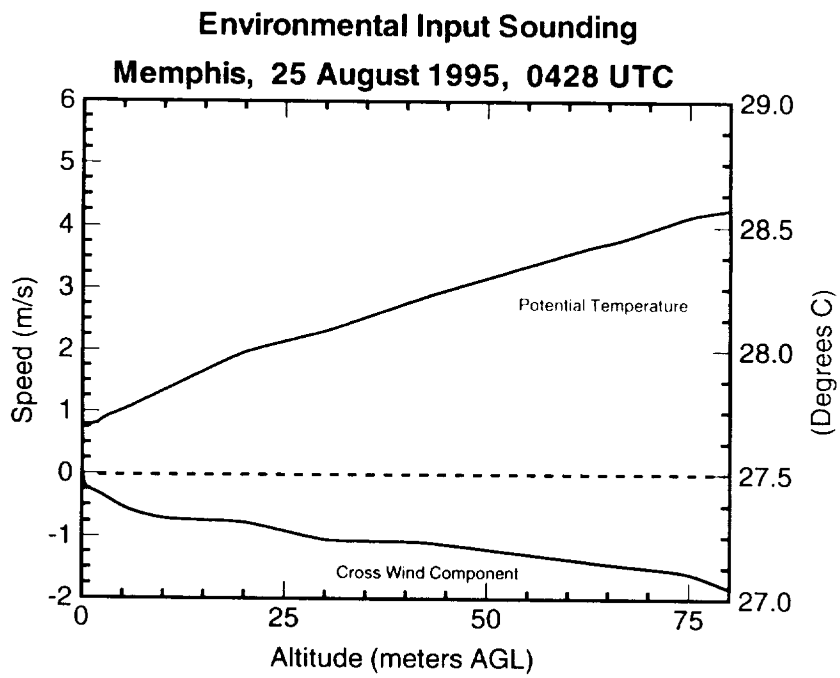
- Numerically simulate wakes from successive aircraft
- Investigate significance of multiple wake interaction

# GENERAL DESCRIPTION OF STUDY

- Environmental conditions and aircraft parameters taken from 1995 Memphis cases #1493 - #1496 -- runway 27 threshold
- Multiple vortex interaction in ground effect with weak crosswinds
- Cases chosen due to closely spaced aircraft and varied strengths of wake vortex systems
- Results obtained for the two-dimensional wake vortex interaction and are compared with observations

# MODEL INPUT PARAMETERS

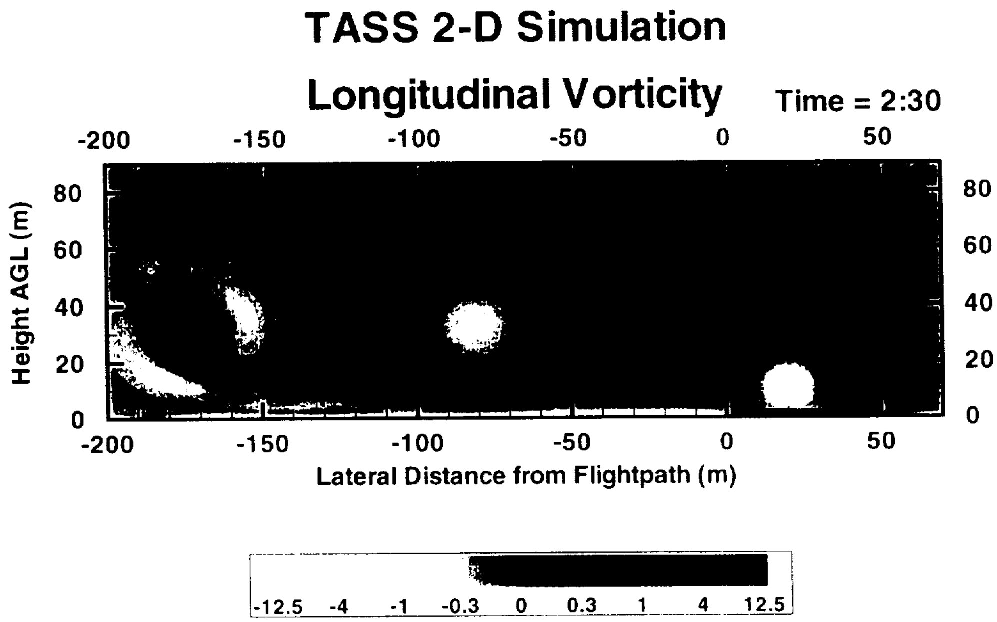
- Two-dimensional domain size:
  lateral - 600 meters
  vertical - 90 meters
- Uniform grid size of 1 meter
- Aircraft generation heights: range from 10 to 25 meters
- Environmental input sounding:
  25 August 1995, 0428 Z
  crosswind about 1 m/s

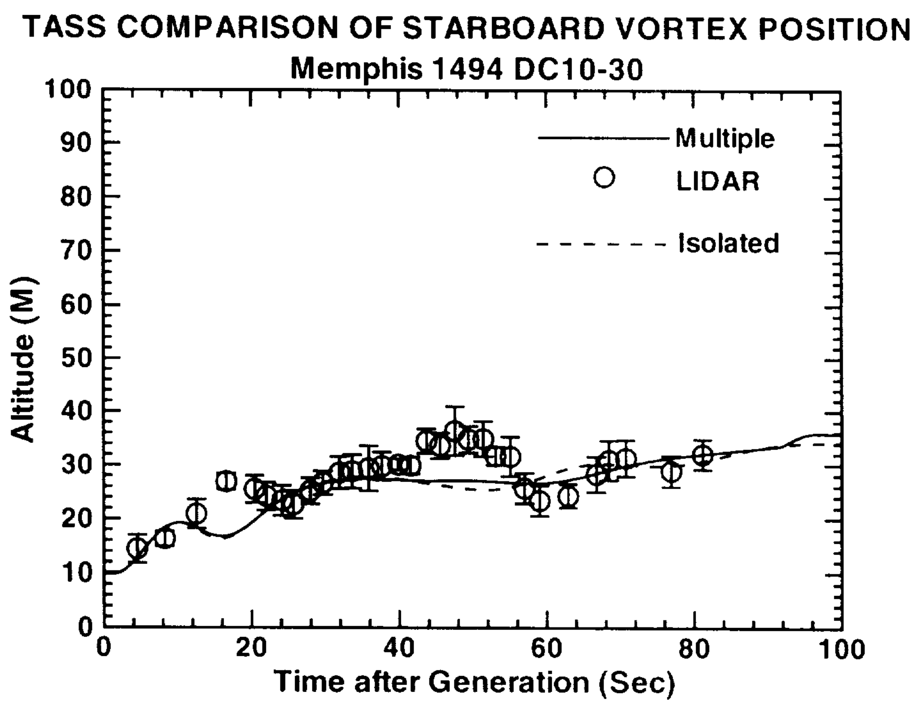


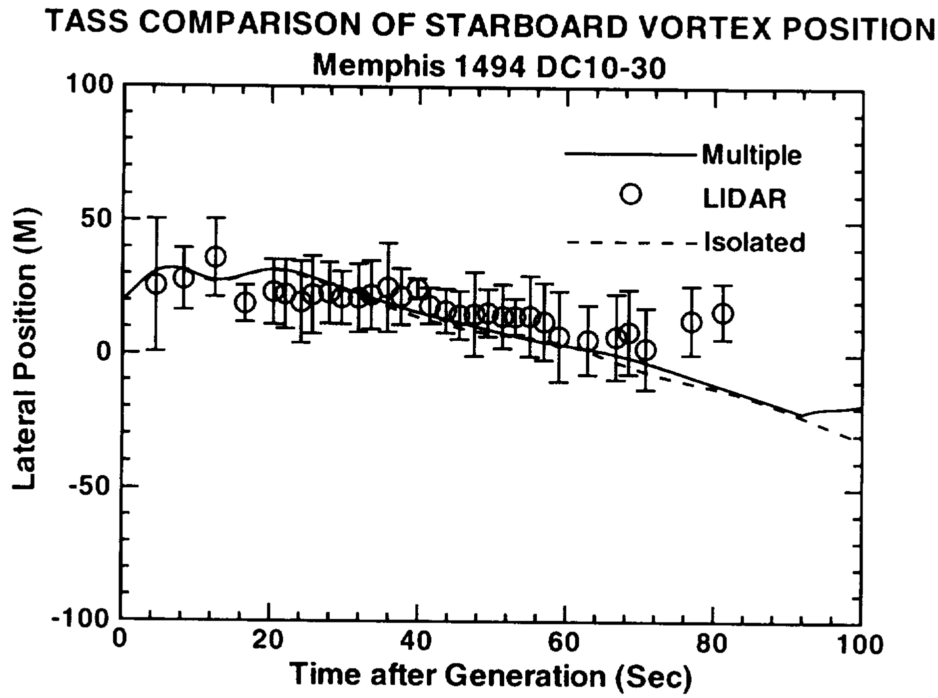

# AIRCRAFT INPUTS

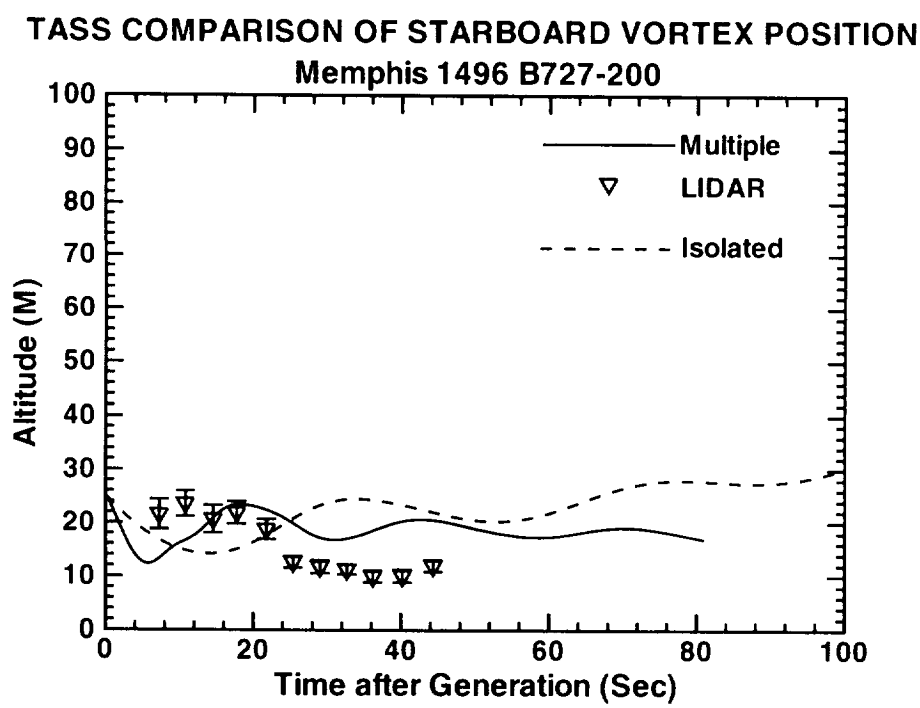
- Four aircraft: three B727-200's and one DC10-30
- Wakes from four successive aircraft injected into simulation over ~5 minute period

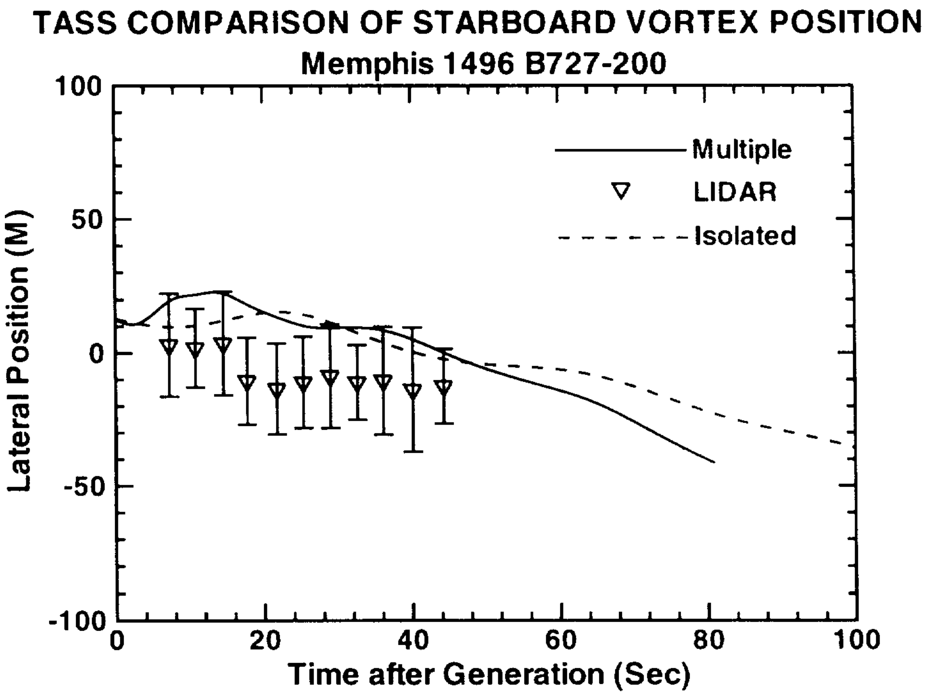
| Memphis Case # | Aircraft | Time | $Z_i$ (m) | $\Gamma_0$ ($m^2/s$) | Initial vortex spacing (m) |
|---|---|---|---|---|---|
| 1493 | B727-200 | 0:00 | 25 | 291 | 25.8 |
| 1494 | DC10-30 | 2:30 | 10 | 467 | 39.6 |
| 1495 | B727-200 | 4:02 | 20 | 313 | 25.8 |
| 1496 | B727-200 | 5:09 | 25 | 302 | 25.8 |


TASS 2-D Simulation
Longitudinal Vorticity
Time = 2:30
Height AGL (m)
Lateral Distance from Flightpath (m)
-12.5 -4 -1 -0.3 0 0.3 1 4 12.5


TASS COMPARISON OF STARBOARD VORTEX POSITION
Memphis 1494 DC10-30
Multiple
LIDAR
Isolated
Altitude (M)
Time after Generation (Sec)


TASS COMPARISON OF STARBOARD VORTEX POSITION
Memphis 1494 DC10-30
Multiple
LIDAR
Isolated
Lateral Position (M)
100
50
0
-50
-100
0
20
40
60
80
100
Time after Generation (Sec)


TASS COMPARISON OF STARBOARD VORTEX POSITION
Memphis 1496 B727-200
Multiple
LIDAR
Isolated
Altitude (M)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Time after Generation (Sec)




## SUMMARY

- Wake vortices from succeeding aircraft may affect the transport of vortices for conditions of low crosswind in ground effect
  - Vortex movement may change direction from downwind to upwind due to influence of other vortex systems
  - Vortices from different aircraft may couple to form new vortex system

**Questions and Discussions Following George Switzer's Presentation (RTI)**

Turgut Sarpkaya (Naval Postgraduate School)
I have one question and one comment. The question, do you know the velocity and circulation distribution at various times as these vortices interact in a very complex manner with each other? That is scientific question. The practical question, that is why we are here, I would suggest that an average circulation be calculated from R core (radius of vortex) to 1/2 of the separation of the vortices at the time of landing. That number should be given in every paper, calculated, or evaluated because I think this group, for its usefulness to the industry, will need a number like this and there are internal limits that are the most usable rather than theoretical separation, half the actual separation distance. Your comments please. Thank you.

Switzer
I think you have a good comment there. We need to have standardization so we can compare results. Looking back at Idaho Falls we have started using 10 meter average circulation. For these cases due to complexity of interaction, I have not calculated circulation. All I looked at was trajectory so I don't have any strength values.

Phil Hogg (United Airlines)
What was cross wind component and what were the initial separations, in time and distance?

Switzer
The cross wind component was approximately one meter per second, about 1/4 to 1/2 meter per second at ground to 2 meters per second at 80 meters altitude. The vortices were separated by 2 minutes and 30 seconds for the first two, 1 minute 32 seconds for the next, and 1 minute and 7 seconds for the last.

Alexander Proskovsky (NCAR)
You put vortices one after another. But it seems the influence of the aircraft itself if there is still vortex from the previous one. When a new aircraft flies it would be physically different quantitatively and qualitatively from simply injecting vortices. How can you handle this problem?

Switzer
I was looking at the first cut of how we can estimate what is the effect of multiple interactions. I can't do a wake roll-up. If I did it right I would need to do roll-up of DC10 at 2 minutes 30 seconds. I injected a fuller rolled-up vortex.

Proskovsky
I didn't mean that, when the aircraft flies it changes the flow jets from the engine, etc. How can you put that influence in the simulator?

Switzer
You're talking about a 3-dimensional effect that a 2-dimensional simulation would not be capable of simulating. I don't know how to initialize this. I am open to suggestions.

Gregg Winchelmans (Transport Canada)
The second pair of vortices was injected after 2 minutes, I am wondering from an operational viewpoint of an AVOSS, what was left of the circulation of the first vortex system? Was it below 100 meters per second? Was the vorticity left there a hazard?

Switzer
That is a good question. However, with the 2-dimensional simulation I do not trust my results, and I have not calculated them for the circulation value. I was looking strictly at transport, not decay. Of course, transport will be affected because decay may not be what real world is, but that was not the focus of my study.

Pal Arya (North Carolina State University)
I wanted to comment on the last discussion of multiple interactions. You can put idealized wakes in but have such multiple wakes been observed? I suspect that the following aircraft would destroy the wake.

Switzer
There could annihilation or coalescence of vortex system.

Tim Dasey (MIT Lincoln Labs)
I would point out we are spending a lot of time on how we model what a vortex looks like after a plane encountered it. The point of AVOSS is to set up separation so planes don't encounter vortices at hazard levels. This is a nice esoteric exercise but I am not sure it's relevant. On the other hand, it does show how wakes of previous aircraft disturb the meteorological condition in the boundary layer that may be present for the next set of wakes that come by.

Philippe Spalart (Boeing)
You are doing a lot of 2-D large eddie simulation, and I don't know what that is. The subgrid scale models you are trying is 3-D to do small eddies from Kolmogorov cascades so what you have is nonlinear, well, nonuniform viscosity. What is the typical level of that viscosity? What is your effective Reynolds number?

Switzer
I don't know. I have not looked into that. Again I am trying to look at transport getting a quick way to simulate what transport would be. From the simulation and the comparison with the lidar data I showed reasonably good agreement. As Dasey pointed out where the wakes are going when are they getting there? I don't have an answer for Reynolds number.

Proctor (NASA LaRC)
Reynolds number is infinity for LES.

Winkelmans
I would like to follow up on what Phillipe Spalart just said. 2-D LES in principle you cannot do, so if you do it and you want decay out of it, which obviously, you don't, but let us assume you want decay out of it, you would have to change the Smagorisky constant by probably a hugh factor in order to capture these vortex decays. You should certainly not run a 2-D LES using the same constant as the one you use in a 3-D LES. LES by definition has to be 3-D to work. So maybe you can fool around with the Smagorisky constant to get proper decay.

Switzer
I don't want to play curve fitting games. As you may recall from Proctor's presentation of Idaho Falls comparison, the decay of the 2-D system was a conservative estimate of real-world. I am effectively looking at a worst case to quickly look at multiple interactions due to closely spaced operations.

George Greene (NASA LaRC)
I wanted to reinforce this. It seems this discussion went a little afield. As I understand this, from an AVOSS perspective you are looking at special situations which you have to look out for such as rising vortices, or whatever. This was more of a pilot study to assess situations.

Sarpkaya
In defense of the value of this paper. It may have occurred to other people, at any case it will occur now. In the case we can increase the frequency of the aircraft, providing they are landing safety, the landing of every successive aircraft will be safer than the previous one because of the mess that the aircraft turbulence has created. Scientifically speaking, the character of the turbulence around the airport would have been changed and the small-scale turbulence had been increased. Among one of the few things we know for certain in this business is that turbulence helps to decay the vortices. Thus, it is not all danger that we want to decrease the separation between aircraft. At the same time we are in the business of increasing the intensity of turbulence, restructured it in the airport if you will so as to create a more conducive environment for the landing of the other aircraft. In this sense, any study that makes the interaction of vortices between the aircraft following aircraft, wind shear, etc. gives one ideas if not numbers about circulation, numbers about the strength of average vortices. Thank you.

Steve Campbell (Lincoln Labs)
I thought it was really interesting and fascinating to see these interactions. I remember when we took all those measurements. These are all Fed Ex planes and they are landing one after the other every 2 minutes. Have you thought of looking at a longer simulation where you run a whole set of aircraft? You might see something strange happening. On the other hand, they do this every day without suffering any ill

effects. Have you considered doing something along those lines?

Switzer
In this particular push there was only one other aircraft that was even close. It was one earlier aircraft, a B727-200. I chose not to do it just because I did not know what the computational resources would entail. It passed by at a minute 47 seconds earlier. This was the best data sample we had right at threshold.

Jim Hallock (Volpe Center)
In the extensive measurements we have made there are many times when we have been able to see the remnants of the vortices of one, two, and in one case three aircraft preceding. The other thing we did notice was in time of low density the wake lasted a certain time, then with meteorological conditions not changing, suddenly get a higher density of aircraft, the average life of the vortices did go down. So there truly is an effect. I hope nobody interprets that we fly at 1-minute intervals and there would be no problem, but it is a measurable effect.

**Wrap Up Discussion and Questions of Day One Presentations**

Unknown
I understand everybody wants to go home. I'll keep it short and simple. I never did get a degree in physics, so I am approaching it from a planning perspective. I heard three things that were new to me perhaps not new to you folks. Number one, vortices stall on runways and can stay there for a while. Number two, they have been observed to stay together up to 12 nautical miles. Number three, the fact that they can move upwards. For all the panel members who are in here throughout the course of the research going on, have any of you thought about the possibility that as a result of this research we may actually increase separations.

Jim Hallock
We did, when we did the measurements in the 70's. We were looking primarily at commercial airlines and came back and said separations then in effect for them were fine. At the same time we said we were worried about small aircraft. That is when the 4 and 6 miles separations came in. So sometimes you don't get the results you first thought you were going to get.

Tim Dasey (Lincoln Labs)
We have seen a lot of simulations. The 2-D simulations especially with TASS model. I guess I am a little bit curious how the model in 2-D doesn't estimate circulation correctly but positions are right on. Is there a weaker coupling between position and strength than I thought there was or is there some other explanation of this that the model takes care of?

Fred Proctor (NASA LaRC)
I guess the answer, the decay of circulation especially at the radius which influences the other vortex, which is 20 to 50 meters, probably does not decay at fast rates, such that it doesn't affect transport much until it reaches the ground. That is what I assume at this point.

Question not recorded.

Proctor
When you talk about circulation, there are a number of ways it can be described. An average circulation, or circulation at a specific radius. I think in the AVOSS program we are primarily interested in the relationship with hazard. A circulation value at 30 or 50 meters, which is very important to descent of vortex, probably plays no role in hazard definition.

Judy Turner (U.K. Meteorological Office)
About earlier questions about separations being increased, and a very much earlier question about reporting systems in existence in the U.S. at the moment, I would like to bring to your attention a talk I will give Thursday which will describe the new system that will soon be operating in Europe actually recording incidents at various airports across Europe which have a capacity problem. This is the problem we will be addressing. Anyone in the modeling community who will not be here on Thursday, I have some information on that and I would like your views or inputs and I can give you the information if you would see me. Otherwise stay tuned until Thursday.

# Wake Sensor Technologies Session

## NASA *First* Wake Vortex Dynamic Spacing Workshop

Session Chairperson - Ben C. Barker/LaRC

# Wake Sensor Technologies Session

- **8:00am - Wake Sensor Technologies (Chairperson - Ben Barker, NASA LaRC)**
  - 8:05am - Wake Sensor Subsystem Requirements Overview (David Hinton/NASA LaRC)
  - 8:15am - Wake Vortex Measurements Using a CW Lidar System (Rick Heinrichs/MIT Lincoln Laboratory)
  - 8:40am - Overview of Pulsed Lidar Measurements at LaRC (Phil Brockman/NASA LaRC)
  - 9:00am - Pulsed Coherent Lidar Wake Vortex Detection, Tracking and Strength Estimation in Support of AVOSS (S. Hannon/CTI)
  - 9:30am - Estimation of Aircraft Wake Vortex Characteristics from Coherent Pulsed Lidar Measurements (Les Britt/RTI)
- **10:00am - BREAK**
  - 10:15am - A 1000Hz Pulsed Solid-state Raman Shifted Laser for Coherent Laser Radar Measurement of Wake Vortices (Grady J. Koch/NASA LaRC)
  - 10:45am - Overview of Wake Vortex Radar System Development at LaRC (Robert T. Neece/NASA LaRC)
  - 11:15am - Simulation Results for Wake Vortex Radar Systems (Rob Marshall/RTI)
  - 11:45pm - Wake Sensor Evaluation Program and Results of JFK-1 Wake Vortex Sensor Intercomparisons (Ben Barker/NASA LaRC, D. C. Burnham/Scientific & Engineering Solutions, Inc., Robert P. Rudis/Volpe Center)
- **12:20pm - LUNCH**

# Wake Sensor Technologies

Workshop

- **Ground Wind Vortex Sensor System (GWVSS)**
  - Volpe Center
- **Light Detection And Ranging (LIDAR)**
  - CW Lidar System - MIT Lincoln Laboratory
  - Pulsed Lidar Systems - LaRC/CTI (Coherent Technologies)/RTI (Research Triangle Institute)
- **Radio Detection And Ranging (RADAR)**
  - LaRC/USArmy Missile Command/Phase IV
  - RTI
- **Radar Acoustic Sounding System (RASS)**
  - WLR Research
- **SOnic Detection and Ranging (SODAR)**
  - BFG Tech Integration
- **Scintillometer**
  - Scientific Technology, Inc. (ScTI)
- **Scanning Microwave Radiometry**
  - Battelle Pacific Northwest Laboratories
- **Infrared Imaging**
  - Vortex Imaging, Inc.
- **Bistatic Sodar Measurements**
  - Aerovironment
- **Ultrasonic Tomographic Imaging**
  - Tufts University

AVSWG

# AVOSS Sensor Working Group (AVSWG)

- **Objectives**
  - **Evaluate** New Wake and Weather Sensor Technologies
  - **Guide** Future JFK Test Programs
  - **Synthesize** AVOSS Sensor System Approaches and Make Appropriate Recommendations to RSO
- **Membership**
  - **Government Agencies**
  - **National Laboratories**
  - **Industry**
  - **Academia**
- **Meetings**
  - **Dates** - As Required
  - **Place** - Volpe Center, Boston, MA
  - **Next Meeting** - Following this Workshop in the Pearl I. Young Theater. Parties Interested in Attending Please Register With Ben Barker Prior to the End of Day 2.

# The Wake Sensor
## (As the AVOSS Principle Investigator Sees It)

"Wake Vortex Miracle Sensor"

- Smaller than a breadbox!
- Cheaper than the latest PC from CompUSA!
- Covers all airport runways with a single sensor!
- Covers the entire glide slope!
- Sees through tall buildings, and all weather & terrain conditions!

# Wake Vortex Sensors Requirements Overview

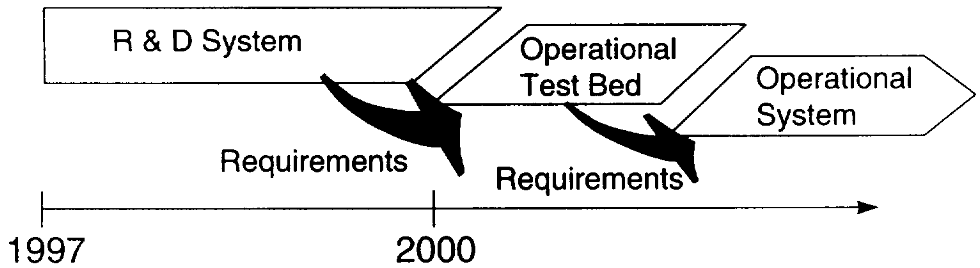
David A. Hinton
NASA - Langley Research Center
First Wake Vortex Dynamic Spacing Workshop
May 13-15, 1997

# Primary Wake Vortex Sensor Requirement

- To provide data products that allow AVOSS to validate predictions of the elapsed time from aircraft passage through an approach window and either:
  - Exit of the generated wakes from the corridor

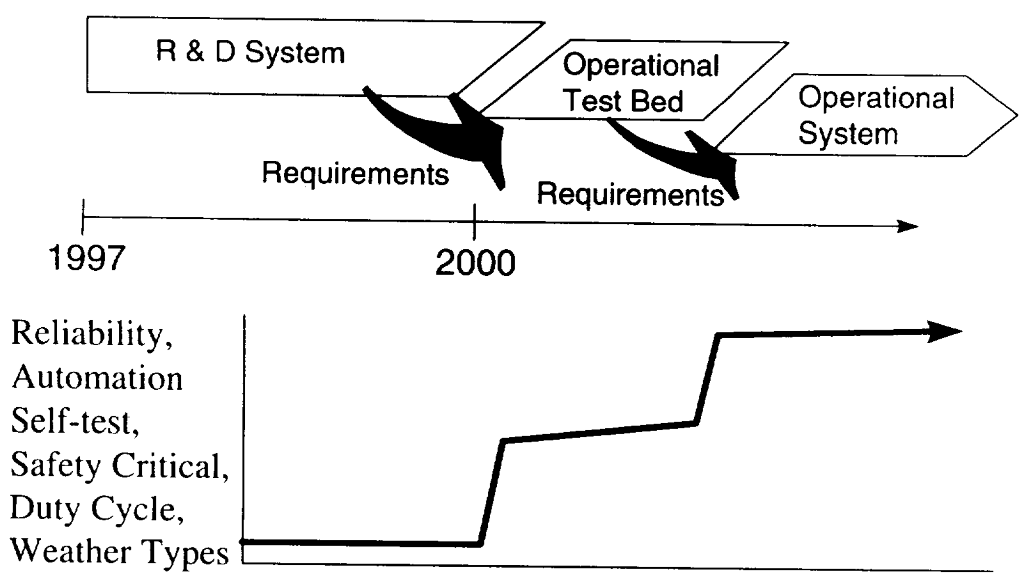
    or
  - Decay/demise of the wakes to an acceptable strength.
- Safety Monitor.

# System Requirements Evolution Model

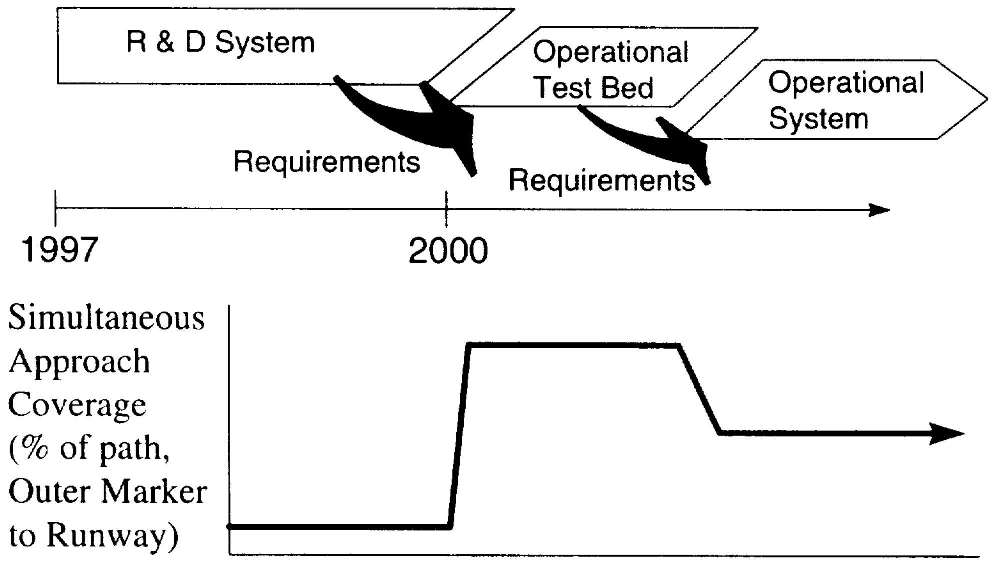



- Wake vortex sensor requirements to vary with evolution of the system.
- Each system generation needed to generate/refine sensor requirements of the next generation.

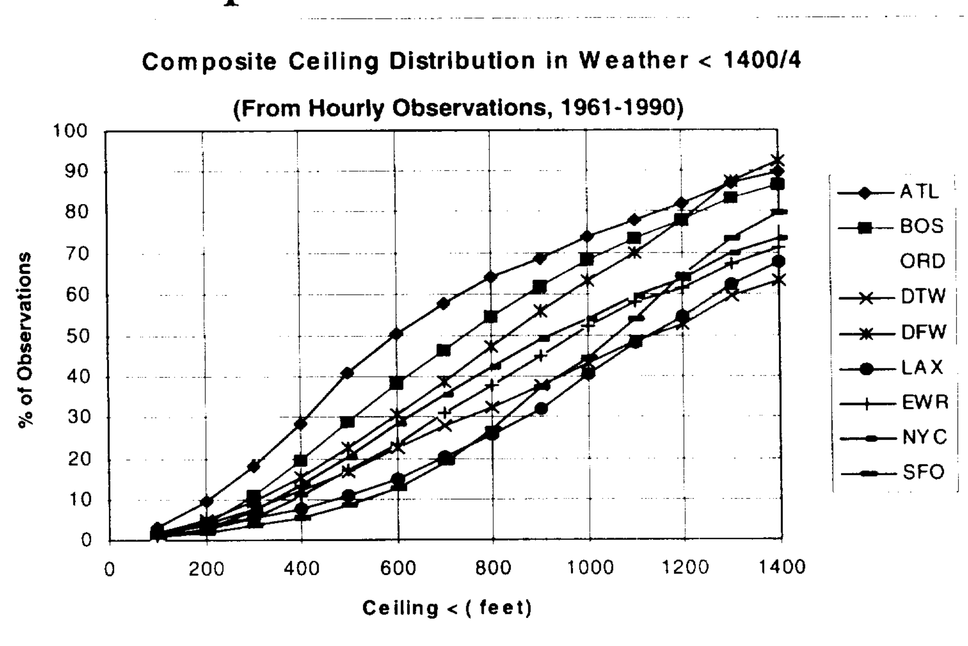
# Wake Vortex Sensor Evolution



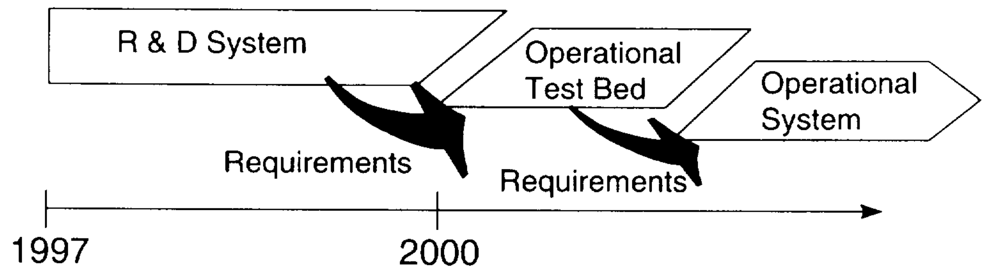
# Wake Vortex Sensor Evolution

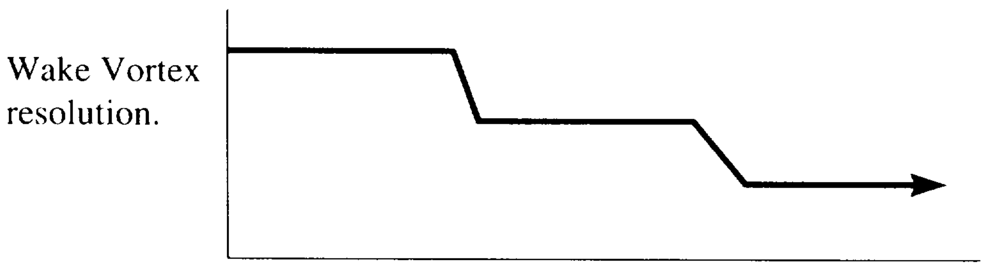



# Site Specific Sensor Tradeoffs



# Wake Vortex Sensor Evolution




# Research & Development System

- Wake Sensor Functions:
  - Numeric wake model validation.
  - Detailed wake behavior studies.
  - Support development of real-time wake prediction tools.
  - System-level integration and testing.
  - Provide near real-time wake strength & position.
- Deployment Considerations:
  - Short period deployments, 2 to 4 weeks.
  - No actual aircraft separations changed, minimal self-test or safety implications.
  - Little automation required.
  - May scan different regions of approach path on different days.
  - Clear weather sensing adequate.

# Operational Test Bed System

- Wake Sensor Functions:
  - Ensure system safety for reduced separations.
  - Detect, track, and quantify wakes until corridor exit or decay.
  - Provide real-time position/strength to AVOSS.
  - Prove or disprove need for full approach coverage in a wide range of weather types and events.
- Deployment Considerations:
  - Long-term operations required, > year.
  - Limited aircraft separations changed.
  - Significant safety and automation implications.
  - Simultaneous coverage of entire defined approach corridor.
  - Sensing in instrument-operations weather (IMC and VMC).

# Operational System

- Wake Sensor Functions:
  - Detect, track, and quantify wakes until corridor exit or decay.
  - Provide real-time safety monitoring to AVOSS and manual or automated ATC systems.
- Deployment Considerations:
  - Continuous operation.
  - Significant sensor safety, automation, and reliability implications.
  - Provide coverage of TBD regions of the approach path.
  - Provide coverage in TBD % of IMC and VMC weather.

# Additional Sensor Requirements

- Compatibility with real-world siting limitations.
- Environmental impact and public nuisance.
- Detection of wakes potentially returning to corridor.
- Unattended, highly reliable operation in a wide range of environmental conditions.
- Tracking wakes in presence of ambient turbulence and shear. Very low probability of premature track loss.
- Removing false detections.
- Discrimination of simultaneous presence of wakes from multiple aircraft.

**Questions and Discussions Following Dave Hinton's Presentation (Langley)**

James Hallock (Volpe Center)
I loved your chart on visibility and cloud cover, etc. When I look at that, DFW is down on your list, so why is that your number 1 test site.

Hinton (Langley)
There are a number of reasons for going to Dallas-Fort Worth. One is we are co-located with ITWS testbed. We are co-located with Ames Center TRACON Automation System (CTAS) testbed. There are systems we need to interface to. Secondly, actually the Dallas-Fort Worth line is basically a straight line which means equal probability of each of those ceilings at Dallas. That chart did not show the total occurrence of IFR conditions. What it showed was among those conditions what is probability distribution of these ceilings. Dallas actually gets quite a bit of instrument condition in the Winter/Spring area. Certainly Logan gets more.

# Wake Vortex Measurements with a CW 10.6-μm Coherent Laser Radar

-02
048399
318635
12p.


R.M. Heinrichs

M.I.T. Lincoln Laboratory



NASA First Wake Vortex Dynamic Spacing Workshop

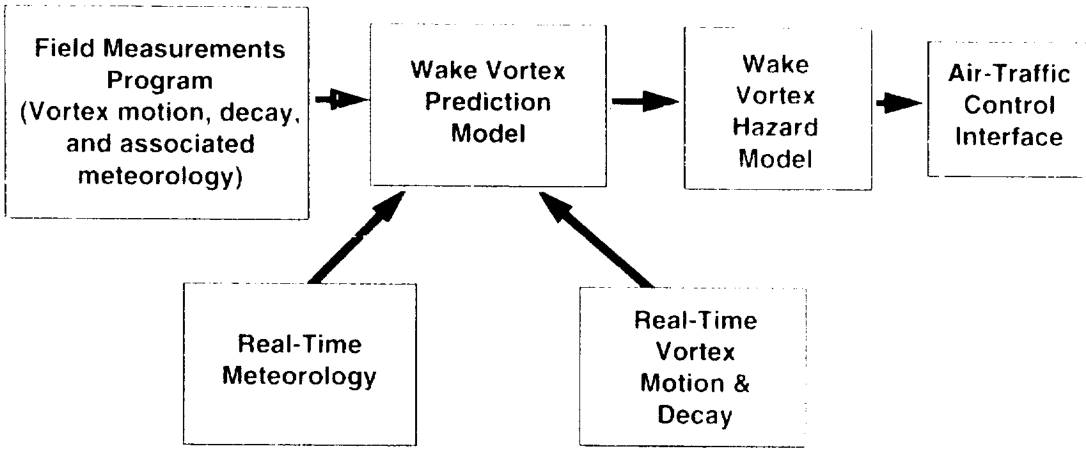
May 14, 1997



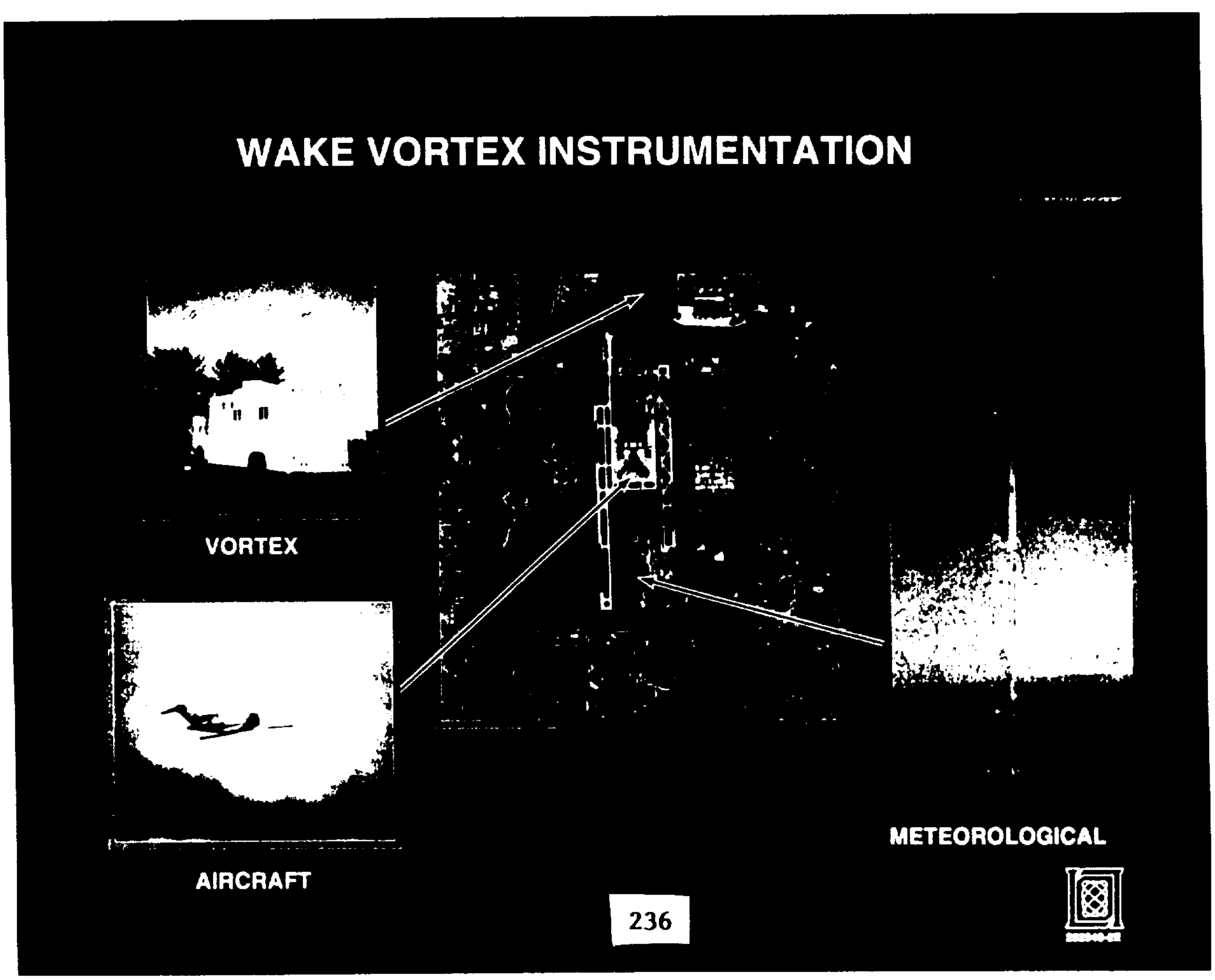

# Outline

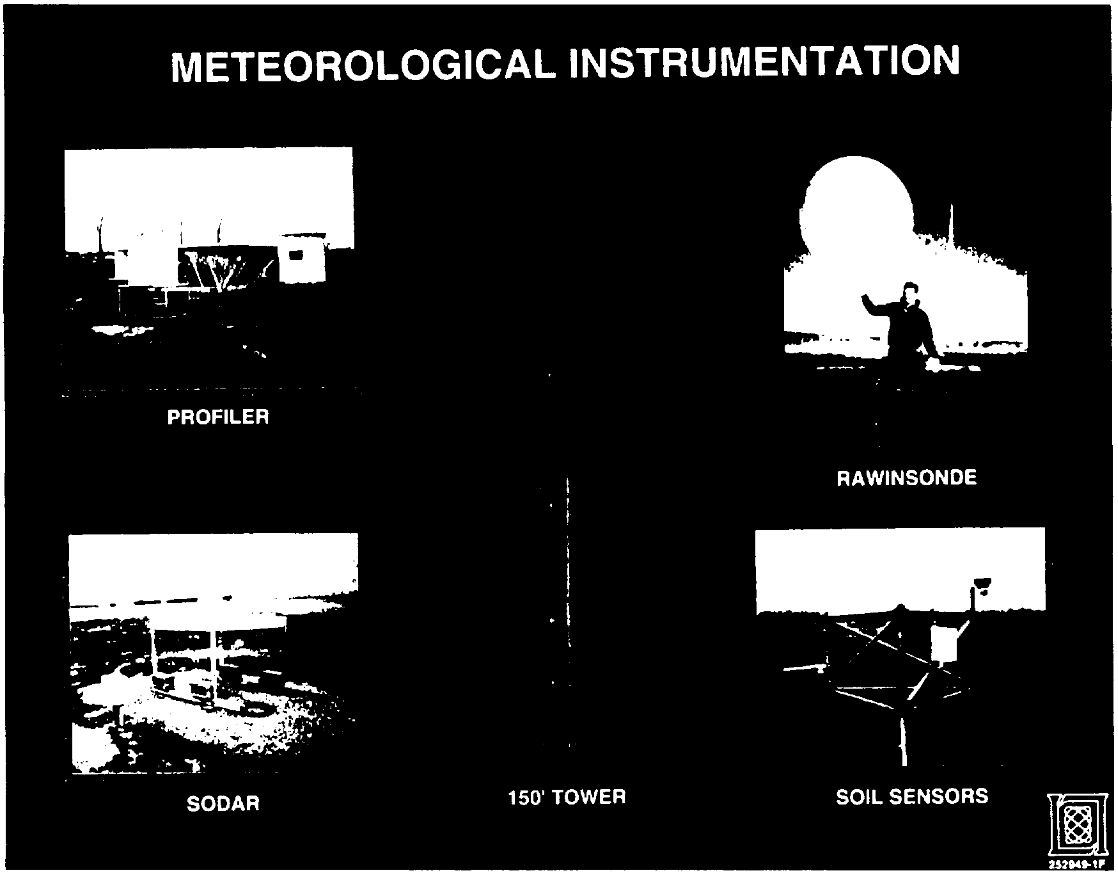
- Overview of Lincoln role in AVOSS program
- Lidar description
- Vortex range determination
- Vortex circulation determination
- Summary

# Requirements for Instituting a Wake Vortex Advisory System

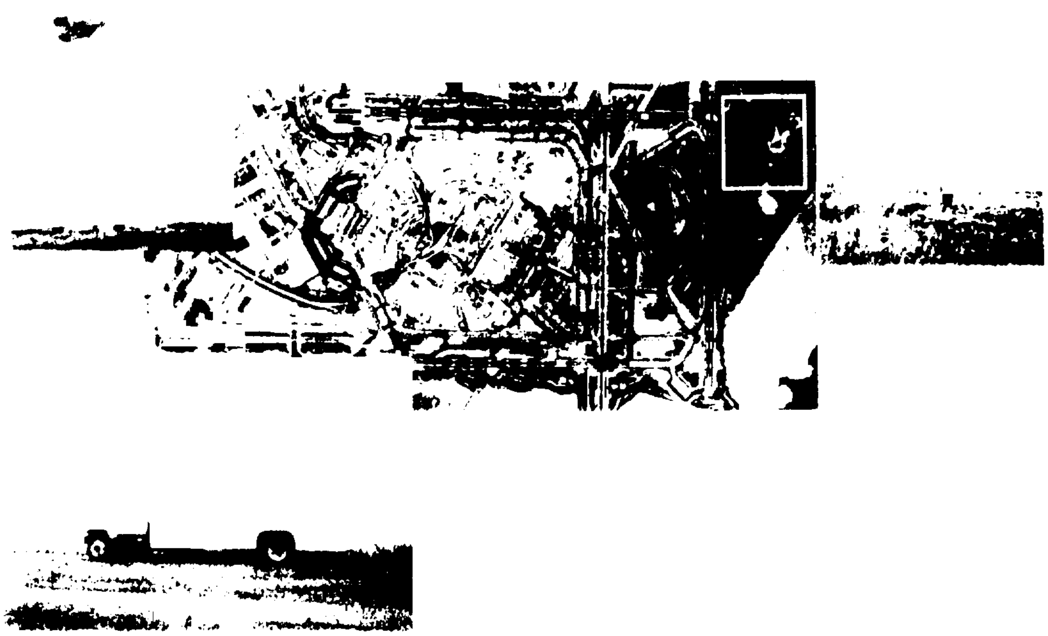


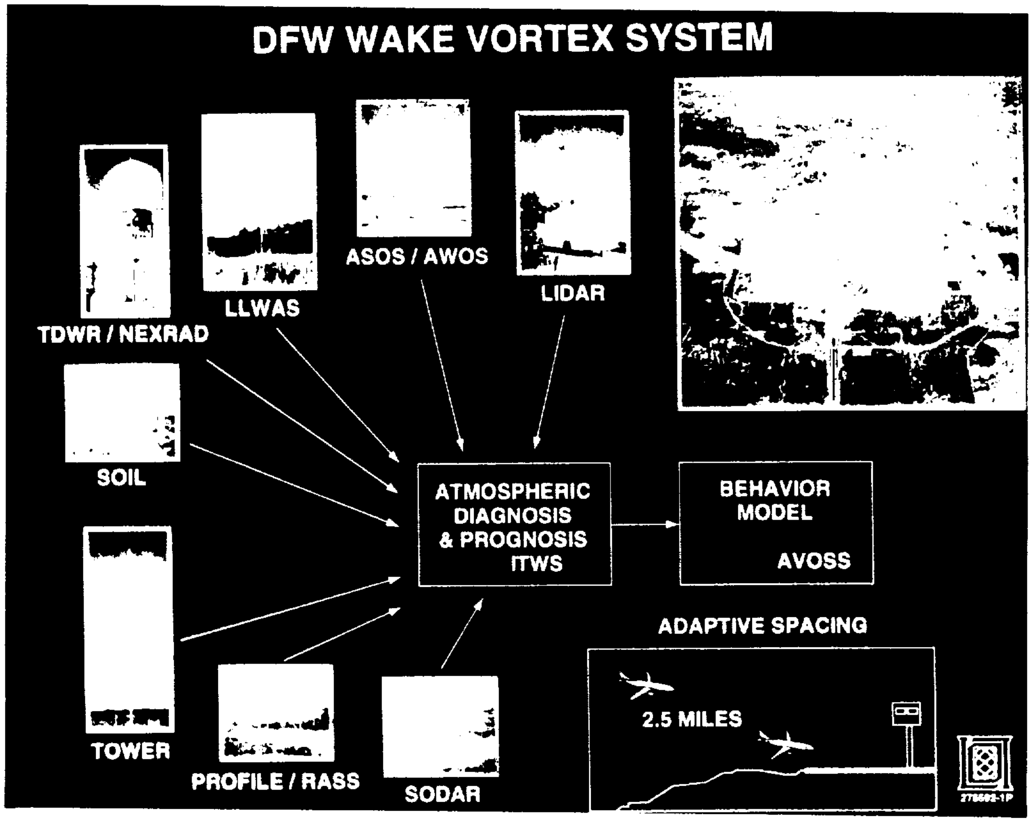


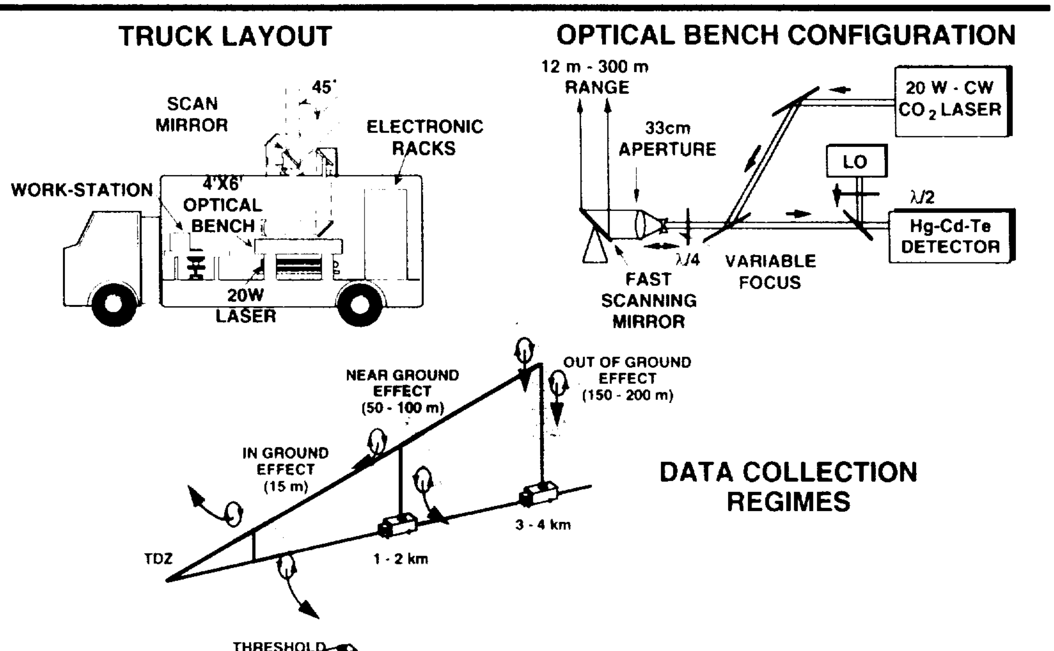



## JFK WAKE VORTEX MEASUREMENTS



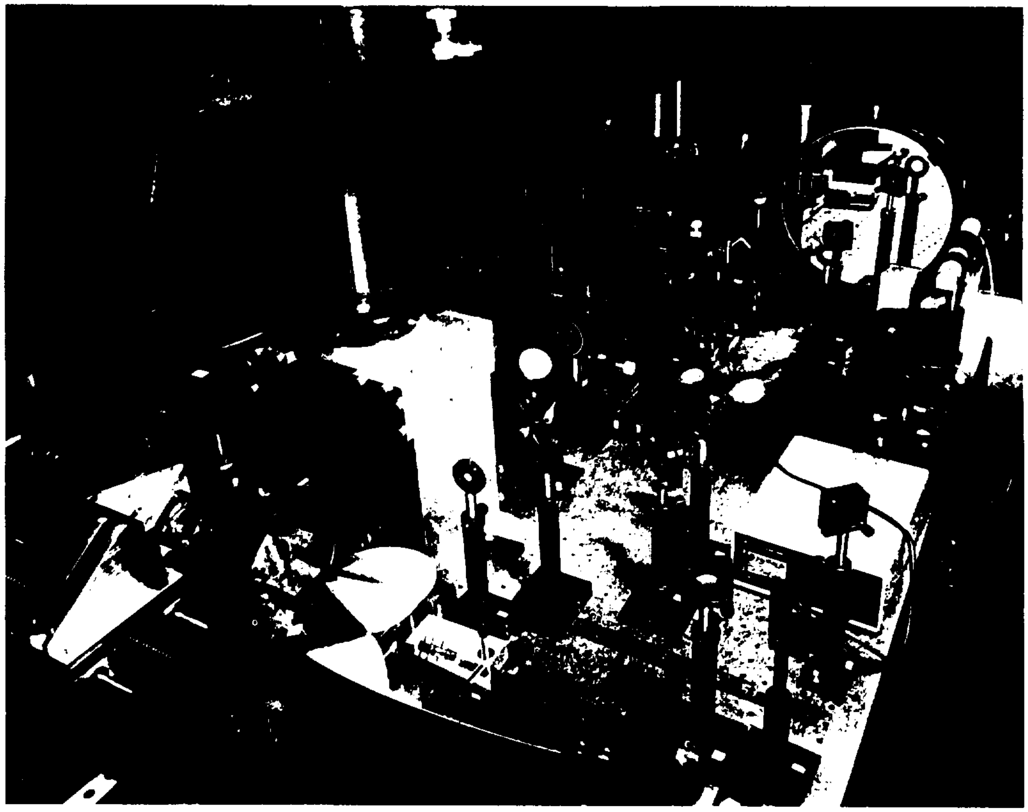


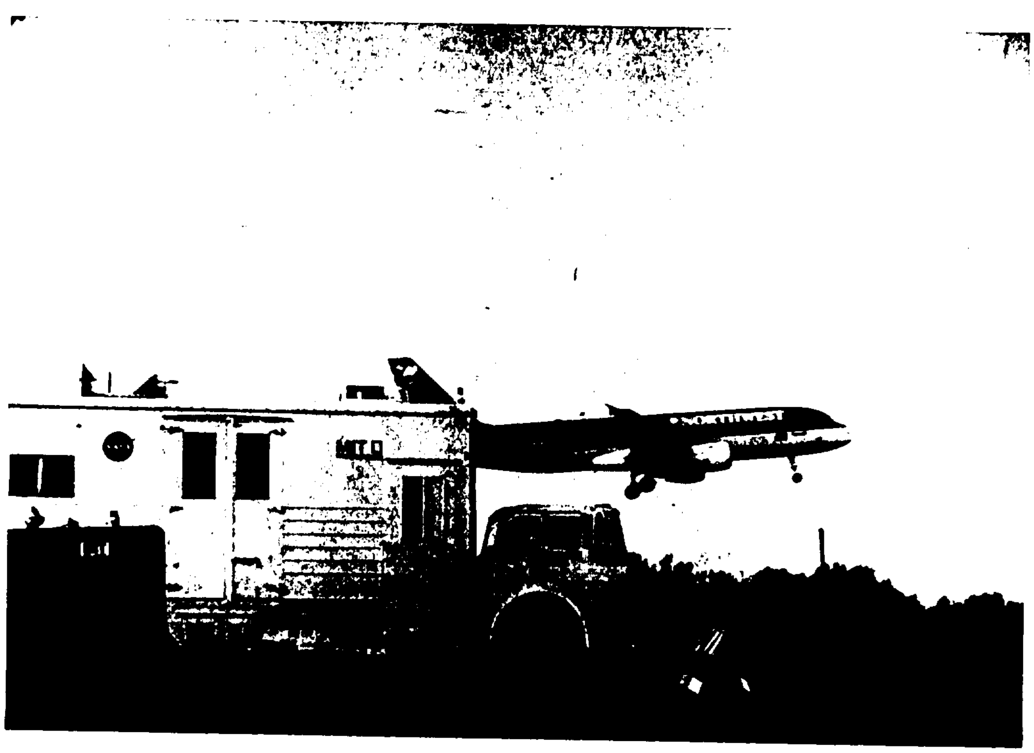

# Lincoln Laboratory CW Coherent Laser Radar



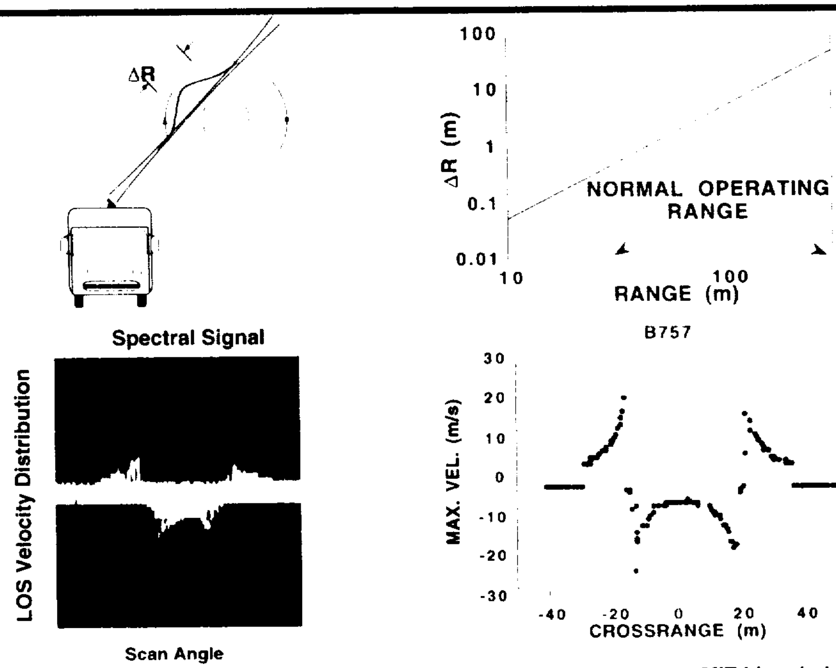

NASA Workshop-4
RMH 5/12/1997

MIT Lincoln Laboratory




NORTHWEST

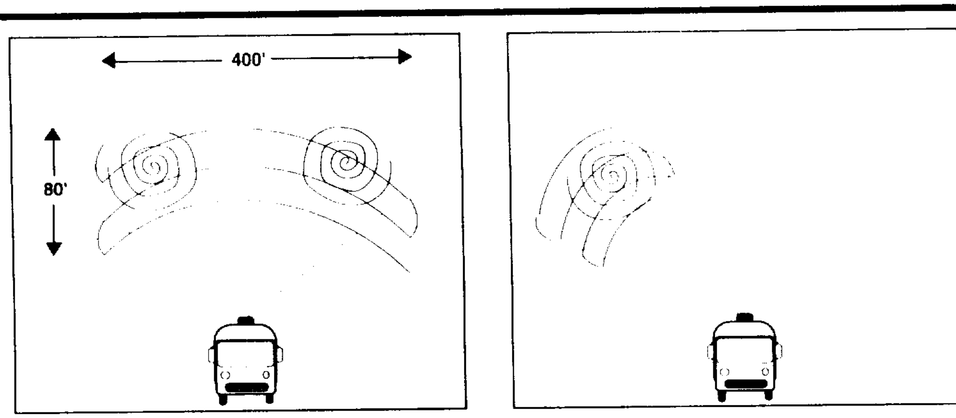
## CW Lidar Vortex Signal




MIT Lincoln Laboratory

NASA Workshop-5
RMH 5/12/1997

## Vortex Scan Strategy

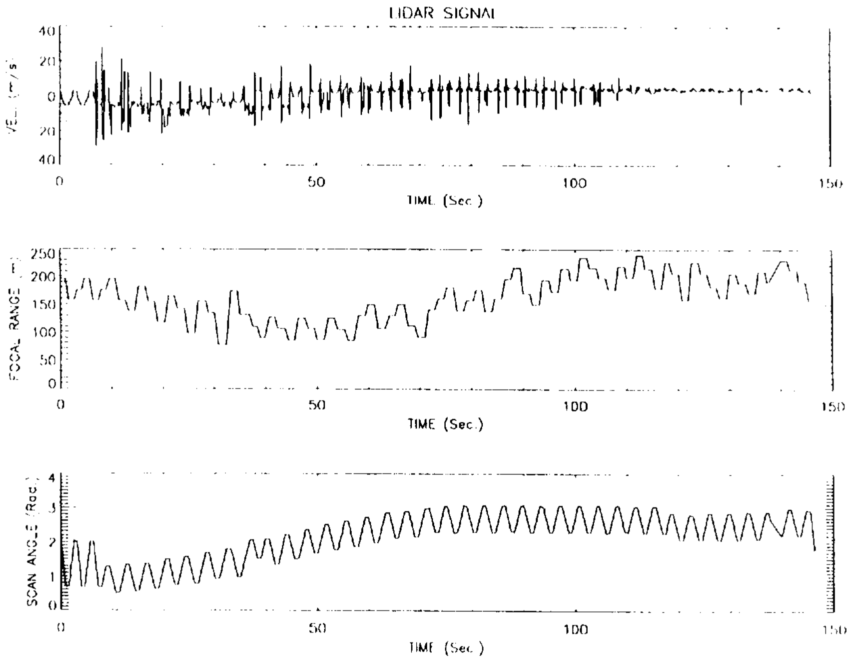



- Initial acquisition
  - Scan region around glide path
  - Identify vortex locations and choose which vortex to track
- Vortex tracking
  - Conduct finer scans in region of space where vortices are located
  - Maintain scan region large enough to allow for vortex motion (predicted from wind velocity meas. and vortex strength)

MIT Lincoln Laboratory

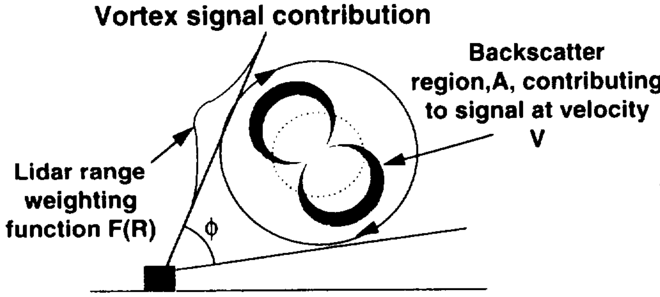
NASA Workshop-6
RMH 5/12/1997

# VORTEX TRACKING EXAMPLE




# Vortex Range Estimation

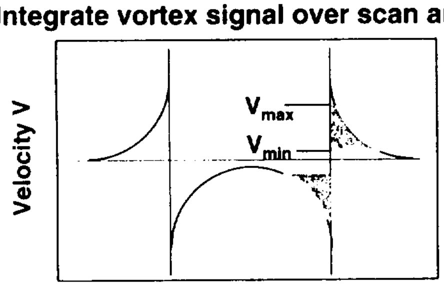
**Vortex signal contribution**




**For a 1/R vortex velocity field:**

$$A = \sum_{\phi} I_{spect}(V) \approx \frac{\alpha F(R)}{V^3}$$

**Integrate vortex signal over scan angle**

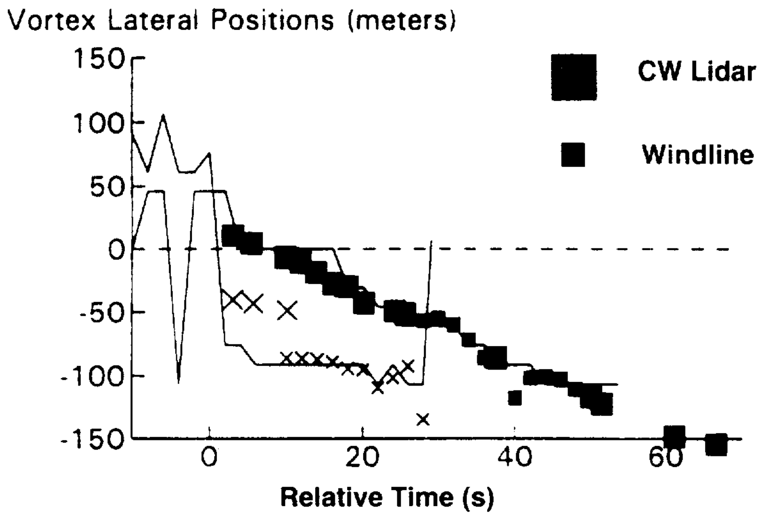



**Algorithm:**

- **Calculate** $\sum_{\phi} I_{spect}(V) \equiv S(V)$ **for each vortex scan**
- **Simultaneously solve** $S(V) = \frac{\alpha F(R)}{V^3}$ **for a running set of 3 sequential vortex scans**

# Vortex Range Results Compare Well with Windline Measurements

**JFK - 11/20/96 A-330**

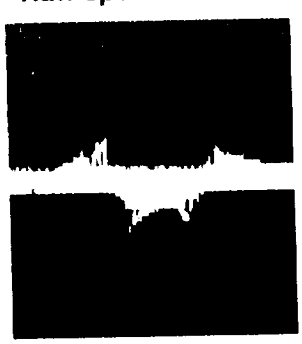



MIT Lincoln Laboratory

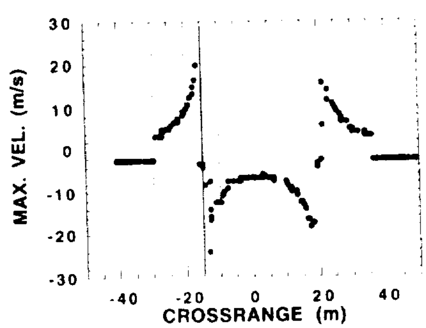
NASA Workshop-8
RMH 5/12/1997

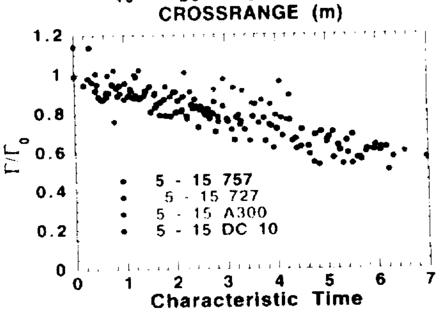
# Vortex Circulation Estimation

**Raw spectral data**



**Spectral maximum velocity**




**Algorithm:**

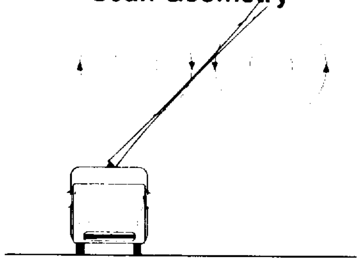
- Extract maximum velocity from spectral data (compensate for spectral spreading)
- Averaged circulation given by: $\Gamma \approx 2\pi \sum_{|r_{min}|}^{|r_{max}|} |r_i V_i|$
- Compare with: $\Gamma_0 = \dfrac{Mg}{\rho v \left(\dfrac{\pi}{4}\right) b}$

MIT Lincoln Laboratory

NASA Workshop-9
RMH 5/12/1997

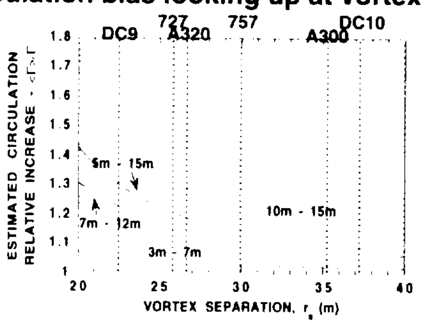
# Circulation Estimate Bias Due to Neighboring Vortex

Scan Geometry

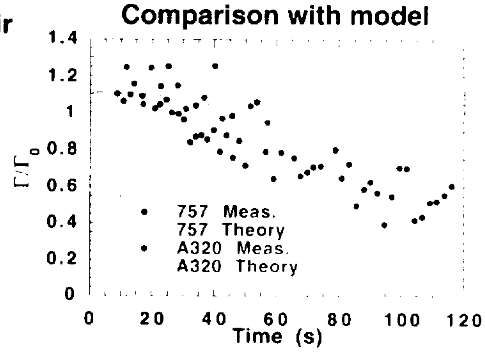


- Circulation calculated from spectra on both sides of core averages out bias due to uniform velocity fields
- Nonuniform flow from neighboring vortex results in residual bias

Circulation bias looking up at vortex pair

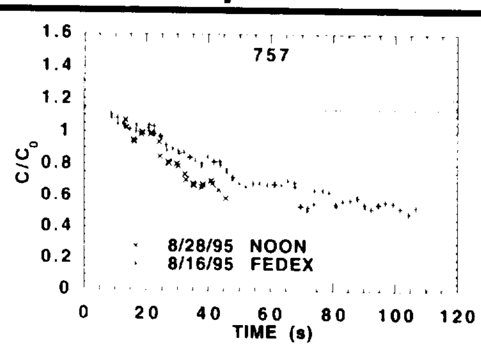


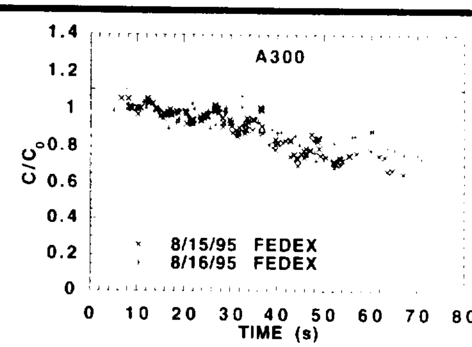

Comparison with model

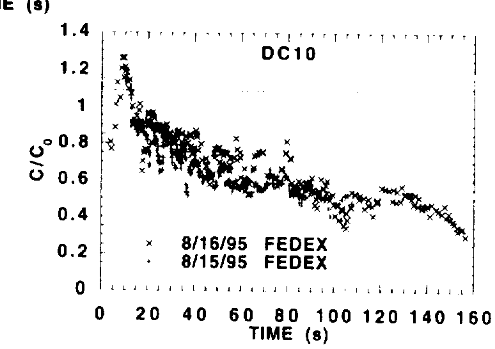




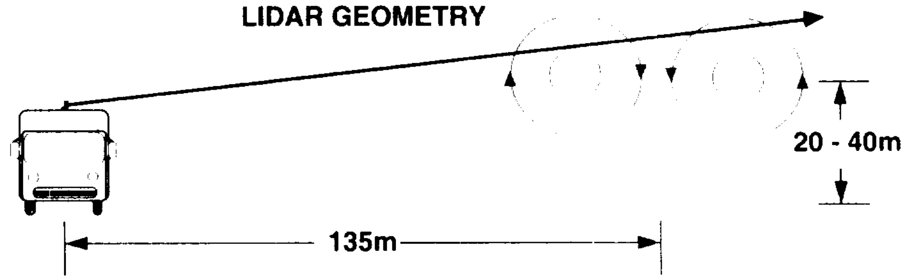

# Relative Circulation versus Time Comparison with Expected Initial Value

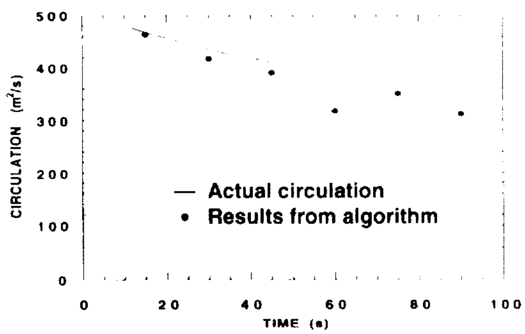


## Use Theoretical Velocity Fields to Test Circulation Algorithm






## Summary

- CW coherent laser radar provides detailed vortex measurements at ranges ≤ 400 m
- Lincoln Laboratory has collected simultaneous wake vortex and meteorological data at Memphis for validation of vortex behavior models
- Vortex range estimated from angular integral of velocity spectra versus velocity
  - Results compare well with windline data
- Vortex circulation estimated from spectral maximum velocities
  - Circulations (especially of smaller aircraft) can be biased due to flow from neighboring vortex
  - Results agree well with theory when bias is considered

**Questions and Discussions Following Rick Heinrichs' Presentation (MIT Lincoln Lab)**

Frank Cheshire (American Airlines)
On one of your earlier slides you had real time meteorology. Could you describe what you mean by that?

Heinrichs
I mean for any kind of wake vortex advisory system. I was afraid people would read too much into it. What I mean is that in any kind of advisory system you have to measure the weather and you have to predict what the weather is going to be in order to predict what the vortices are going to do. So you have to measure the weather in realtime. At Dallas-Fort Worth, as part of the AVOSS demonstration, we will have Lincoln wake vortex sensors as well as with the Integrated Weather System which was developed by Lincoln Laboratory that will feed in.

Klaus Sievers (Vereinigung Cockpit)
What is the reliability of the automated vortex tracking function that you have implemented? Would it be suitable in the role to know that no vortices exist in an approach pass?

Heinrichs
Yes, I believe so. Sometimes we will lose vortices out of range, but we can say there is not a vortex.

Sievers
So that would be a very important component of any system like AVOSS.

Heinrichs
I don't think there is any question that a CW lidar can make detailed measurements of wake vortices. As far as eventual use of monitor system in AVOSS, the real problem because of the range, means you would need at least one system, maybe even more than one system per runway. That is one of the major considerations there.

Pal Arya (North Carolina State Univ.)
Have you calibrated lidar against another standard sensor and do you have any idea of measurement uncertainty of velocity and the circulation?

Hienrichs
As far as coherent lidar calibration, what that refers to is calibrating the sensitivity of the lidar, not velocity measurements themselves. The calibration on velocity measurement is clock calibration. We use a temperature control crystal clock that is highly accurate. The velocities themselves usually have less an uncertainty, where the uncertainty exists is in interpretation of that data. We have not done that kind of calibration because it is in a sense, if we know velocities, we know that. As for us comparing it with other sensors, that is one of the purposes of the JFK field test in the

comparing of lidar with other sensors. The comparison seems to have been very positive based on preliminary data, giving good comparisons when looking at the same vortex.

Tom Holbrook (Virginia Tech.)
Is your weighting function similar to a sample volume and can you increase your resolution by increasing the angle intersection between your beams?

Hienrichs
The weighting function to the first order is Lorentz for those who are electrical engineers. It is basically a function with long tails, unlike sample volumes that radar or pulse lidar have in which the sample volume is well defined. Because of these long tails we can get contributions from ambient wind or even clouds that happen to be far away. That is why we use the algorithm we do to estimate vortex range. In order to increase the resolution, one way is to decrease range to the vortex since resolution goes as square of range. The other way is to increase the aperture size because resolution goes as square of aperture diameter.

Ben Barker (Langley)
On one of your slides you compared position measurement with that of the wind line and showed how that compared. I didn't catch what the X's were.

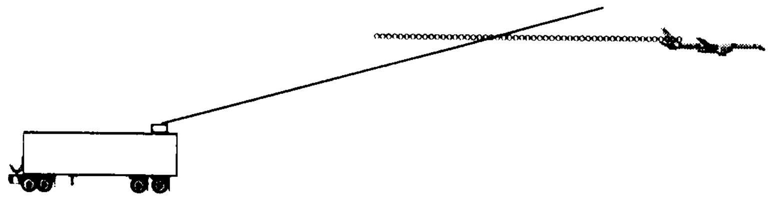
Hienrichs
One is the port vortex and the other is starboard. The X's in this case are the other vortex. The small X being the wind line, the large X's being the CW lidar. I highlighted the squares, not only because they read a little better, but also because it was tracking this particular vortex, so you would expect to have better results because the focus was centered around that vortex as opposed to other.

Barker
Thank you Rick. I expect people to do the same to our data when we present it.

# WAKE VORTEX LIDAR SYSTEM

## OVERVIEW OF LARC PULSED LIDAR MEASUREMENTS

S17-02
048100
318636
14P.



PHILIP BROCKMAN

March 14 1997

WAKE VORTEX LIDAR

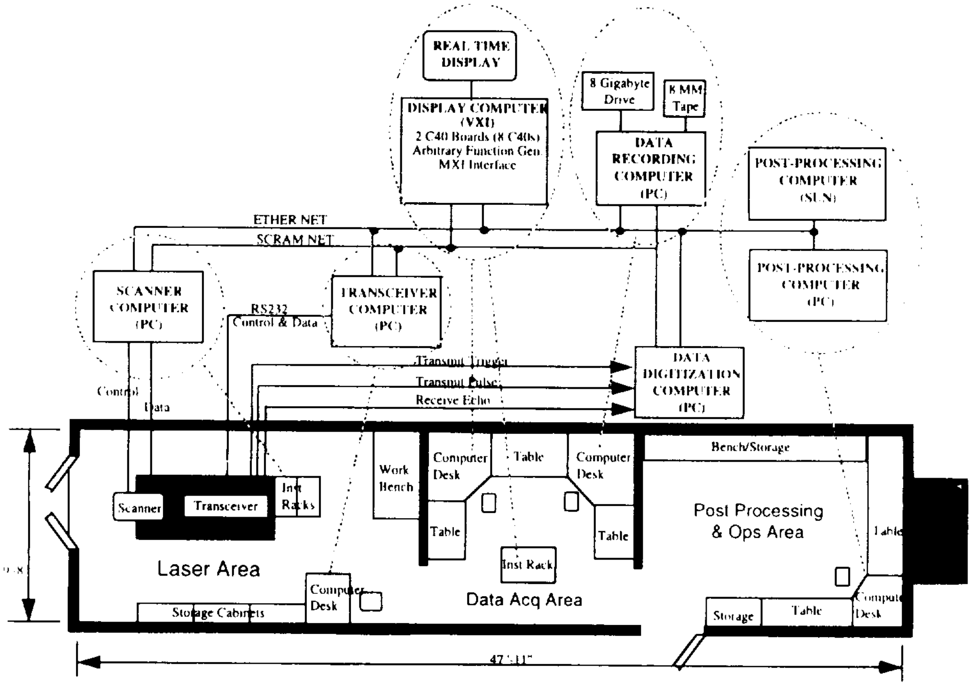
TEAM:
NASA-LARC, LESC/NYMA, STC, SAIC,
RTI, CTI, CLEMSON UNIV., UNIV. OF S. FLA.

AGENDA:

- TRAILER FACILITY
- LASERS/TRANSCEIVERS
- SCANNERS
- DATA SYSTEMS
- DEPLOYMENTS

## LaRC Lidar Trailer

# LIDAR TRAILER LAYOUT

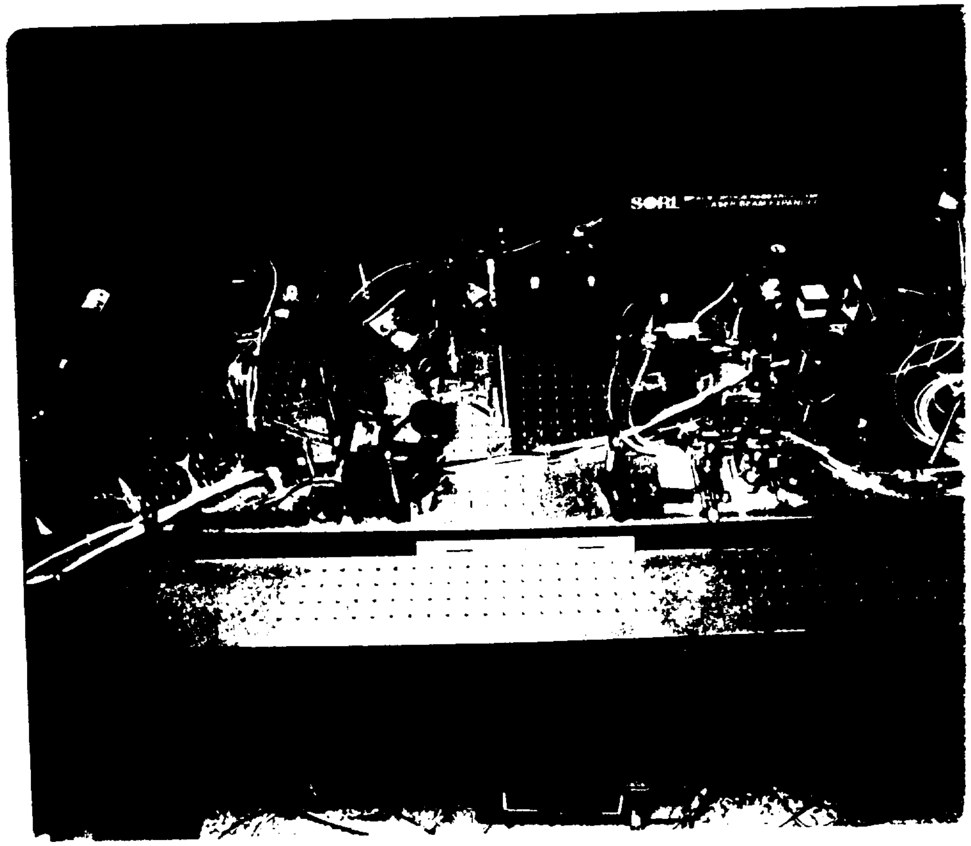



## LASERS/TRANSCEIVERS

- LARC/ARPA-LOCKHEED SANDERS/AIRFORCE
  2 µm, 3 mJoule, 20 pps, 180 ns
- CTI SBIR
  2 µm, 7 mJoule, 100 pps, 380 ns
- LARC/LITE CYCLES INC.
  1.5 µm, 10 mJoule, 1000 pps, 100 ns

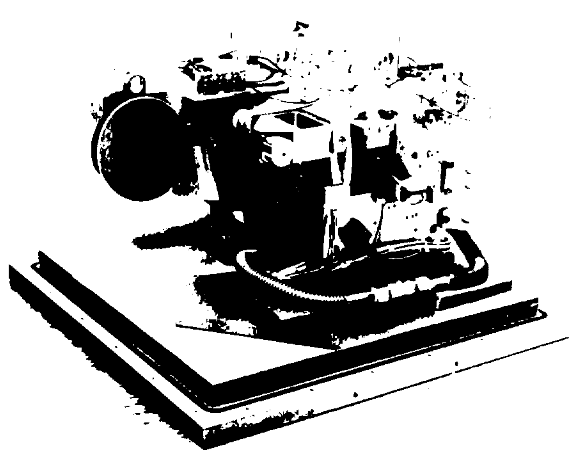
## SCANNERS

- DFM
  2 Hemispherical, 20 cm dia., λ/10 @ 633nm



## Transceiver Hardware (Enclosure Removed)

COHERENT TECHNOLOGIES, INC

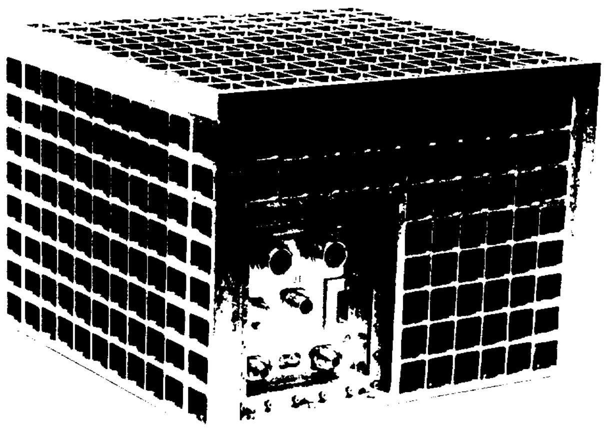


NASA WAKES Final Review

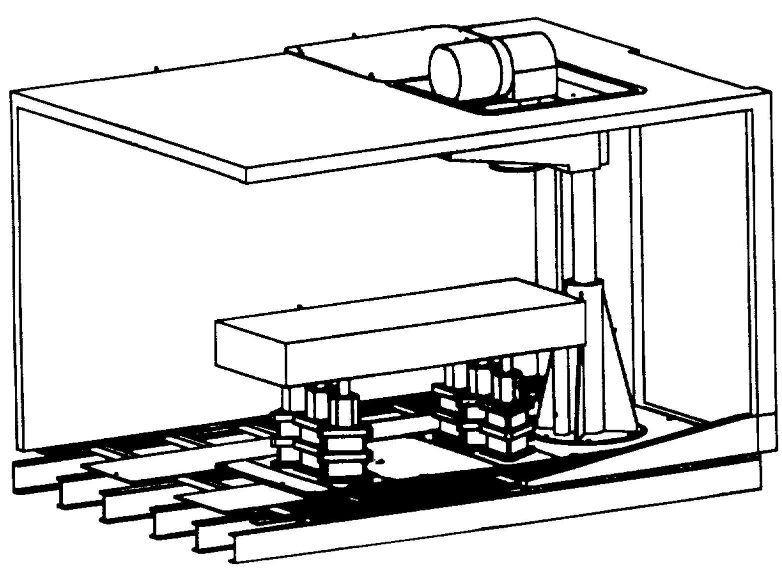
## Environmental Enclosure

COHERENT TECHNOLOGIES, INC

Pressure vessel back-filled with dry air to 16 psiA, capable of operation in vacuum.



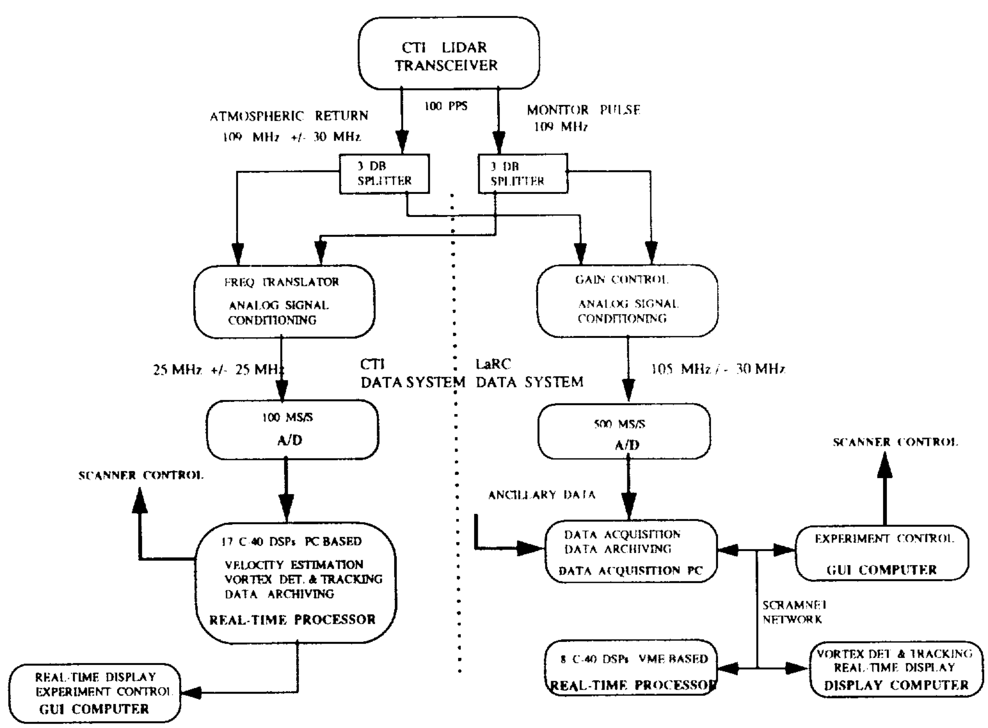
# Mobile Lidar Test Facility
# Optical Bench and Scanner Installation



# DATA SYSTEMS

• NASA/LESC/RTI
8 C-40 DSPs
105 MHz IF 75-135 MHz sampled at 500 Msamples/second
Doppler frequency (measured from laser pulse frequency) and spectrum calculated in DSPs, other products in PC
-Digital filter bank front end being developed for 1000 pps system

• CTI SBIR
14 C-40 DSPs
~105 MHz IF (measured from laser pulse) downconverted to 25MHz. 0-50 MHz sampled at 100 Msamples/second. All products calculated in DSPs.




LaRC AND CTI SBIR DATA SYSTEMS IN DUAL OPERATION

## DEPLOYMENTS

• NOMINAL TRAILER POSITION BEHIND BD. 1202
LOW ANGLE VIEWS BLOCKED BY TREES, WATER TOWER PROVIDES 700 m HARD TARGET.

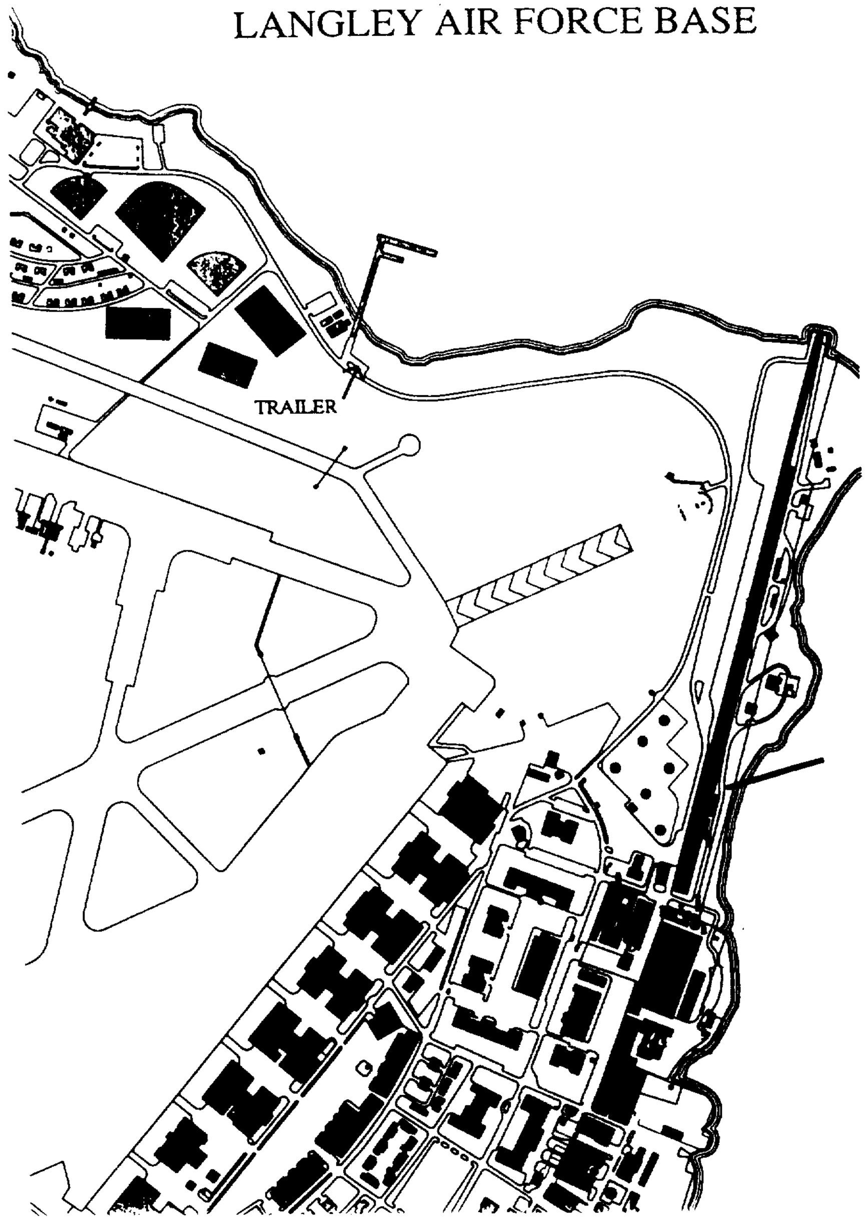
• LANGLEY AFB
11/96 3 WEEKS. SYSTEMS TESTS USING 3mJ LASER. POSITION CLOSE TO TOUCHDOWN POINT.

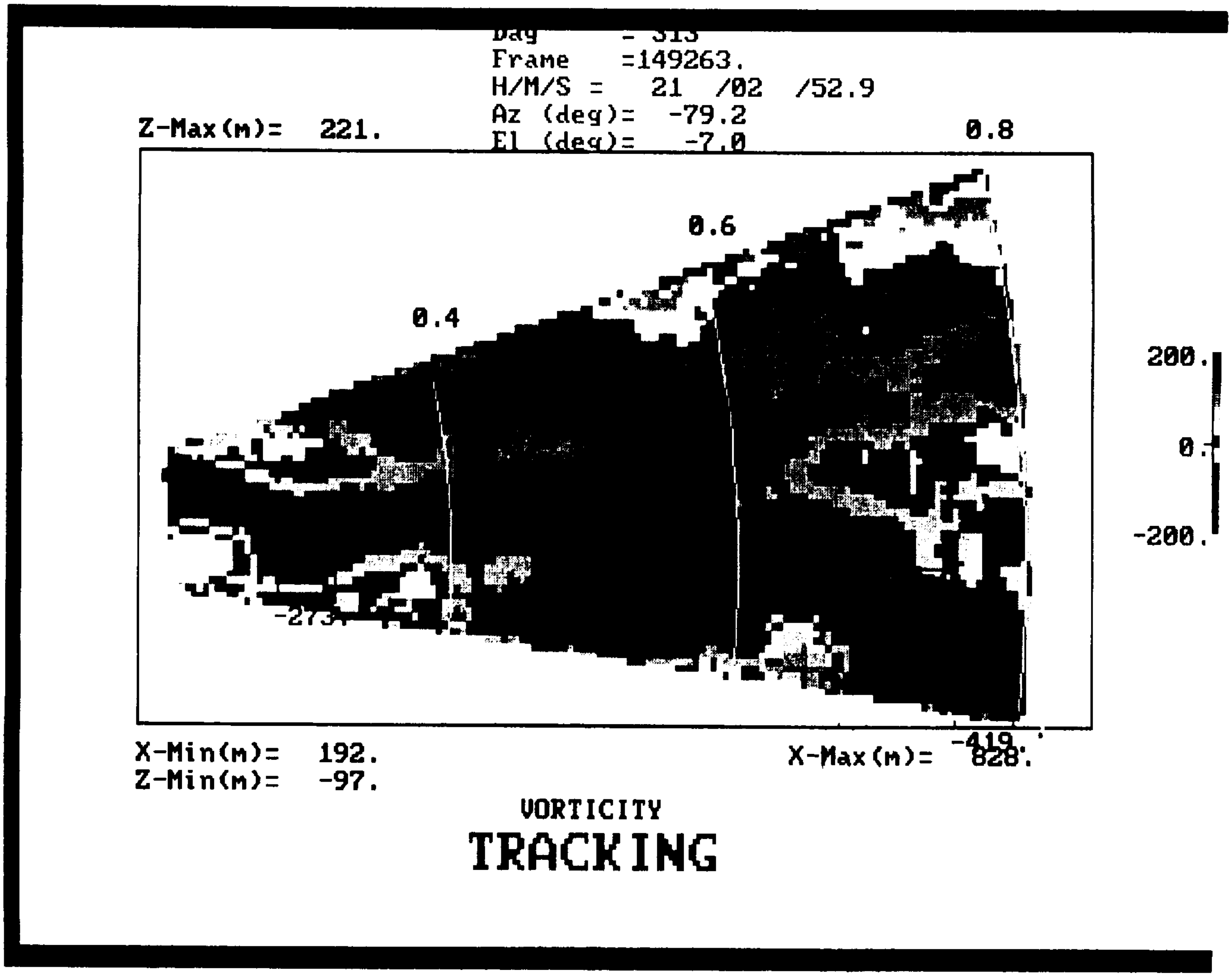
• NORFOLK AIRPORT
2/18-3/20 97 SYSTEM TEST USING BOTH LASERS AND DATA SYSTEMS. 445 m FROM FLIGHT PATH 509 m FROM THRESHHOLD RUNWAY 5. GROUND VIEW AT FLIGHT PATH BLOCKED BY VEGETATION

• JFK LATE MAY 97

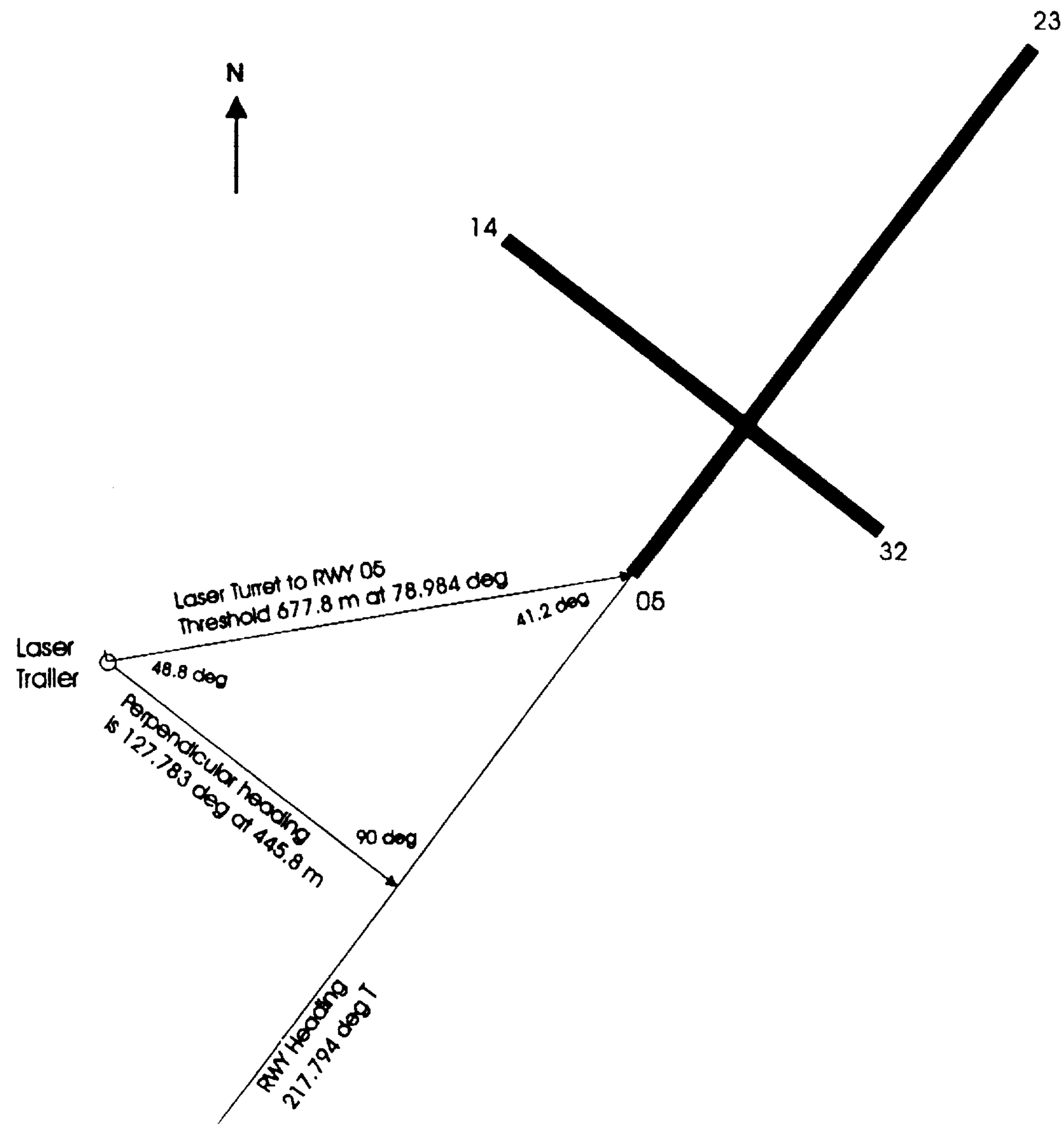
•DFW SUMMER 97

# LANGLEY AIR FORCE BASE




Frame =149263.
H/M/S = 21 /02 /52.9
Az (deg)= -79.2
El (deg)= -7.0
Z-Max(m)= 221.
0.8
0.6
0.4
200.
0.
-200.
X-Min(m)= 192.
Z-Min(m)= -97.
X-Max(m)= 828.
VORTICITY
TRACKING

# Laser Trailer / Norfolk Airport Runway Geometry

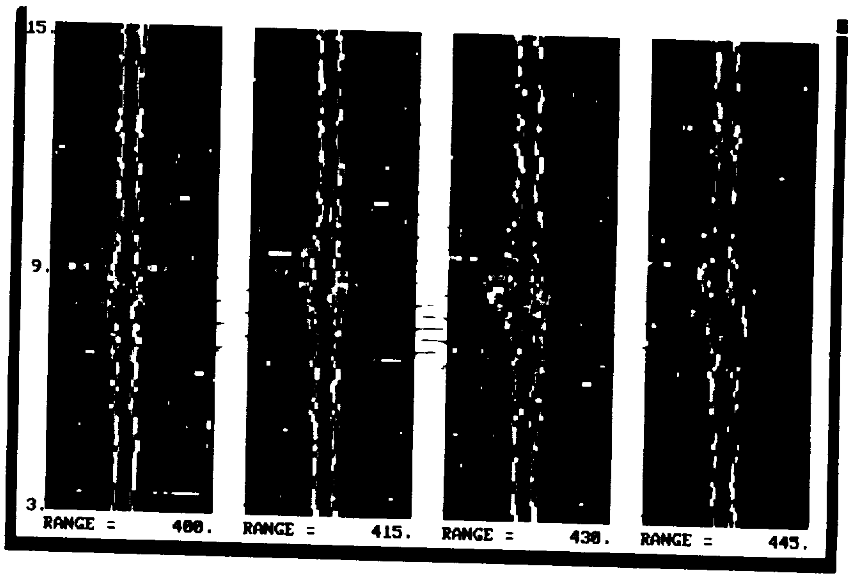


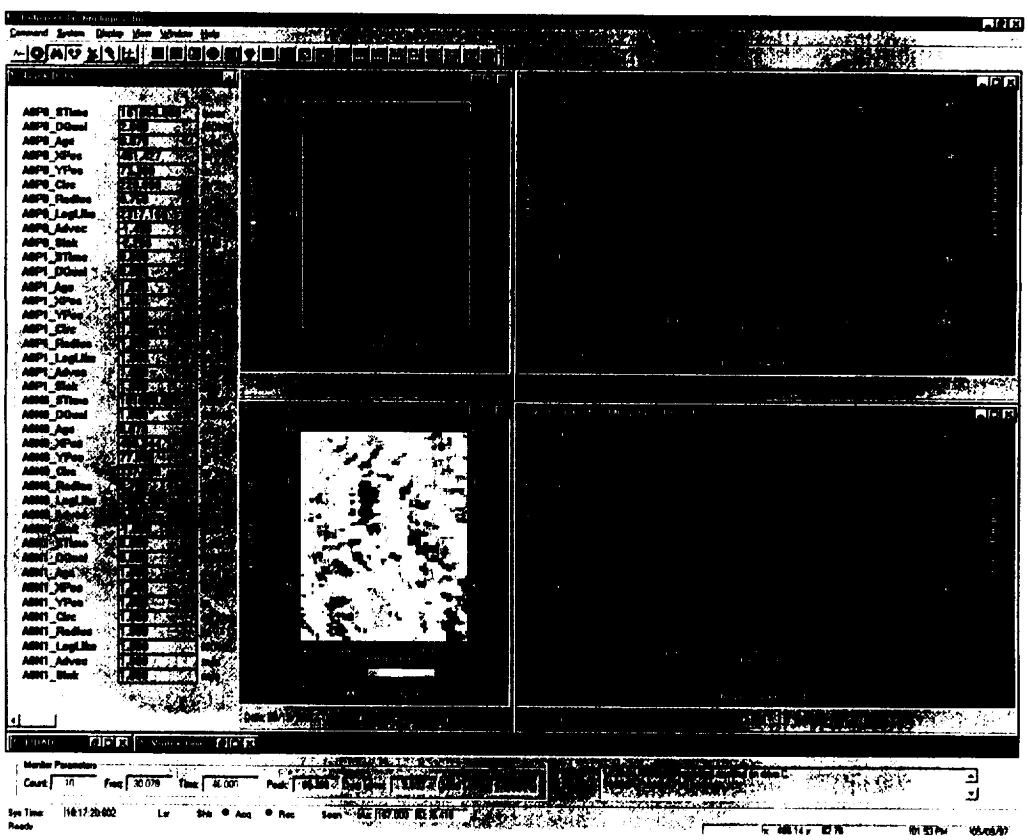
NASA-RTI DATA SYSTEM

MD-80 LANDING AT NORFOLK

FFTs vs VERTICAL SCAN ANGLE AT 4 RANGE CELLS

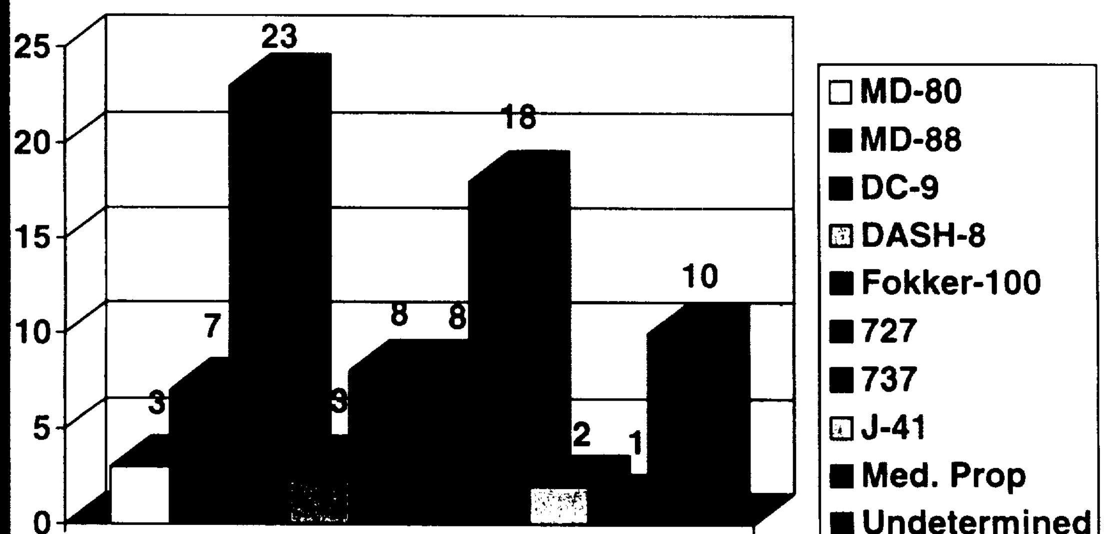
VELOCITY RANGE +/-16 m/s



DC-9 @ NORFOLK

# *Types of Aircraft*
## *Observed at ORF*




Research Triangle Institute RTI 05/14/97

## Norfolk International Airport Deployment Data Set

| Date | Number of Data Files | Configuration | Weather | Data Acquisition System |
|---|---|---|---|---|
| 2-18-97 | 6 | Take-offs on 23 | clear, sunny | LaRC |
| 2-19-97 | 2 | Take-offs on 23 | clear, sunny | CTI |
| 2-20-97 | 16 | Landings on 5 | clear, sunny | LaRC |
| 2-21-97 | 8 | Take-offs on 23 | rain, cloudy | LaRC, CTI |
| 2-24-97 | 8 | Landings on 5 | clear, sunny | LaRC, CTI |
| 2-25-97 | 5 | Landings on 5 | clear, sunny | LaRC, CTI |
| 2-27-97 | 7 | Take-offs on 23 | windy, cloudy | LaRC |
| 2-28-97 | 10 | Landings on 5 | rain, cloudy | LaRC |
| 3-4-97 | 8 | Landings on 5 | mist, cloudy | LaRC |
| 3-13-97 | 8 | Landings on 5 | partly cloudy | LaRC |
| 3-18-97 | 10 | Landings on 5 | overcast | CTI |
| 3-19-97 | 12 | Landings on 5 | rain, cloudy | LaRC, CTI |
| 3-20-97 | 3 | Take-offs on 23 | cloudy | LaRC |

Back to the Main Page

This page was last update by Chi Nguyen on May 2, 1997.

# March 19, 1997

- The local media was invited out today to cover the experiment story. No data was taken in the morning.
- The CTI transceiver was used.
- Landings were made on Runway 5
- Weather conditions were rain and mist. The data was taken through the CTI RASP and LaRC DAS. Data files ending with "raw" were recorded on the CTI RASP.

At 1:10 p.m., weather reports indicated winds blowing out of magnetic direction of 040 at 13 knots. Visibility was 6 miles with overcast skies.

These are the files that were taken that day.

| Data File Name | Aircraft Type | Fly through time | Scan Parameters |
|---|---|---|---|
| 03191454.raw | DC-9 | Unknown | AZ -168 EL 3 to 12 |
| 03191520.raw | DC-9 | 20:21:04 | AZ -168 EL 3 to 12 |
| 03191616.raw | DC-9 | Unknown | AZ -168 EL 3 to 12 |
| v319971.615 | DC-9 | Unknown | AZ -168 EL 3 to 12 |
| 03191620.raw | 737, Dash 8, Fokker-100 | Unknown | AZ -168 EL 3 to 12 |
| v319971.619 | 737 | Unknown | AZ -168 EL 3 to 12 |
| v319971.621 | Dash 8 | Unknown | AZ -168 EL 3 to 12 |
| v319971.628 | Fokker-100 | 21:24:52 | AZ -168 EL 3 to 12 |
| 03191628.raw | 737 | 21:29:07 | AZ -168 EL 3 to 12 |
| v319971.627 | 737 | 21:29:07 | AZ -168 EL 3 to 12 |
| 03191636.raw | MD-88 | 21:37:32 | AZ -168 EL 3 to 12 |
| v319971.636 | MD-88 | 21:37:32 | AZ -168 EL 3 to 12 |

Back

This page was last update by Chi Nguyen on May 5, 1997.

**Questions and Discussions Following Phil Brockman's Presentation (NASA LaRC)**

Buck Williams (Lockheed Martin)
A pulse width of 100 nanoseconds was the shortest pulse you showed. That results in a range resolution of about 30 meters. Are there any plans to get better range resolution?

Brockman
There is a trade here between the pulse length and the accuracy of the velocity, which is basically Fourier Transform limit. The best you can do is 1 over 2Π. If you have enough signal to noise you can do processing every few nanoseconds into the pulse and separate things that appear to be overlapping in the pulse. You can use a shorter pulse but the velocity accuracy goes down. It isn't as sharp a trade as you would like. As the wavelength goes shorter you do better and the 100 nanoseconds at 1.5 microns we can do a little better.

S/8-03

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19p

COHERENT TECHNOLOGIES, INC.

# Pulsed Coherent Lidar Wake Vortex Detection, Tracking and Strength Estimation in Support of AVOSS

NASA *First* Wake Vortex Dynamic Spacing Workshop
May 13-15, 1997

Stephen M. Hannon, Mark W. Phillips,
J. Alex Thomson, Sammy W. Henderson

Coherent Technologies, Inc.
Lafayette, Colorado



## Overview

COHERENT TECHNOLOGIES, INC.

- Technology background
- Phase II SBIR development efforts
  - Transceiver
  - Real Time Signal Processor
- Real-time vortex algorithm overview
- Validation efforts
  - Air Force Program: C-5, C-17, C-141, C-130
  - Norfolk Airport: 727, 737, F-100, DC-9, DASH-8
- Summary and prognosis
  - Dedicated vortex measurements
  - Local environment assessment

## CTI Development Team

COHERENT TECHNOLOGIES, INC.

- Transceiver Development
  - Mark Phillips, Pete Wanninger, Sammy Henderson
- RASP Development
  - Jerry Pelk, Pat Kratovil, James Junkin, Matt Osminer
- Air Force Model/Lidar Comparisons
  - William Blake, Wright Laboratory Flight Dynamics Directorate

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## Pulsed Coherent Lidar Technology Background

COHERENT TECHNOLOGIES, INC.

- CW lidar sensors primary 'vortex' lidar before 1990
  - limited in range to < 300 m
- Initial pulsed measurements with 1.06 μm sensor
  - Vandenberg AFB, 1992
- Eyesafe pulsed lidar for vortex detection and tracking
  - 2.09 μm pulsed lidar at Stapleton Airport in 1993
    - low PRF (5 Hz) limits to single scan plane (25-50 LOS)
  - emergence of high PRF diode-pumped sensors
    - 100-1000 Hz PRF, 1-20 mJ pulse energies
    - multiple scan plane 'imaging'
    - robust (flight-hardened) designs at near-IR wavelengths

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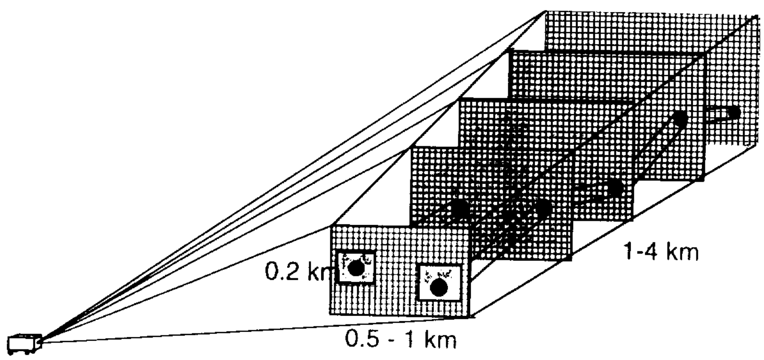
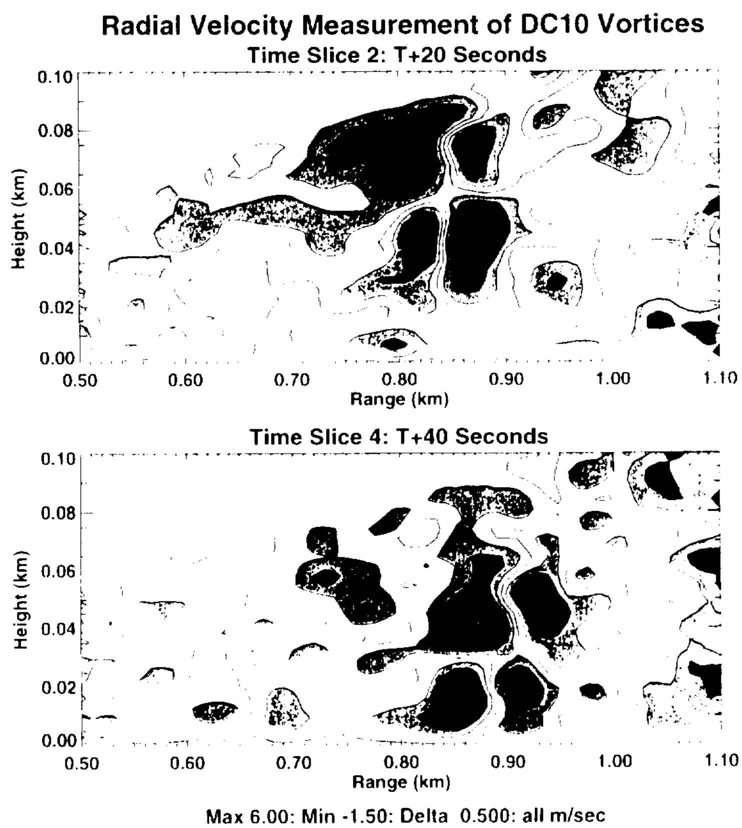
# Scanning Geometry - Glide Slope Imaging





## Pulsed Lidar Resolution Capability

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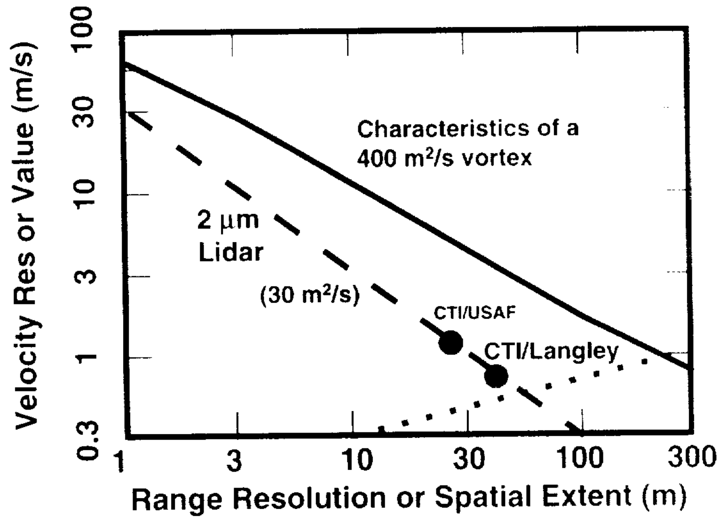



Pulsed lidar:
$\Delta R \sigma_v = 0.15 c\lambda/\pi$

***Weak pulse length trade expected relative to resolution of an isolated vortex***

## Transceiver Development and Specifications

COHERENT TECHNOLOGIES, INC.

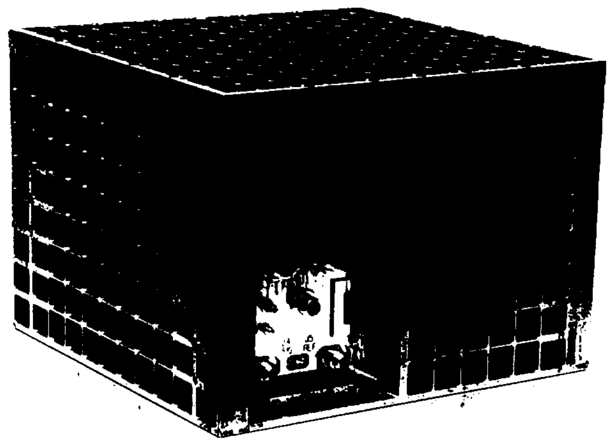
- Developed under Phase II SBIR funding from NASA/Langley
  - P. Brockman, technical monitor

- Diode-pumped, 2.0125 µm Tm:YAG
- 7 mJ, 100 Hz (10 mJ, 100 Hz)
- 380 nsec (300 nsec) FWHM intensity pulse duration
- 10 cm clear aperture
- Hardened, flight worthy enclosure
- Turnkey operation

## Environmental Enclosure

COHERENT TECHNOLOGIES, INC.

- Pressure vessel back-filled with dry air to 16 psiA, capable of operation in vacuum.



NASA WAKES Final Review

## Algorithm and Signal Processor Development

COHERENT TECHNOLOGIES, INC.

- Phase II SBIR sponsorship from NASA/Langley
  - P. Brockman, technical monitor
- Real time algorithm development
  - spectral-space algorithm
  - Kalman-hydro algorithm
- Real time signal processor development
  - Real Time Advanced Signal Processor (RASP)

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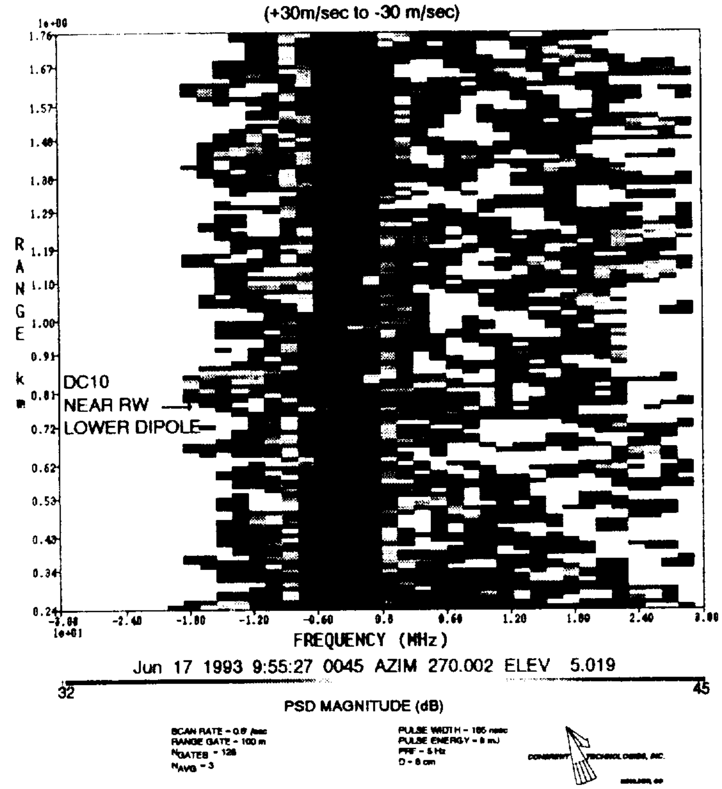
SPECTRAL SIGNATURES FOR DC10 WAKE VORTICES

RANGE-RESOLVED DOPPLER SPECTRUM (T + 2 sec)

(+30m/sec to -30 m/sec)




## ML Estimation of Circulation Strength

COHERENT TECHNOLOGIES, INC.

- **Observable is Doppler spectrum $\phi_v$ as a function of x, y, v (and t)**
- **Vortex model parameters: $\Gamma$ (circulation strength) and $a$ (core size)**
- **Spectral-space likelihood ratio**

$$LR = \max_{(x_o, y_o, \Gamma, a)} \left\{ \frac{PDF\left(\phi_v(x,y) \middle| x_o, y_o, \Gamma, a\right)}{PDF\left(\phi_v(x,y) \middle| \Gamma = 0\right)} \right\} \Rightarrow \frac{PDF(\text{Vortex Present})}{PDF(\text{Vortex Absent})}$$

$$\Rightarrow \max_{(x_o, y_o, \Gamma, a)} \left\{ \sum_v \left[ \phi_v(x,y) * MF_{\phi_v}(x, y, \Gamma, a) \right] + LL_o(\Gamma, a) \right\}$$

DATA FILTER

- **Dependence on Vortex Model Prescription**
  - Ground effect distortion limited through spectral high-pass filter
  - Circulation strength dependence on pulse duration must be quantified
  - Track performance less sensitive to model prescription

# Spatial Resolution Enhancement Using Spectral Processing

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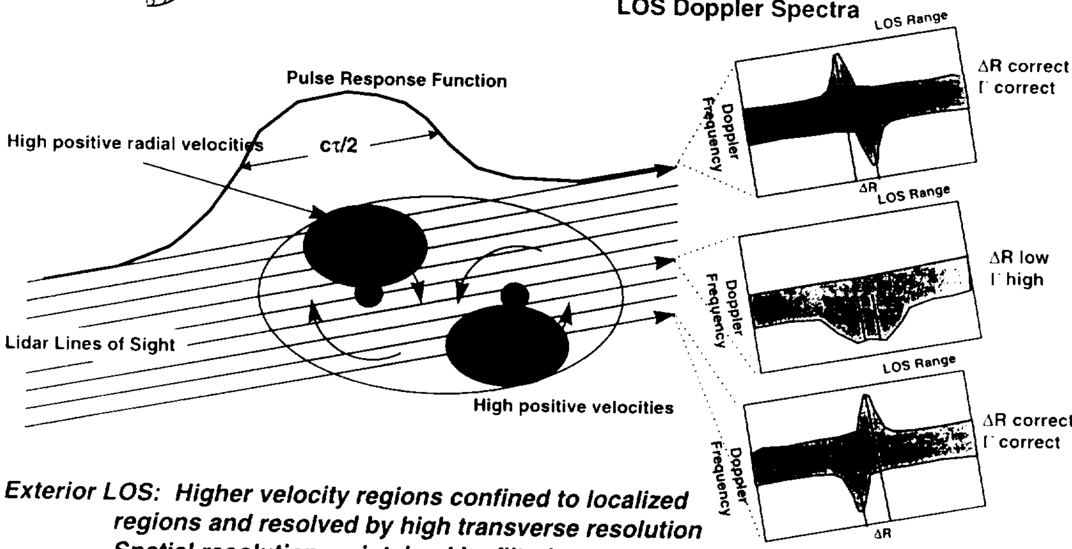


*Exterior LOS: Higher velocity regions confined to localized regions and resolved by high transverse resolution*
*Spatial resolution maintained by filtering, even for long range gates*

*Interior LOS: Overlap of pulse response functions biases separation low, circulation high*

*ML Solution: Iterate and search for vortex pair*

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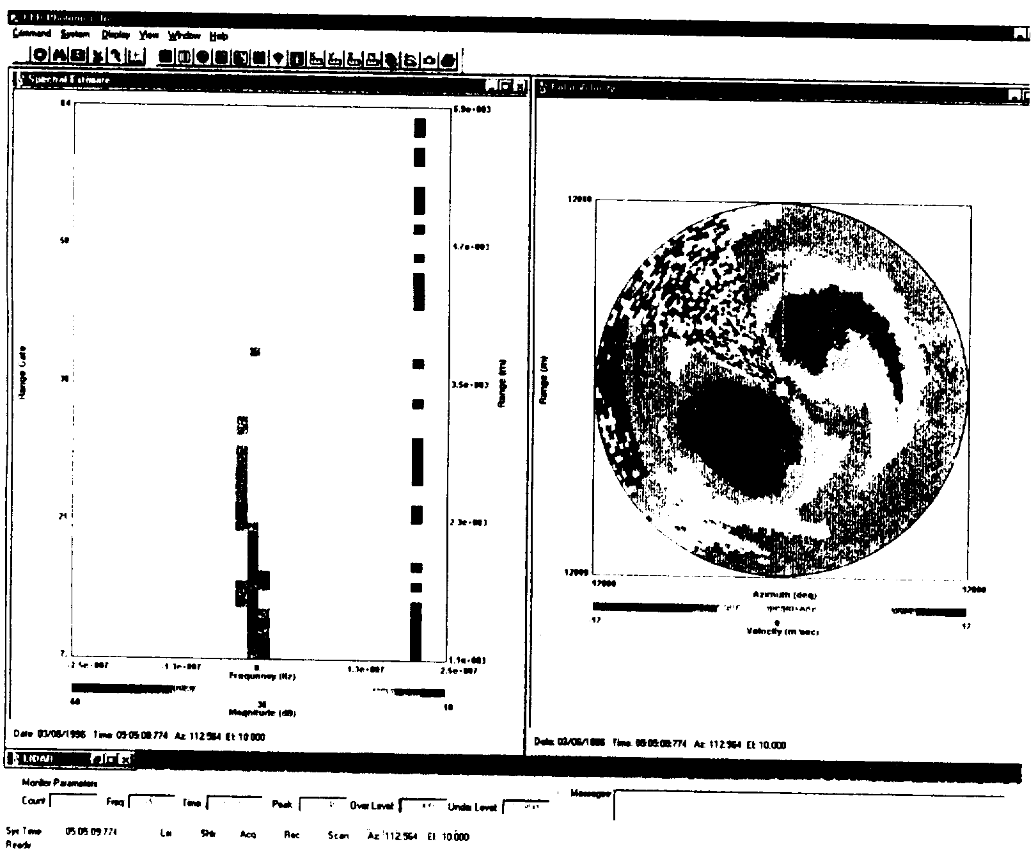

# Real Time Spectral-Space Algorithm Specifications

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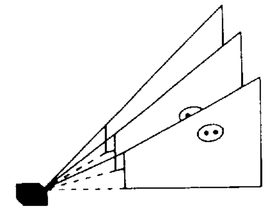

- Multiple azimuth plane scanning
  - 2-3 sec per scan plane
  - 2 pos, 2 neg vortex tracks per scan plane
- 64x64 data grid for each analysis window
  - 50-500 m spatial extent for analysis window
- ML search over circulation strengths
  - Rankine vortex velocity distribution (alt models possible) with user-specified core size
- Multiple hypothesis tracking algorithm for ML output
- Vortex Products:
  - x-position, y-position, circulation, sink rate, advection rate, age
  - likelihood, data quality flag
  - in-plane velocity, mean radial velocity, spectral width

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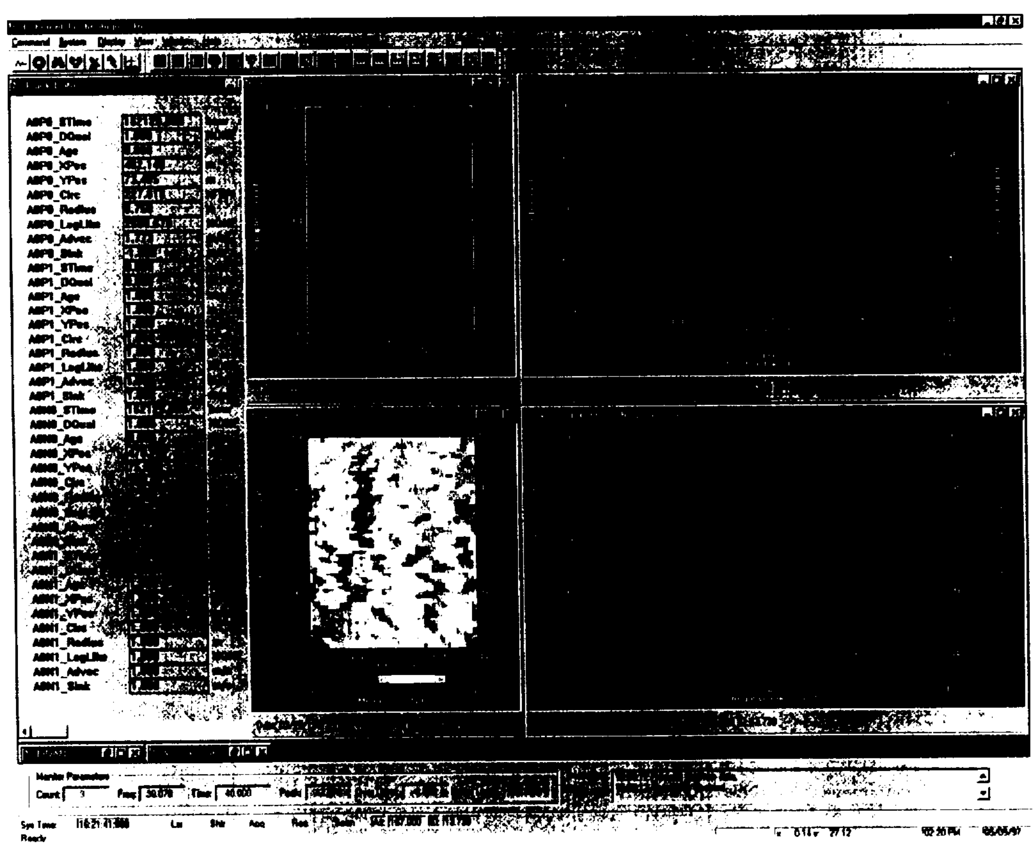

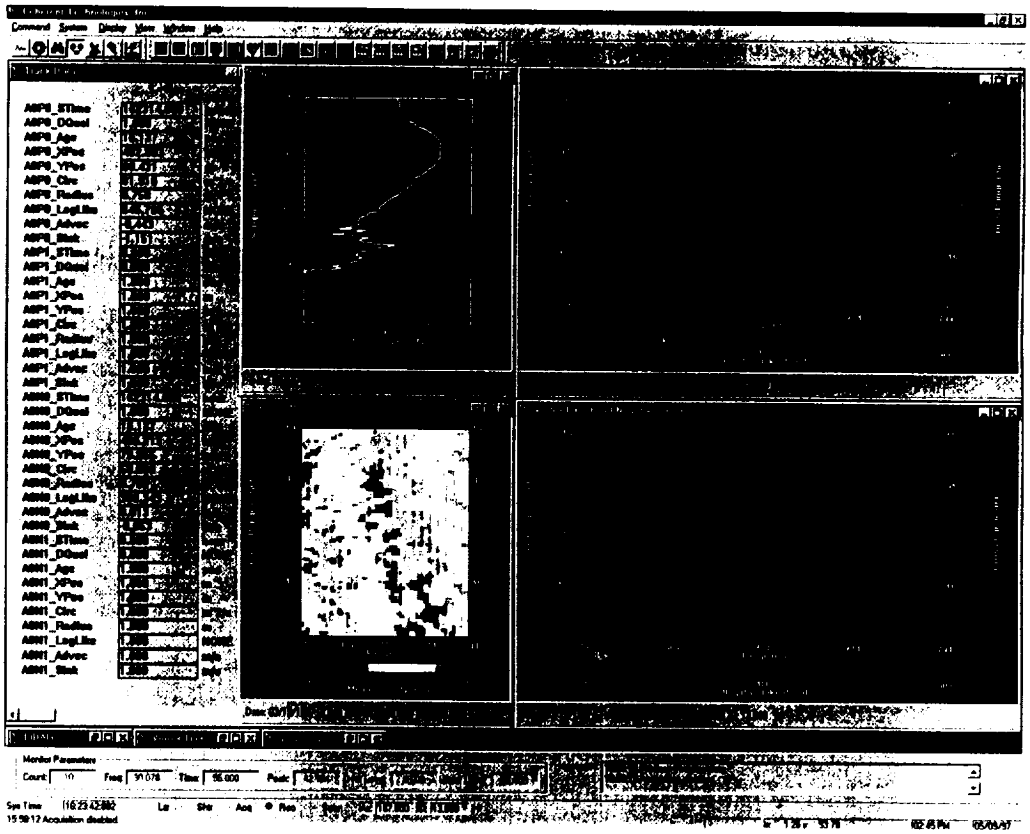

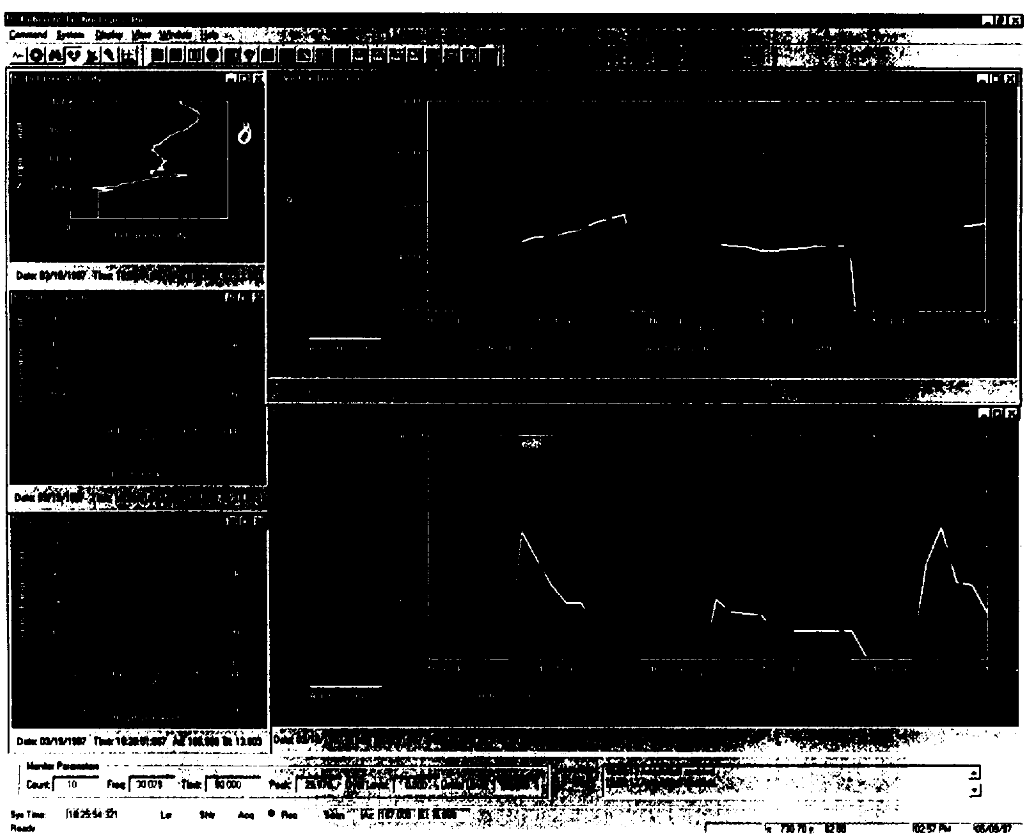

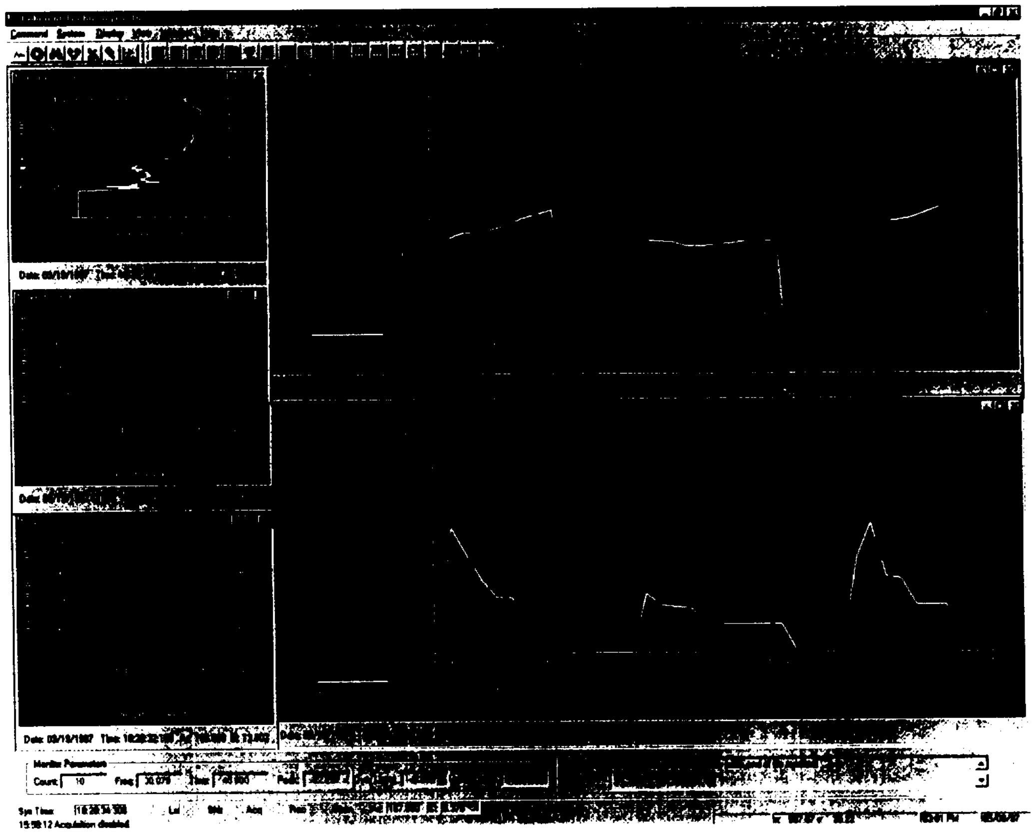

# Algorithm Validation Efforts

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- Track precision
  - simulated lidar vortex data
  - least squares analysis in out of ground effect
  - comparison with wind-state estimates and model predictions
- Circulation strength
  - simulated lidar vortex data
  - predictions based on weight, wingspan, speed, wing loading
  - comparison with sink-rate-inferred strength estimates
- Real data sources
  - Air Force deployments (1995-1996)
  - Norfolk airport deployment (March 1997)



# U.S. Air Force Program

COHERENT TECHNOLOGIES, INC.

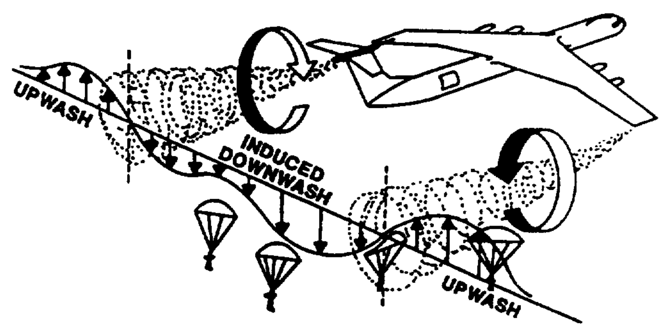
- Army mission: Strategic Brigade Airdrop
  - Seizure of a small, austere airfield in a third world area
- Drop requirement:
  - 2552 troops (26 shiploads)
  - Over 200 "wheeled vehicles", howitzers and tanks
  - Single drop zone in minimum time at night
- Aircraft flying in single file with FAA type spacing:
  - nearly 3 hours to complete the mission, which far exceeds the Army requirement
- Need exists to develop optimal ship formations to minimize seizure time and maintain paratrooper safety

*Courtesy William Blake, Wright Laboratory*

## Paratrooper Vortex Encounters

COHERENT TECHNOLOGIES, INC.

- **Jumpers from a formation of aircraft can encounter a vortex from a ship upstream (AIAA paper 96-3387-CP)**




*Courtesy William Blake, Wright Laboratory*

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## Paratrooper Vortex Encounters: Solution

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- **Improve airdrop tactics to minimize probability of wake encounter**
  - change formation geometry *within operational constraints*
- **Requires knowledge of wake vortex descent, decay and lifetime**
  - LIDAR investigation of wake vortices under airdrop conditions*

| | Passes | Weight (Klb) | Location | Dates |
|---|---|---|---|---|
| C-130 | 23 | 123-147 | Edwards AFB | Sept 6-9, 1995 |
| C-141 | 22 | 175-270 | Edwards AFB | Sept 6-9, 1995 |
| C-17 | 74 | 326-512 | Edwards AFB | Sept 6-12, 1995 |
| C-5 | 32 | 475-671 | Wallops Island | Feb 7-8, 1996 |

* Edwards tests sponsored by ASC/YC, Wallops test sponsored by AMC

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# Descent Track Performance Comparison

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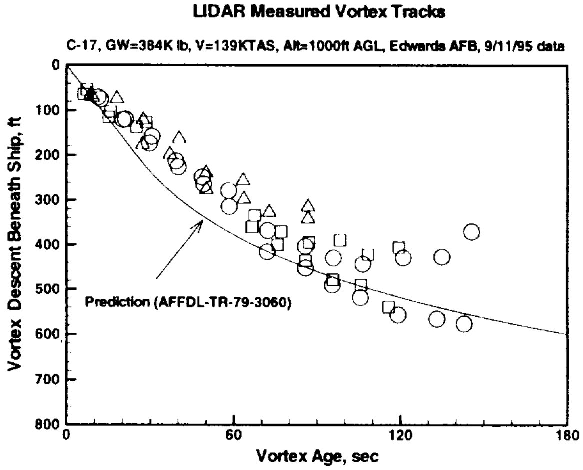


*Courtesy William Blake, Wright Laboratory*



# Sample C-17 Wake Vortex Tracks Measured with 2 μm Pulsed Coherent Lidar

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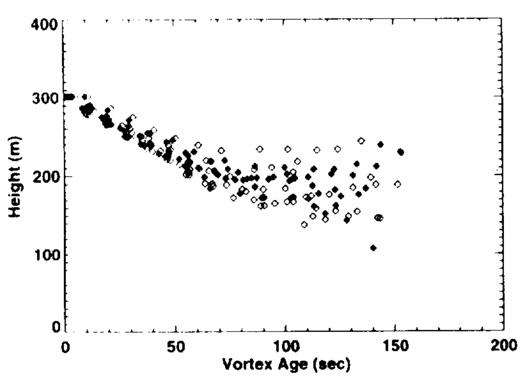
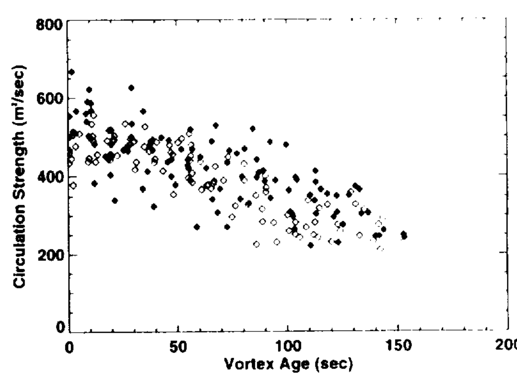
**Height versus Time** **Strength versus Time**




Date: 9/11/95
Location: Edwards Air Force Base, California
Aircraft: C-17
AGL Passage Height: 300 m

◇ = Upwind Vortex
◆ = Downwind Vortex

## Additional Air Force Measurements

COHERENT TECHNOLOGIES, INC.

- Lidar data used to develop a C-17 personnel airdrop formation suitable for IFR (nighttime ops)
- Tested at Ft Bragg, June 96-January 97
  - Over 3000 mannequins and personnel dropped from final formation geometry
  - No vortex encounters
    - Cleared by USAF, case number ASC-96-2918

*Courtesy William Blake, Wright Laboratory*



## Core Separation Distance Estimation - spectral-space algorithm -

COHERENT TECHNOLOGIES, INC.

| Aircraft | Predicted[1] Vortex Separation (m) | Measured Separation (m) | RMS Variability (m) |
|---|---|---|---|
| C-5 | 53.3 | 48.9[2] | 9.5[2] |
| C-17 | 39.5 | 44.6[2] | 9.1[2] |
| C-141 | 38.3 | 32.1[2] | 8.7[2] |
| B-737 | 22.7 | 15 | n/a |
| DC-9 | 22.4 | 20 | n/a |
| F-100 | 22.0 | 10-15 | n/a |
| Dash-8 | 20.3 | 10 | n/a |

[1] Assumes elliptical wing loading
[2] CTI/USAF sensor data: 165 nsec pulse duration (N>25)
[3] CTI/NASA sensor data: 380 nsec pulse duration (N=1 or 2)

- Core separation estimates reasonable for larger aircraft
- Longer pulse operation appears to sometimes underestimate core separation for smaller aircraft (more analyses/runs required)

## Large Aircraft Position and Strength Performance Summary

COHERENT TECHNOLOGIES, INC.

- Position (track) information to less than 3 m RMS
- Strength estimates rely on model-based matched filter algorithm
  - reasonable estimates when compared to both predicted and sink-rate-inferred estimates

| Aircraft | Sink-Rate-Inferred Estimated/Predicted Strength | Model-Based Direct Estimate Estimated/Predicted Strength |
|---|---|---|
| C-17 | 0.79 | 0.77 |
| C-5 | 0.96 | 1.16 |
| C-141 | 0.88 | 1.26 |

C-17: 46 Runs (Edwards AFB - Sept 1995)
C-5: 28 Runs (Wallops Island - Feb 1996)
C-141: 13 Runs (Edwards AFB - Sept 1995)

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## Smaller Aircraft Circulation Strength Estimation

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- Limited data analyses thus far: consider 5 cases @ Norfolk

| | *Measured*[1] | | *Predicted* |
|---|---|---|---|
| – B-727: | 326 $m^2$/sec | cf | 295 $m^2$/sec (180 klbs, 140 kts) |
| – DC-9: | 220 $m^2$/sec | cf | 195 $m^2$/sec (90 klbs, 140 kts) |
| – B-737: | 209 $m^2$/sec | cf | 192 $m^2$/sec (90 klbs, 140 kts) |
| – F-100: | 210 $m^2$/sec | cf | 186 $m^2$/sec (85 klbs, 140 kts) |
| – Dash-8: | 100 $m^2$/sec | cf | 71 $m^2$/sec (30 klbs, 140 kts) |

[1] Core radius of 0.75 m

- With Air Force database, these results indicate:
  - reasonable prediction of circulation strength over 100-600 $m^2$/sec
  - minimum detectable circulation below 100 $m^2$/sec

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## Summary and Prognosis

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- **Pulsed coherent lidar sensor and algorithms appear to provide accurate track information**
  - 3 m RMS precision, depending on analysis parameters
  - track performance shows weak dependence on pulse duration over 100-400 nsec range
  - multi-sensor validation measurements needed to better quantify accuracy
- **Circulation strength estimation achieved through parametric ML algorithm**
  - reasonable strength estimates over 100-600 $m^2$/sec and multiple aircraft types; possible bias (high) for small a/c or long pulse
  - 10-15% accuracy expected
- **Alternate algorithms require additional development and/or modified implementation**
  - Kalman - hydro: wake/vortex model 'independent'
  - Two vortex matched filter to account for range overlap

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## Summary and Prognosis (cont.)

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- **Turnkey lidar transceivers delivered!**
- **Real-time algorithm implemented in RASP**
  - ML spectral-space algorithm
  - multiple azimuth planes
  - position, strength and transport rate estimates in real-time
- **Pulsed lidar roles for AVOSS:**
  - vortex detection, tagging and tracking
  - local wind state estimates
    - mean winds
    - turbulence levels
    - spatial variability
    - input to AVOSS prediction

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## Turbulence Measurement Along Single LOS
## - benign turbulence conditions -

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**Velocity structure function:**

$$D_u(R) = \left\langle \left[u(R_o) - u(R_o + R)\right]^2 \right\rangle$$

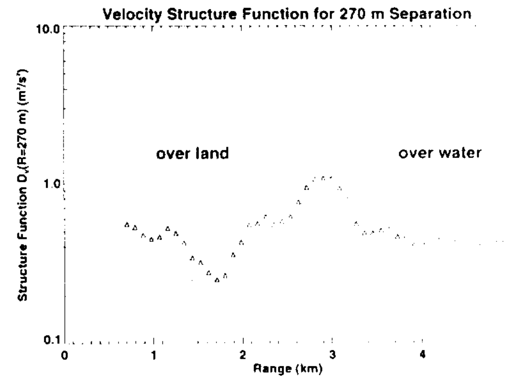
**Lidar estimate:**

$$\hat{D}_u(j\Delta R) = \frac{1}{N}\sum_{k=1}^{N}\left\{u_k(j_o\Delta R) - u_k[(j_o + j)\Delta R]\right\}^2 - \hat{\sigma}_e^2(j_o) - \hat{\sigma}_e^2(j_o + j)$$

**Related to eddy dissipation rate:**

$$D_u(R) = C_v \varepsilon^{2/3} R^{2/3}$$

**2° Elevation Angle toward WSW**




**Improved structure function estimates:**
Frehlich et al., "Coherent Doppler Lidar Measurements of Wind Field Statistics," *Boundary Layer Meteorology*, submitted April, 1997.

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## System Performance and Area Coverage

COHERENT TECHNOLOGIES, INC.

- **Pulsed lidar vortex capability:**
  - glide slope imaging
  - +/- 60 deg with stand-off ranges of 0.3 km (min) to 5 km
    - out to 2 km in 10 mm/hr rain
  - multiple runways
  - 2 seconds per vertical scan plane
- **Pulsed lidar wind state capability:**
  - in-plane wind profile updates with vortex observations
  - high resolution vertical profiles of vector wind through lower 1000 m altitude (higher altitude coverage with lower resolution)
  - large area 'volumetric' scanning
    - out to 10 km radially with multiple scan planes
    - 15-20 deg/sec scanner slew rates with 1-2 deg spatial sampling for results
    - radial velocities, spatial velocity variance, other turbulence metrics

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## Validation Efforts: AVOSS Implications

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- Edwards/Wallops out-of-ground-effect data indicates vortices often last >2 minutes with circulations >50% initial value
  - covers all current spacing windows (3-6 nm)
  - 25+% of every day
  - shorter lifetimes expected/observed in ground effect
  - TBD which altitude band poses largest threat
- Track information is vital
  - Wind state plus vortex motion model required to gain 30 minute predictive capability
  - lidar can provide detailed wind state information and track validation
- Smaller jets and commuter aircraft are the most liable to vortex upset
  - they do not encounter vast majority of these vortices
  - analysis of likelihood and severity of encounter given winds, glide slopes, etc. versus observed 'incidents' is needed



## Aviation-Oriented Coherent Lidar at CTI

COHERENT TECHNOLOGIES, INC.

- CTI believes coherent lidar systems will serve a key roll in next-generation aviation systems such as AVOSS
- Significant synergy with companion development efforts
  - Air Force, Navy, commercial, CTI IR&D
  - AVOSS has and should continue to leverage and benefit from these thrusts
- CTI focus is operational coherent lidars:
  - higher power, lower cost, longer-lifetime
  - more robust sensors and software

**Questions and Discussions Following Steven Hannon's Presentation (CTI)**

Buck Williams (Lockheed Martin)
What are the weather limitations of lidar systems? Are there wavelength selections that would improve capability?

Hannon
The primary one people worry about is fog. It's flat wave length dependent. Rain rate and other things favor some of the other wave lengths. Two micron has pretty decent performance there but if you have an inch per hour of rain, these systems are not going to work beyond a couple of kilometers. If you have fog with low visibility, you are going to see a little further than the visibility number would lead you to believe. A multi-sensor system is what is really required and that is what the emphasis has been in AVOSS. There are condition, low cloud cover, that lidar can penetrate some, but it won't be able to go 5 kilometers in a cloud bank.

D. Griffin Read (Aero Electronic Leasing Corp.)
This type of system I would guess would end up multi-sensor because it is the feedback loop which verifies your prediction is going on. So it is important that it be reliable. So I am delighted to hear of your progress.

## Estimation Of Vortex Characteristics from Coherent Lidar Measurements

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048102
318638


**Charles L. Britt**

**Research Triangle Institute**

**One Enterprise Parkway, S-310**

**Hampton, VA**


12p.

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## Objective

Estimate vortex positions and strengths from lidar measurements in real-time

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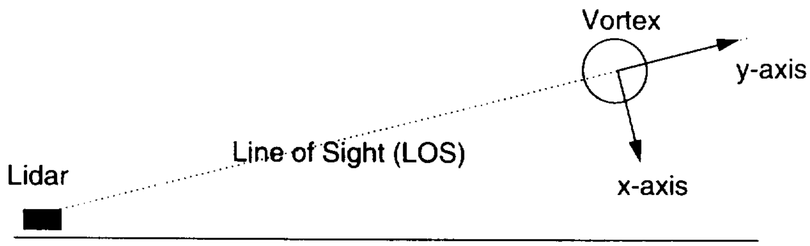
# Coordinate System

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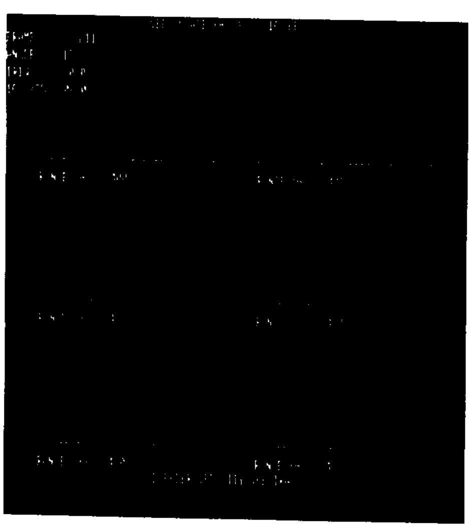
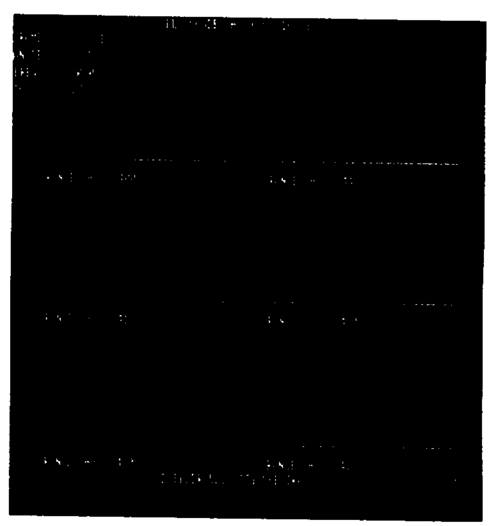
# Doppler Spectra at 6 Range Bins

No Vortices



Vortices



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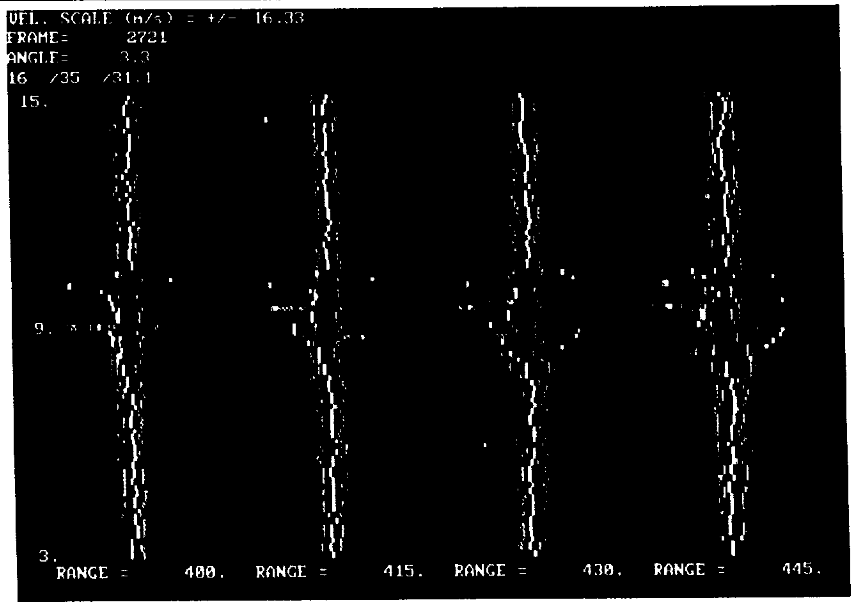
## Examples of Doppler Spectra vs Elevation Angle for MD88 Vortices

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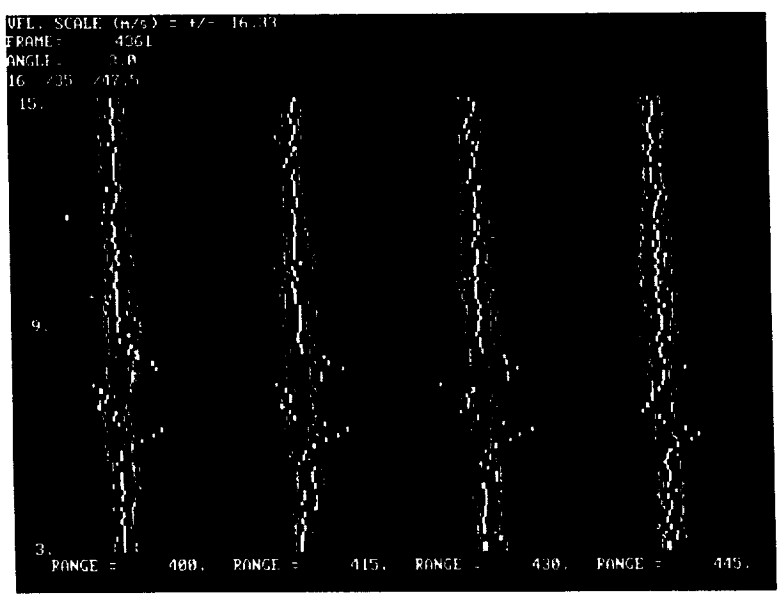
## Doppler Spectra vs Elevation Angle - MD88 Vortices (16 secs After Previous Plot)

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# Minimum Variance Estimation

- Relationship between n observations (V) with noise (N) and m parameters to be estimated (B)

$$V_{nx1} = A_{nxm} B_{mx1} + N_{nx1}$$

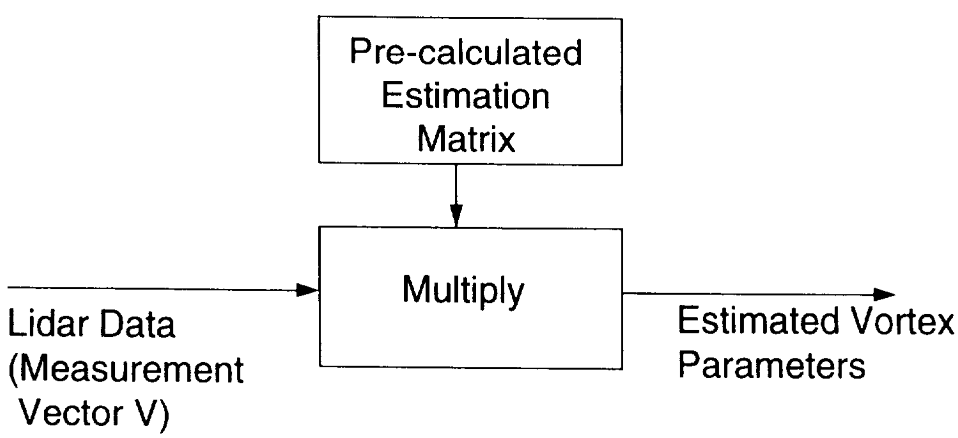
- Solution

$$\hat{B} = \left[ (A^T \Phi^{-1} A)^{-1} A^T \Phi^{-1} \right] V$$

where $\Phi$ = Noise Covariance Matrix



# Estimation Calculations



# Measurement Models Developed to Date

- Average Doppler Velocity - Isolated Vortex & Pair
- Maximum Doppler Velocity -Isolated Vortex & Pair
- Minimum Doppler Velocity - Isolated Vortex & Pair
- Largest Velocity Shift - Isolated Vortex & Pair

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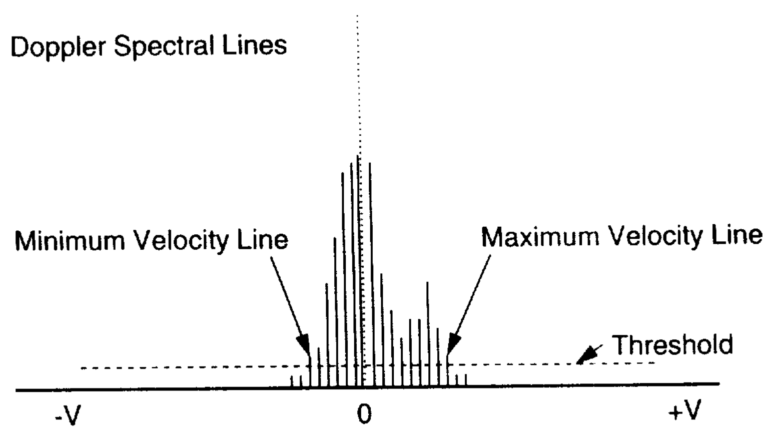
# Maximum and Minimum Velocities

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# Example of Measurement Model

Velocity Averaged over Distance S in y-direction

$$V_a = \frac{\Gamma x}{2\pi S G}\left[\tan^{-1}\left(\frac{y+\frac{S}{2}}{G}\right) - \tan^{-1}\left(\frac{y-\frac{S}{2}}{G}\right)\right]$$

where

$$G = \sqrt{x^2 + a^2}$$

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# Linearized Estimation Equation for Circulation and Radius

$$V_a = H(a_m, x, y)\Gamma + D(\Gamma_m, a_m, x, y)q$$

where $q = a - a_m$

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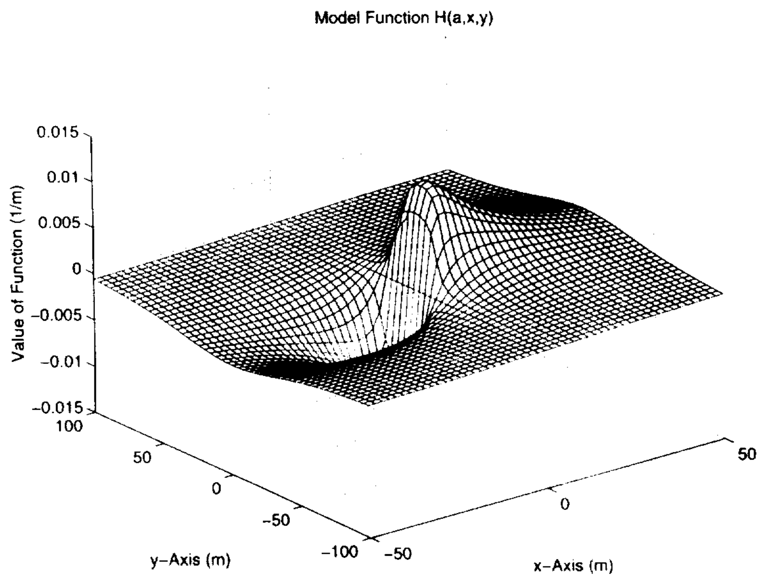
# Model Function for Average Velocity

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# General Procedure - Sample Calculations

- Generate a Simulated Set of Noisy Doppler Measurements
- Determine Location of Vortices by Estimation of Circulation Parameter at each Measurement Point using a prori vortex radii.
- At Vortex Centers, Estimate Circulation and Radius

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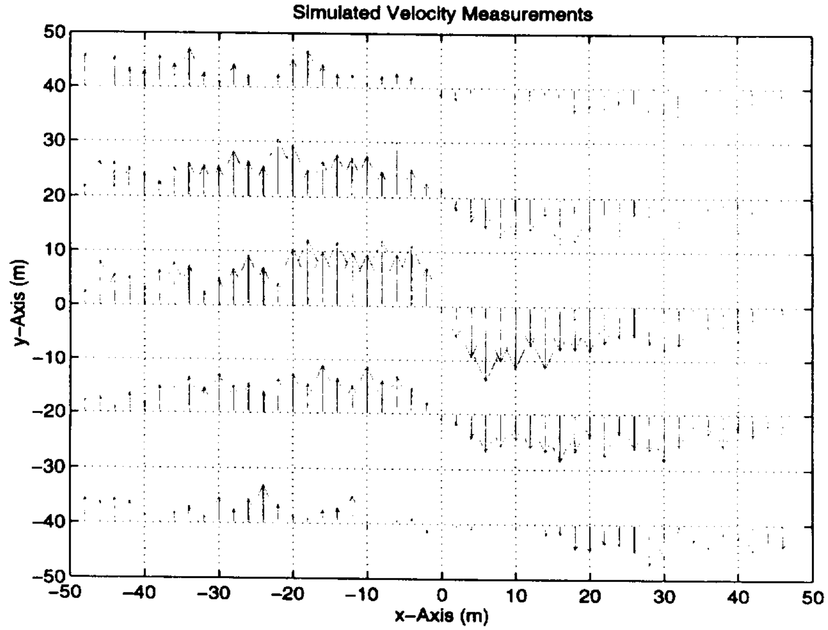
# Example of a Simulated Set of Doppler Velocity Measurements - RMS Noise=0.5m/s

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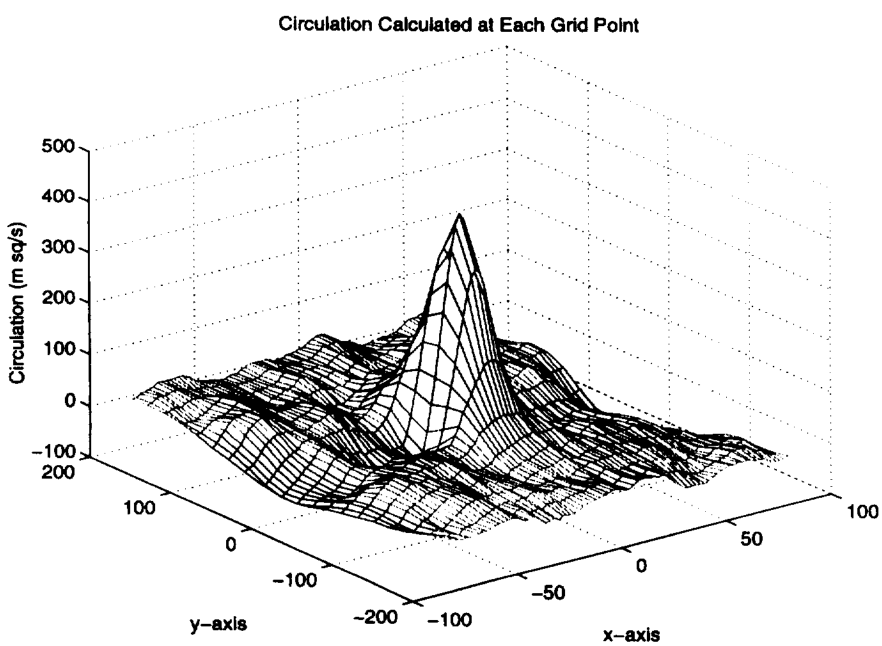
# Circulation Estimated at each Grid Point

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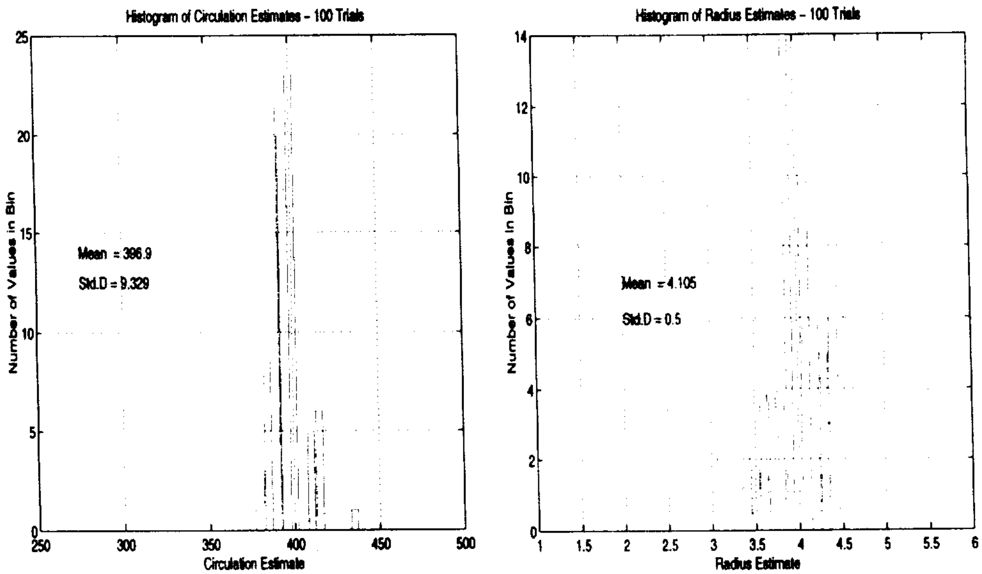
# Histograms of Circulation and Radius Estimates
# 100 Trials

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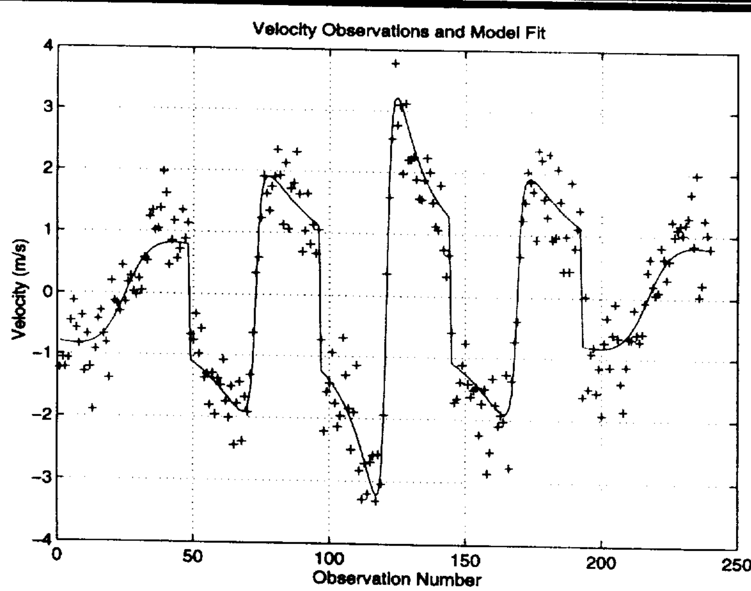
# Example of Fit of Model Function to Simulated Data

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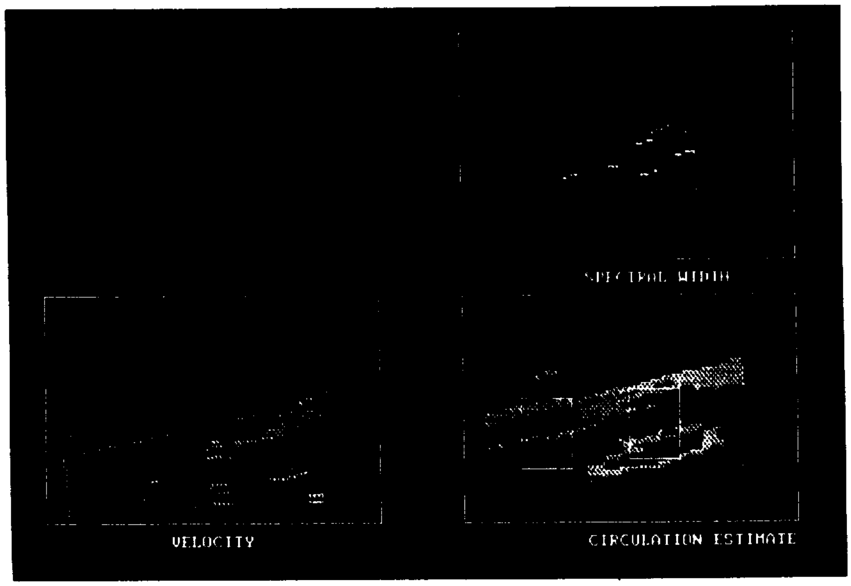
## Example of Displays from the Real-Time Console

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## Conclusions

- Mathematical Framework Developed
- Real-Time Operation Achieved
- Long Lidar Pulse Causes Resolution Problems
- Max. and Min. Velocities Appear to be the Best Measurements to use with Long Pulse
- High Lidar SNR is Necessary with Long Pulse
- More Work to be Done
  - Data from Heavy Aircraft Needed
  - Use Data to Develop Better Measurement Models
  - Current Tracking Reliability needs Improvement
  - Accuracy Must be Determined

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**Questions and Discussions Following Les Britt's Presentation (RTI)**

Steven Campbell (Lincoln Lab)
You said you needed a good starting point to make your estimate. You need initial estimate of vortex location. Suppose you had a false detection to start off with or lost track and then attempted to do model fitting. Would you come up with an estimate of probability of goodness of the fitting or would it always come out with an answer?

Britt
We calculate a goodness of fit, of course with the estimation procedure you get the residuals, like in a least squares fit. We haven't used this as yet.

Campbell
Suppose you start off with a false track. Would you fit it to a vortex pair, or would you say you can't fit it and give up?

Britt
Our tracking algorithm is using an alpha-beta tracker and the tracking algorithm have parameters you setup. We don't declare a track exists until we see it in two separate scans. That is a setable parameter.

Frank Rees (Flight Safety Technologies)
You mentioned the minimum variance technique and when you are forming the co-variance matrix, how do you ensure that it is not biased by the presence of vortexes? Do you apply a split range gate or do you apply some constraints to optimization?

Britt
What you minimize is a risk function and if you pick the co-variance matrix properly, it becomes a minimum variance estimation. The co-variance matrix has to represent the noise co-variance. We know independently the standard deviation of our noise from our data. We used overlapped range measurements so you have to adjust the weighting because of the overlap. In other words, every measurement we have is not independent from next measurement. So you adjust it by hand say a 50% overlap and compare it to independent samples. It is basically just a weighting matrix.

Buck Williams (Lockheed)
I believe you said you pre-computed your noise co-variance matrix, so that means you're assuming it's stationary the whole time.

Britt
Yes, basically that is true.

Williams
So you don't feel the noise is changing with time as meteorology changes or looking at remnant of previous vortex.

Britt
No, not really. It's pre-calculated before a data run. It is just a weighting matrix.

Charlie Zheng (Univ. of South Alabama)
In one of the slides there is an average velocity. Could you explain in what range you averaged that and why?

Britt
When we used average velocity, we used just a standard spectral averaging technique for an average of the spectral lines.

Zheng
At what range, within the vortex core or throughout some radius?

Britt
I'm talking about a weighted average of the spectral lines. We do a standard spectral average to get the average frequency and thus the average velocity.

Zheng
You have two that are tangent as a function of R.

Britt
Let us discuss this after the meeting to straighten out.

Zheng
OK.

# A 1000 Hz Pulsed Solid -State Raman Laser for Coherent Lidar Measurement of Wake Vortices

LaRC

Grady Koch--NASA Langley Research Center

James Murray--Lite Cycles, Inc.

Carroll Lytle--NYMA, Inc.

Chi Nguyen--Research Triangle Institute



## 1.5 micron Laser Specifications

LaRC

- Wavelength = 1.56 microns
  - high maximum permissible exposure for eyesafety
- Pulse Repetition Frequency = 1000 Hz
  - allows fast scan coverage
- Pulsewidth = 100 ns (full width half maximum)
  - 15 meter range resolution
- Pulse Energy = 10 mJ
  - good range capability

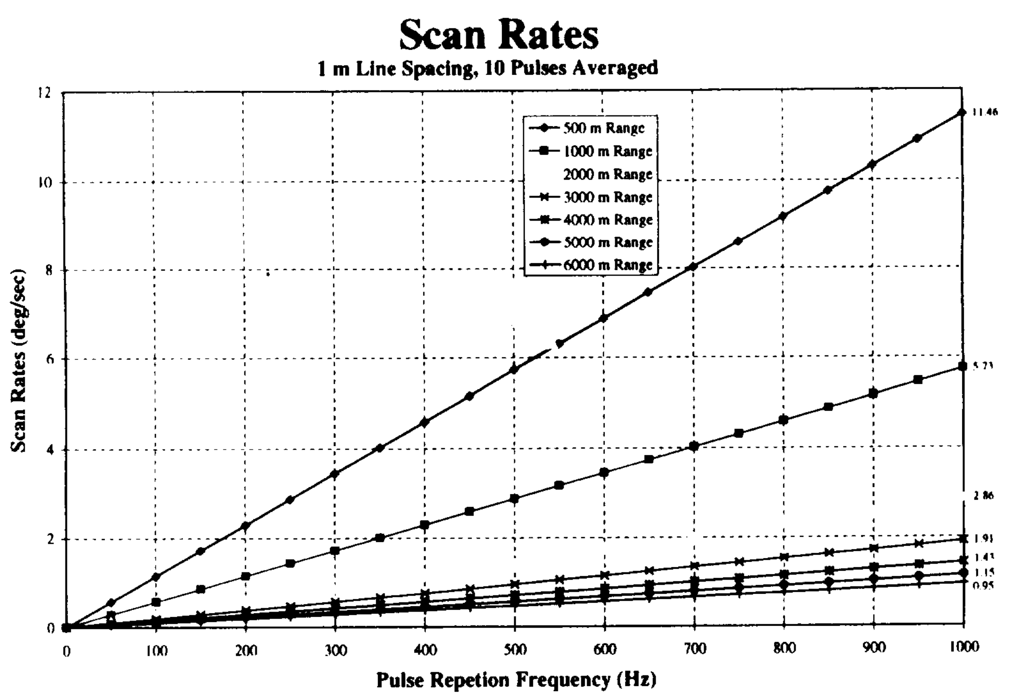
NASA

# Eyesafety and Cost

LaRC

- ANSI Z136.1-1993 lists maximum permissible exposures
  - 1 J/cm² for 1.5 microns
  - 0.1 J/cm² for 2.0 microns
  - 0.000001 J/cm² for visible wavelengths

- 1.5 microns is the wavelength of choice for telecommunications
  - detectors, optics, and instrumentationare off-the-shelf items
  - for example: photodiode/preamp, 1 GHz BW, fiber optic input, immediately availablefor $1,250

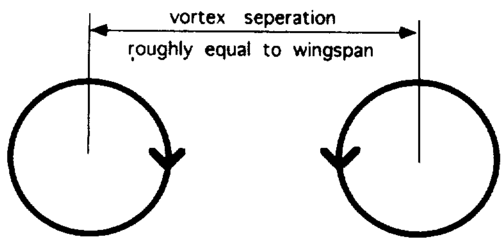



RTI

C.Nguyen

# Pulselength

LaRC




100 ns pulse gives range resolution of 15 m.

Wingspans:

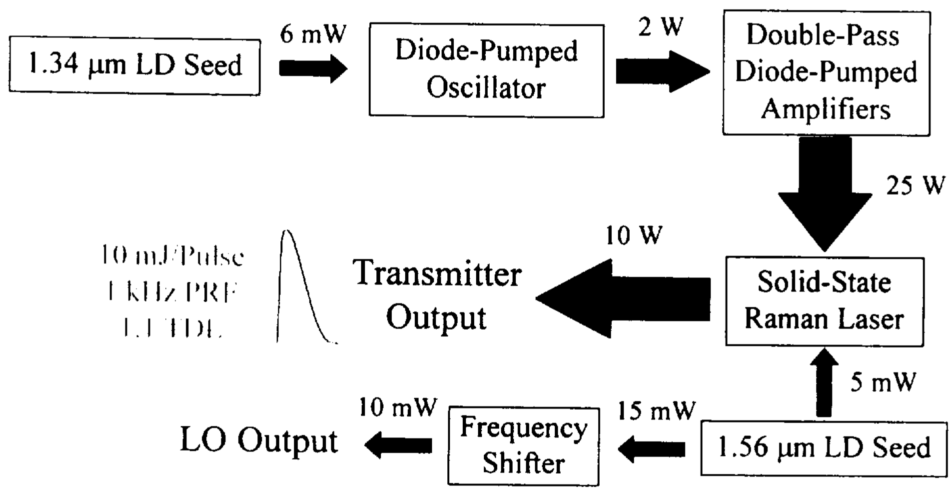
| | | |
|---|---|---|
| 747 = 59.6 m | 737 = 28.8 m | DC9 = 28.5 m |
| A300 = 44.8 m | A320 = 33.9 m | F100= 28.1 m |

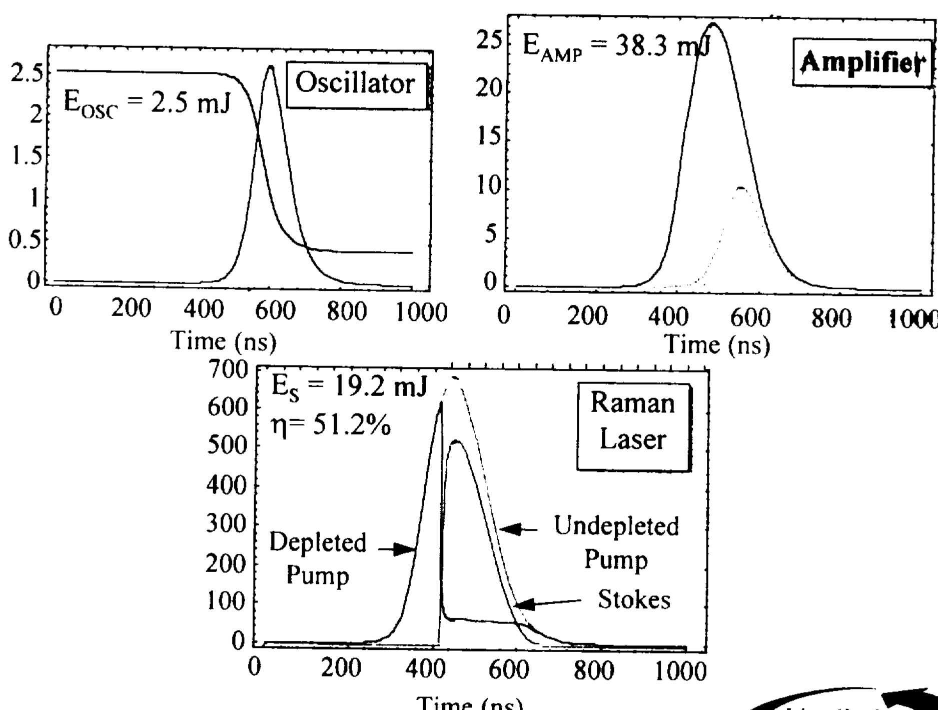
# Range Capability Issues

LaRC

- Backscatter
  - about the same as 2 μm
- Atmospheric Attenution
  - Weak $H_2O$ lines are present, but none at 1.560 μm
- Turbulence
  - $C_n^2$ a bit higher than 2 μm

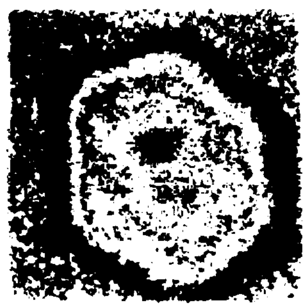
# High-Power All Solid-State Raman Transmitter



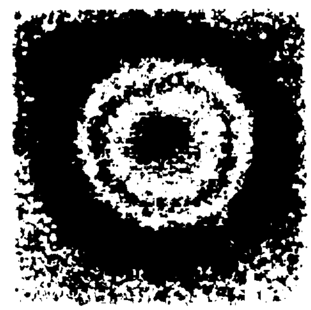



# Raman Beam Cleanup (RBC)

- RBC is due to Four-Wave-Mixing and Intensity Averaging in the Raman Crystal
- Multimode Pump - to - Single Mode Stokes Conversion



Multi-Mode
1.34 μm Pump
Beam Profile

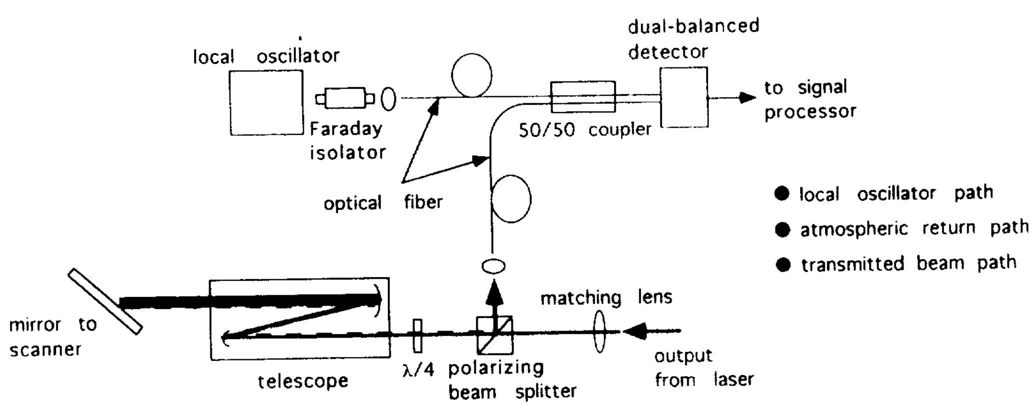


Single Mode
1.56 μm Stokes
Beam Profile

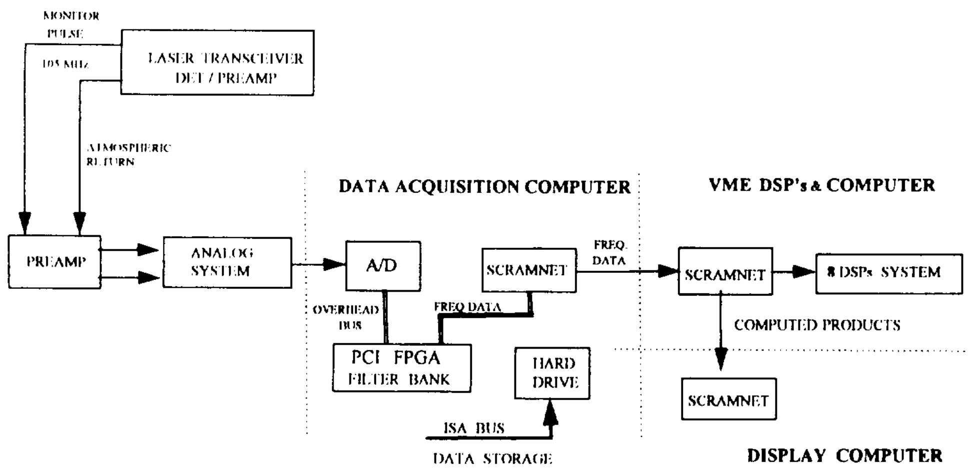
Lite Cycles

# Receiver Layout

LaRC

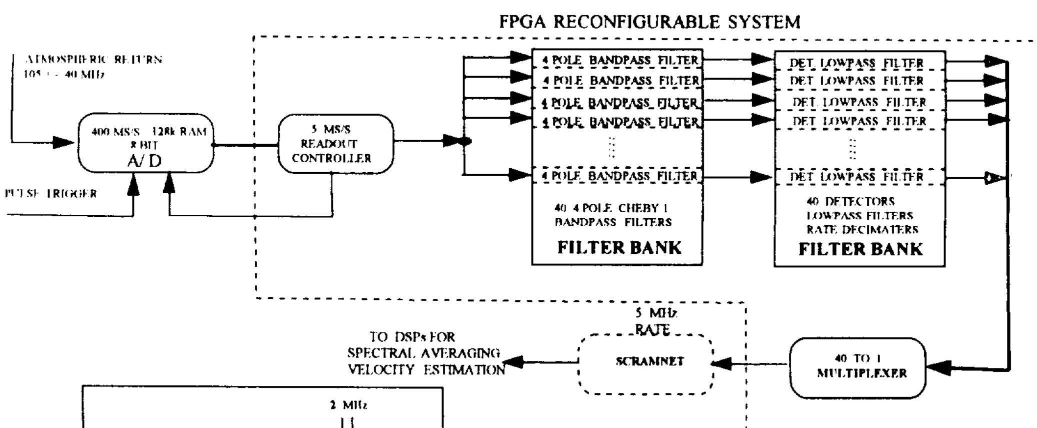


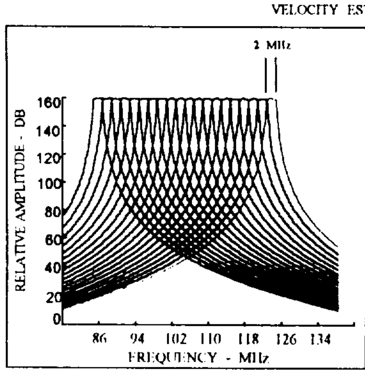
# Real-Time Processor and Display




C Lyle
NYMA

# Time Domain Pre-processor




Bandpass
Filter Profiles

C Lyle
NYMA

**Questions and Discussions Following Grady Koch's Presenation (NASA LaRC)**

Steve Hannon (Coherent Technologies)
You have a fast rise time on that pulse. It is probably 5 to 10 nanoseconds. Do you know the bandwidth relative to transform limit for the laser and what do you expect the implications to be for you.

Koch (Langley)
That is an effect of the nonlinear conversion process. We don't know how much chirp that is going to be. From previous work the chirp is always worse in the design than in the simulation. You are right; that is an issue that will affect the frequency resolution.

Rick Heinrichs (MIT Lincoln Lab)
Is there any optical distortion due to thermal loading on the Raman shifting crystal?

Koch (Langley)
No, I haven't seen any and it's been run to produce energies of...

Heinrichs (MIT Lincoln Lab)
How big is the beam in the crystal?

Koch (Langley)
I don't know that particular spec off-hand. But you are right; it is controlled to get the best possible Raman conversion while avoiding damage due to excess thermal loading. The crystal doesn't have to be cooled so it is very rugged thermally.

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048104
318670
10P.

# *Wake Vortex Radar System Development*

## *Overview*

Robert T. Neece
NASA Langley Research Center
May, 1997

## *Objectives*

**Investigate microwave and millimeter wave sensors to locate, track, quantify, and observe the wake vortex hazard.**

- **Develop and evaluate system concepts and designs using sensor system models and employing a theoretical reflectivity model for the wake vortex.**
- **Test the validity of the theoretical model.**
- **Acquire sensor systems and conduct field testing to evaluate.**
- **Refine a system for field testing as a wake vortex sensor.**

## Approach

- Initial Research
  - Scattering and Reflectivity Studies
  - Radar Systems Investigations
  - Clear Air Reflectivity Experiments
- Low Visibility Sensor Development
  - Design Studies & Performance Predictions
  - Procurement/Market Investigation
  - Sensor Development & Testing

## Team Members

- NASA Langley Research Center
- U.S. Army Missile Command
- Research Triangle Institute
- Phase IV Systems
- Associated RF Sensor Efforts
  - Lockheed Martin
  - Applied Physics Laboratory
  - WLR Research

## *Clear Air Reflectivity*

- Mechanism: small variations of index of refraction over eddies with diameter = $\lambda/2$
- Eddies must be in non-dissipative range
- Reflectivity model uses TKE dissipation rate to estimate reflectivity and scales of turbulence from TASS output

| F (Ghz) | $\lambda/2$ |
|---|---|
| 5 | 3 cm |
| 10 | 1.5 cm |
| 35 | 4.3 mm |
| 95 | 1.6 mm |

## *Wallops Island Experiment*

- Objective - Attempt clear air detection with available X- and C-band radars
- C-130 with smokers
  - 400m to 1200m range
  - 1500′ to 2500′ altitude
- Results
  - X-band - returns masked by clutter
  - C-band - difficult detection via reflectivity
- Conclusion - clear air capability requires too much development and expense

# X-Band Characteristics

## 9.3 GHz Pulsed Doppler Radar:

| | | | |
|---|---|---|---|
| Peak Power | 1 kW | Antenna Dia. | 10 m |
| Pulse Width | 0.22, 0.48, 0.96 μs | Cross Range Res. @ 2 km | < 10 m |
| PRF | 9581 Hz | Beam Width | 0.25° |
| Range Res. | 37.5 m | Ant. Gain | 55 dB |
| Min. Range | 400 m | Scan Rate | 2°/s |

# C-Band Characteristics

## AN/FPQ-6 C-Band Pulsed Tracking Radar:

| | | | |
|---|---|---|---|
| Frequency | 5765 MHz | Antenna Dia. | 8.84 m |
| Peak Power | 2.2 MW | Ant. Gain | 51 dB |
| PRF | 640 Hz | Beam Width | 0.4° |
| Range Res. | 112.5 m | 1st Sidelobe | -16.5 dB |
| Range gate | 0.75 μs | Scan Rate | 2°/s |

# Lockheed Martin - WSMR

- Data Collection: collect local windfield and wake vortex data for 16 aircraft runs in 3 orientations (vertical, transverse, and radial)
- Analysis: discriminate WV via spectral analysis and Doppler history plots
- Radar: MOTR, C-band, 1 MW(peak), $\tau = 1\ \mu s$, 45.9 dB ant. gain, 1.05° beamwidth, E scan
- Conclusion: vortices can be detected when aircraft passes overhead (vertical orientation), in other configurations vortices are indistinguishable from clutter and ambient winds

# Applied Physics Lab - BWI

- Internal Research and Development funding
- Commercial and NASA C-130 flights on BWI runway 33L
- Bistatic configuration to utilize better forward scatter
- X-band used due to many available components
- Single tone CW reference horn for spillover cancellation
- Acoustic pumping at 1 - 5 kHz based on geometry
- 100 - 300 feet common volume
- Demonstrated vortex detection based on Doppler offset due to vortex sink rate

# A Low Visibility WVR

- Desired Capabilities

  complementary to a lidar clear air instrument

  35 to 44 GHz coherent radar using COTS technology

  Range Resolution: 5 m

  Crossrange Resolution: 7.5 m @ 1 km, or better

  Fog Capability: 0 dB S/N for -40 dBZ reflectivity factor @ 1.5 km
  - corresponds to 500 m visibility in advection fog
  - and 175 m visibility in radiation fog

  Min. Range: 500 m

  Useful Range to 3 km

# WVR System

- 35 GHz radar provided by MICOM for modification
- 500 W peak transmitter for developmental testing
- Parabolic antenna, Cassegrain feed, 58 dBi gain
- Scan rate of 1 to 10 degrees/sec
- 25 kHz and 12.5 kHz PRFs
- 128 range cells and 512 Doppler frequencies
- 88 bit phase code
- 5 m compressed pulse length
- 440 m uncompressed pulse length

# Performance Predictions

| Condition | 2 kW | 500 W |
|---|---|---|
| *Advection Fog* | | |
| light to moderate | poor S/N | poor S/N |
| thick | capable to 1.3 km | capable to < 800 m |
| dense | capable | capable |
| *Radiation Fog* | | |
| light to moderate | poor S/N | poor S/N |
| thick | poor S/N | poor S/N |
| dense | capable | capable |
| *Drizzle & Rain* | capable | capable |
| *Snow* | | |
| light to moderate | capable | capable |
| heavy | capable to 900 m | capable to 800 m |

# Plans

- Conduct 500 W WVR field test at Redstone Arsenal
- Develop real time detection, tracking, hazard measurement capabilities
- Upgrade system to 2 kW
- Investigate lidar/radar sensor integration
- Develop AVOSS interfaces
- Conduct AVOSS testing and demonstration

## *Lidar/Radar Similarities*

- Siting geometry and target features
  - aerosols vs. for fog/rain droplets
- Fixed resolution cell size at all ranges
  - 60 m vs. 5 m (compressed)
- Both produce radial velocity field
  - similar vortex feature extraction & display
- Operation is complementary
  - Lidar for clear, radar for low visibility

## *Lidar/Radar Differences*

- Fundamental
  - Throughput data rates
  - Clutter suppression requirements
  - Doppler processing: lidar - within PRI, radar - incoherent P to P
  - Pulse compression within PRI for radar
- Implementation
  - Offset final vs. I & Q
  - 8 vs. 12 bit A/D resolution
  - Time domain pulse compression for radar

# References


- Marshall, Scales, and Myers, Nov. 1996, "Spacio-Temporal Characteristics of Radar Reflectivity in Wingtip Generated Wake Vortices," Research Triangle Institute Technical Report RTI/4500/41-07S, NASA contract NAS1-18925.
- Marshall, deWolf, and Kontogeorgakis, June 1996, "Visibility and Radar Reflectivity Factor in Fog and Haze," Research Triangle Institute Technical Report RTI/4500/41-06S, NASA contract NAS1-18925.
- Mackenzie, Jan. 1997, "Measured Changes in C-Band Radar Reflectivity of Clear Air Due to Aircraft Wake Vortices," NASA Technical Paper TP-3671.
- Katz, Hudson, and Lupnacca, Mar. 1997, "Investigation of Agile Beam Radar for Meteorological Surveillance," Lockheed Martin, Final Report, Contract No. DTFA01-95-C-00021.
- Marshall, Davis, and Caswell, July 1996, "Wake Vortex Ka-Band Radar Technology," Research Triangle Institute Technical Report RTI/4500/41-05S, NASA contract NAS1-18925.

**Questions and Discussions Following Robert Neece's Presentation (Langley)**

Turgut Sarphaya (Naval Postgraduate School)
I would like to make a comment that your talk, more than any other, has pointed out some important factors and I think would require a subtle change in evaluating the wake hazard problem. So far with lidar, it has been on detecting the vortices and calculating their strength and finding out when they reach a particular minimum value. I think what is needed is a total assessment of the aerodynamics of the landing corridor every 10 seconds or so at all times. When we look at it that way, whether there are vortices in it or not, whether vortices are coming from another ship, whether there is rain, hail, or ice, wind or whatever. In that sense if we assess the entire conditions, we can hang up a sign at door of corridor and say occupied, you cannot land for another 15 seconds. In that sense, since most accidents happen 50% of time or more due to human error loading of the mind of the pilot who will be stressed more, subjected to more turbulence, as well as stress to aircraft itself. All of these will have to be assessed in what I would call total assessment of the conditions of the landing corridor, not just a couple of vortices. This will require measurement of turbulence, measurement of wind and gust and also vortex strength.

Neece
I don't think there was a question there that I could answer adequately. There certainly are a lot of issues that are raised. It may be lidar and radar can provide more information about what is in the corridor than just vortices. For example, information about weather states, ambient wind and that sort of thing, perhaps turbulence. Yes, there is potential to get a lot of information about the approach corridor and use it in AVOSS. One of the objectives of AVOSS is to predict what is going to happen in the approach corridor so planes can be dynamically spaced as they are coming to airport, not so we have a situation where a pilot is making his approach, he has to wave off. That is an important consideration.

# Wake Vortex Radar Simulation Studies


**Rob Marshall**
**&**
**Ashok Mudukutore**

**Center for Aerospace Technology**
**Research Triangle Institute**

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- **Wake Vortex Radar Reflectivity Models in Clear Air and Fog**
- **35 GHz Wake Vortex Pulse Compression Radar Simulations in Fog**

RTI

## Refractive Index Structure Constant ($C_n^2$) and Clear Air Radar Volume Reflectivity ($\eta$)

- $\eta \approx 0.38\, C_n^2\, \lambda^{-1/3}$ $(m^2\, m^{-3})$
- $C_n^2 \approx 3.6 \bullet \varepsilon^{-1/3}\, u \bullet l \left[\left(\frac{\partial \Phi}{\partial x}\right)^2 + \left(\frac{\partial \Phi}{\partial z}\right)^2\right]$
- $\eta \approx 1.4 \bullet \varepsilon^{-1/3}\, u \bullet l \left[\left(\frac{\partial \Phi}{\partial x}\right)^2 + \left(\frac{\partial \Phi}{\partial z}\right)^2\right] \lambda^{-1/3}$
- **Refractive Index Structure Constant for C-130 30 sec after rollup $u = 8\,m\,sec^{-1}$, $l = 6\,m$ $(dB\; m^{-2/3})$**

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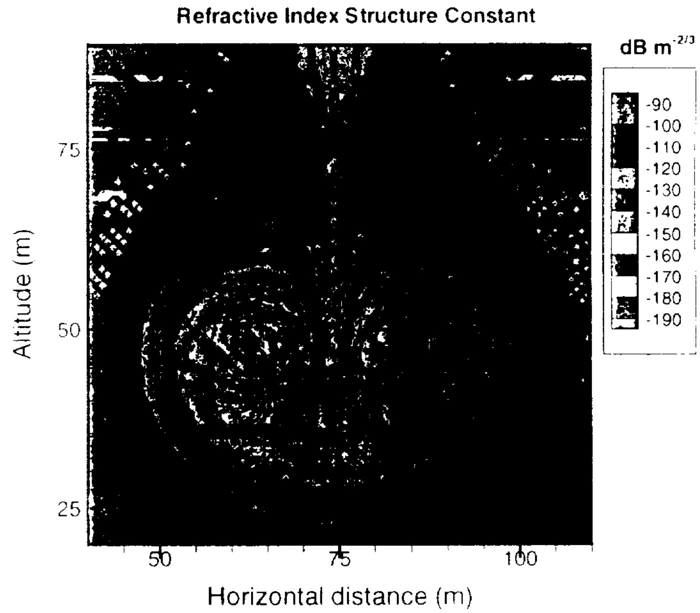
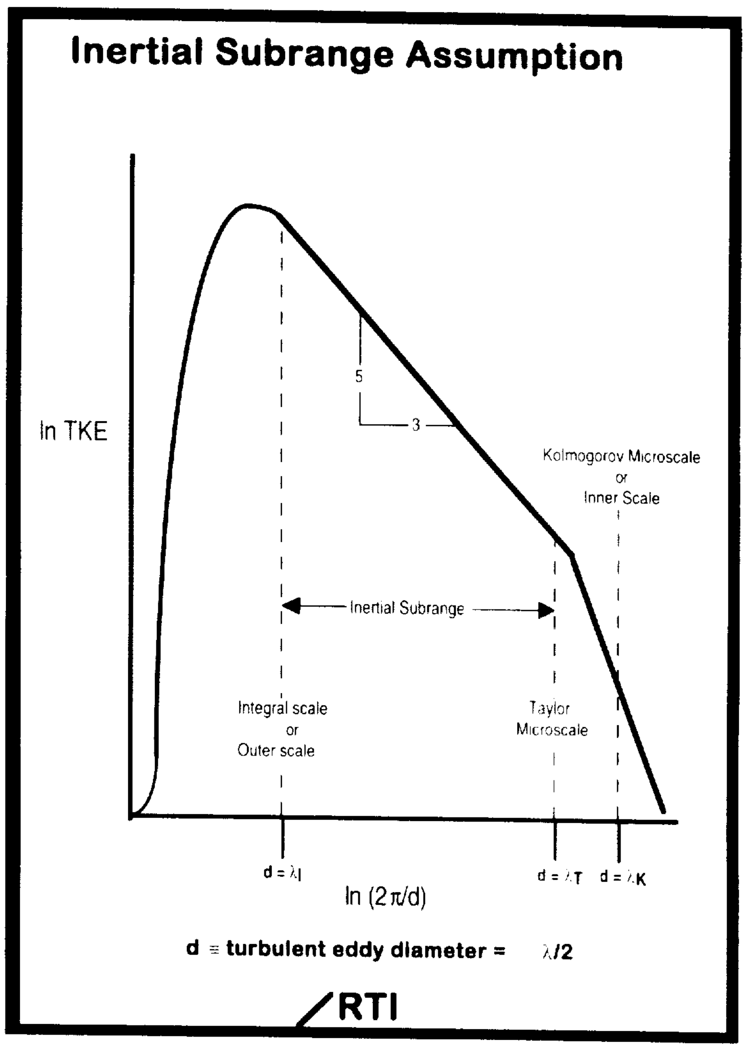


Refractive Index Structure Constant
dB m^-2/3
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
Altitude (m)
75
50
25
50
75
100
Horizontal distance (m)

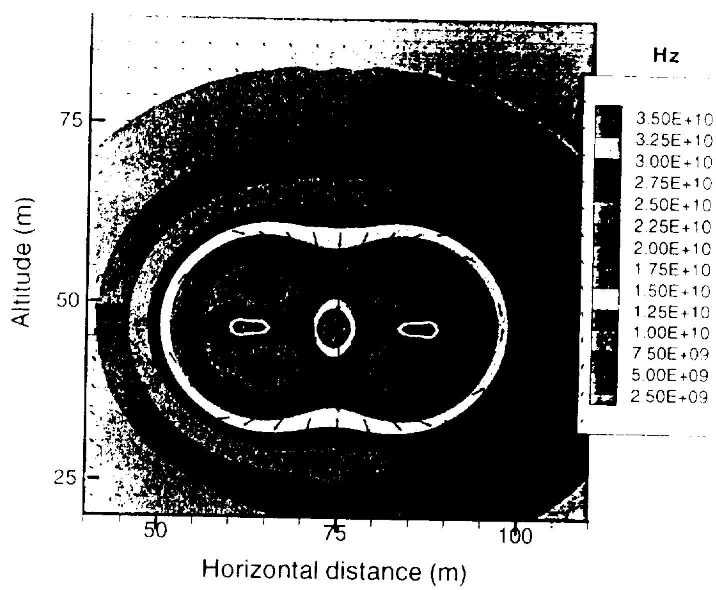
Inertial Subrange Assumption
ln TKE
5
3
Kolmogorov Microscale
or
Inner Scale
Inertial Subrange
Integral scale
or
Outer scale
Taylor
Microscale
d = λI
d = λT
d = λK
ln (2π/d)
d = turbulent eddy diameter = λ/2
RTI

# Taylor Microscale and Maximum Radar Frequency

- * $\lambda_K \equiv$ Kolmogorov microscale $= (\nu^3/\varepsilon)^{1/4}$ (TASS)
- * $\lambda_T \equiv$ Taylor microscale $= \lambda/2 = ?$
- * $\lambda_T = (\lambda_K)^2\, 15^{1/2}\, u\, \nu^{-1}$ microscale Reynolds number
  $u \equiv$ scale velocity = avg core wall velocity
- * $f_{max} = c\ \nu / 2\, (\lambda_K)^2\, 15^{1/2}\, u$
- * maximum radar frequency for C-130, 30 sec after rollup
  $u = 8\ m\ sec^{-1}$

RTI

Maximum Radar Frequency - Reynold's Number



## Radar Reflectivity Factor in Fog (Z)

* $Z \equiv \int_{D_{min}}^{D_{max}} N(D)\, D^6\, dD$

  dBZ = 10 log (Z)
  -60 dBZ< Z < -13 dBZ in fog
  D ≡ drop diameter
  N(D) ≡ drop size distribution

* $M \equiv (\pi\, \rho_w/6) \int_{D_{min}}^{D_{max}} N(D)\, D^3\, dD$

  M ≡ liquid water content (TASS)

* VAFB fog data set

  $Z = 0.0243\, M^{1.494}$

* Radar Reflectivity Factor for C-130, 30 sec after rollup in VAFB fog

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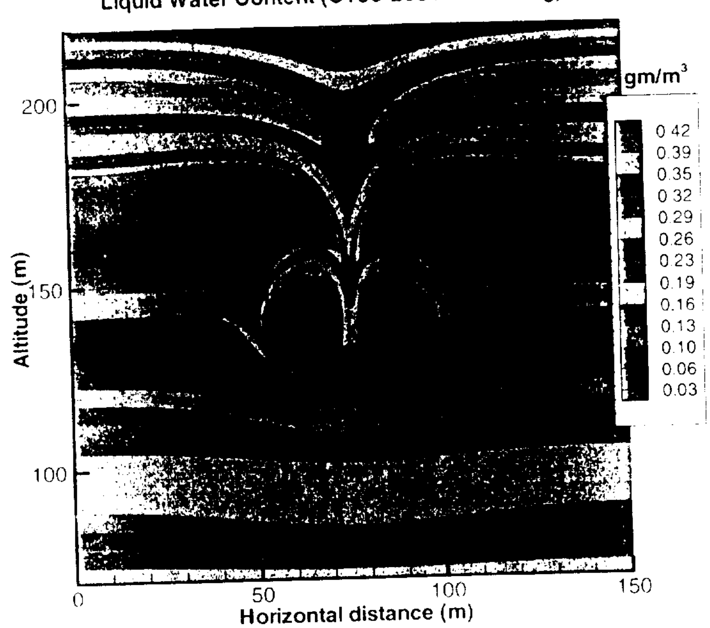
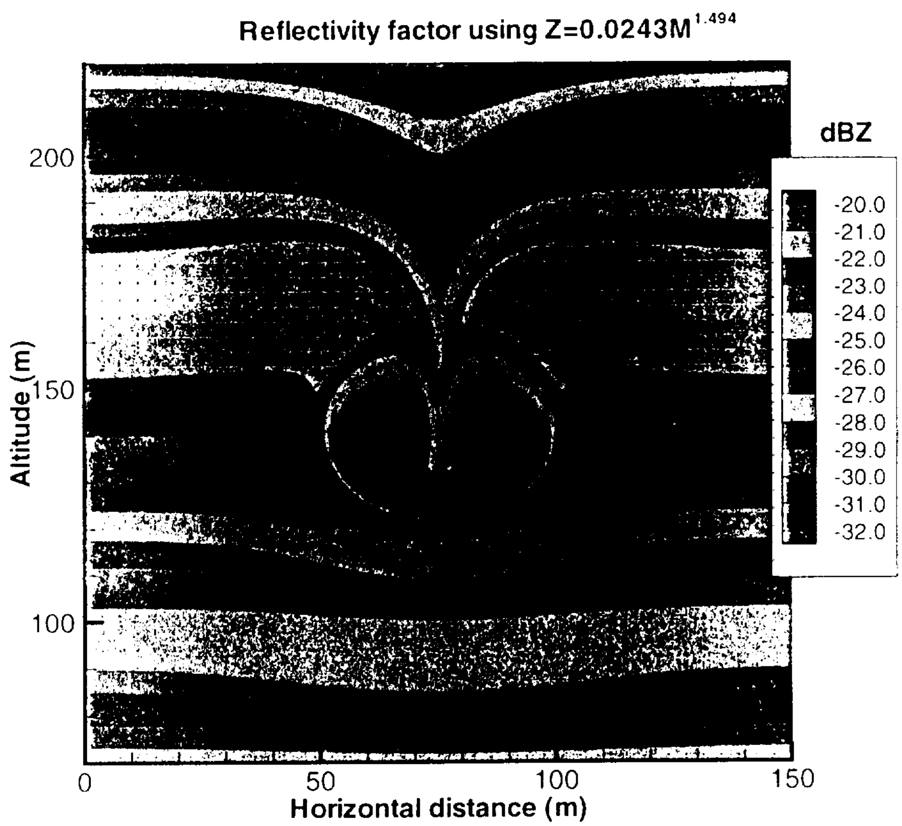
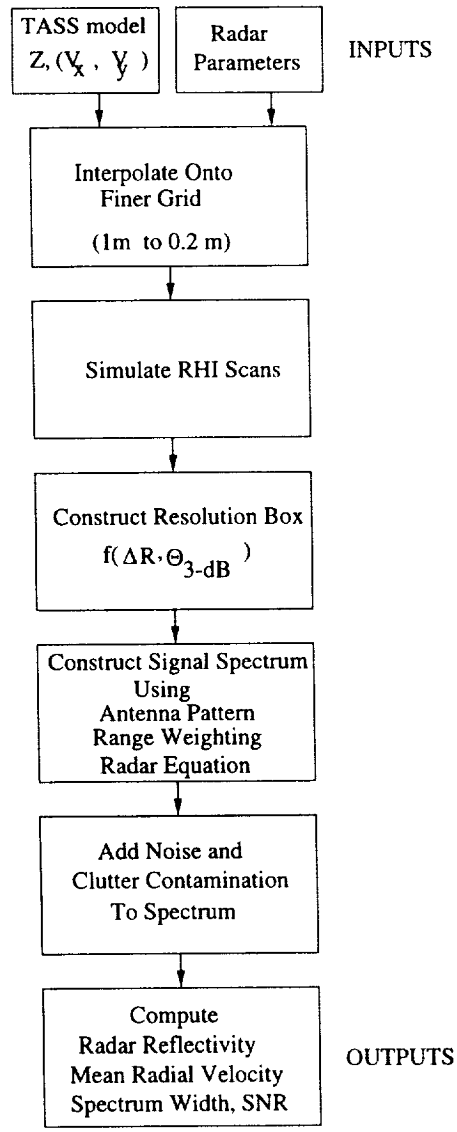
Liquid Water Content (C130-20s in VAFB fog)

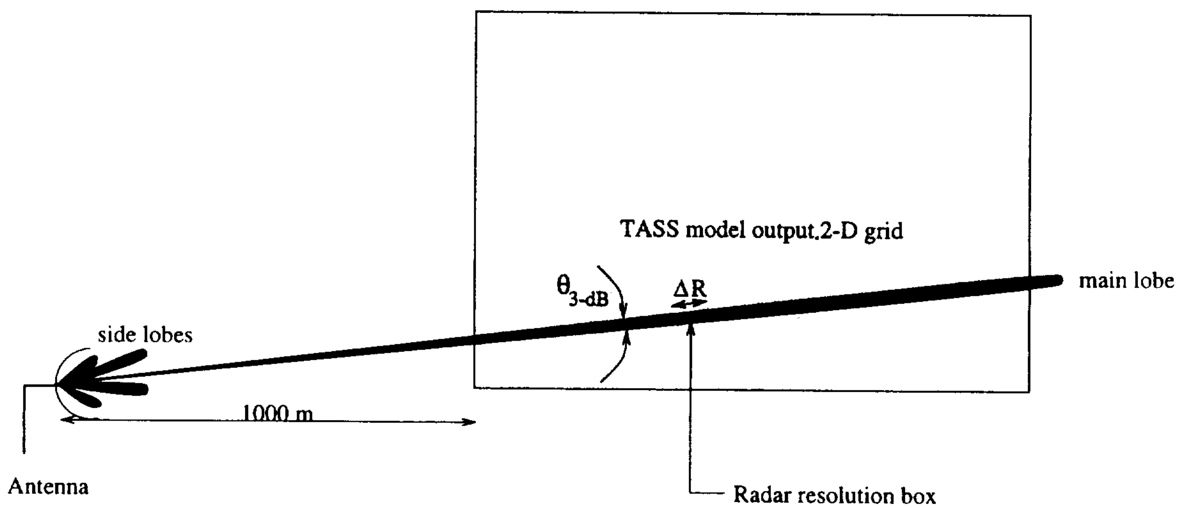



Reflectivity factor using Z=0.0243M^1.494
dBZ
-20.0
-21.0
-22.0
-23.0
-24.0
-25.0
-26.0
-27.0
-28.0
-29.0
-30.0
-31.0
-32.0
Altitude (m)
200
150
100
0
50
100
150
Horizontal distance (m)

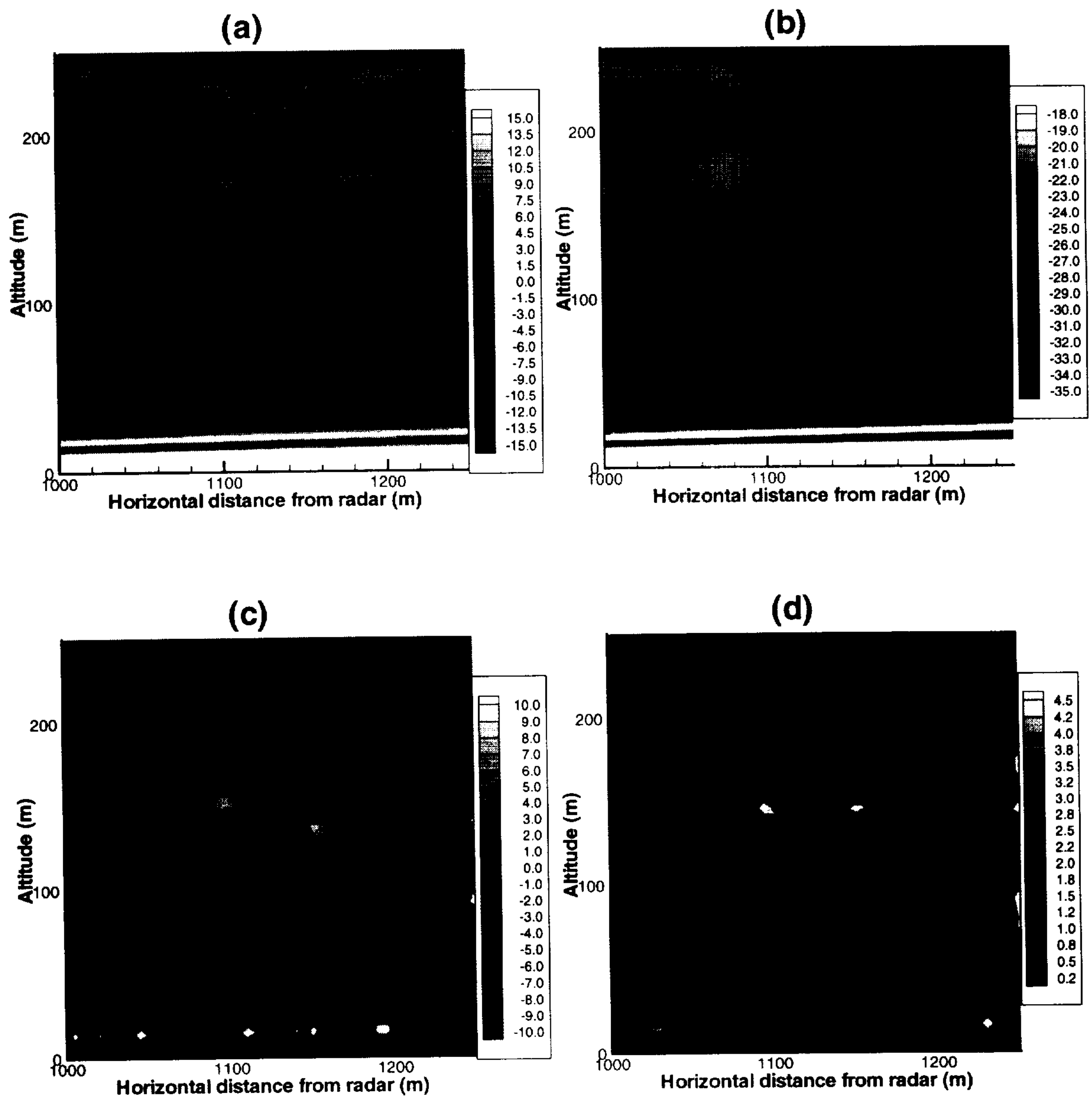

TASS model
Z, ($V_x$ , $V_y$ )
Radar
Parameters
INPUTS
Interpolate Onto
Finer Grid
(1m to 0.2 m)
Simulate RHI Scans
Construct Resolution Box
f( $\Delta R$, $\Theta_{3\text{-dB}}$ )
Construct Signal Spectrum
Using
Antenna Pattern
Range Weighting
Radar Equation
Add Noise and
Clutter Contamination
To Spectrum
Compute
Radar Reflectivity
Mean Radial Velocity
Spectrum Width, SNR
OUTPUTS

**RADAR MODEL**

## Schematic diagram of radar model

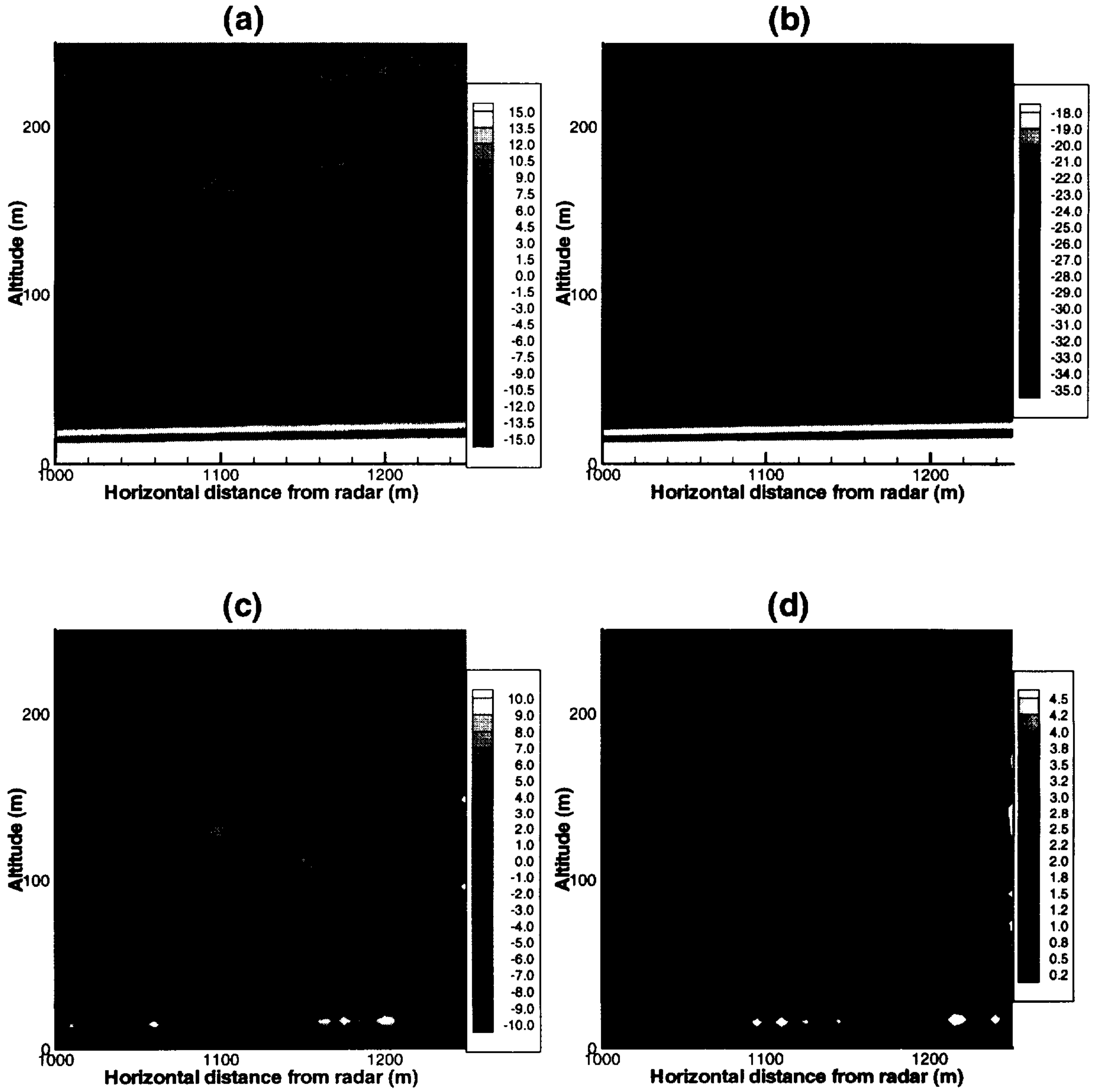


**C-5A wake, 20 s after rollup, dense fog dataset**
**Waveform-filter = MPS69-MF, $f_o$ = 35 GHz, $P_t$ = 500 W**
**Wake released at 210 m altitude**



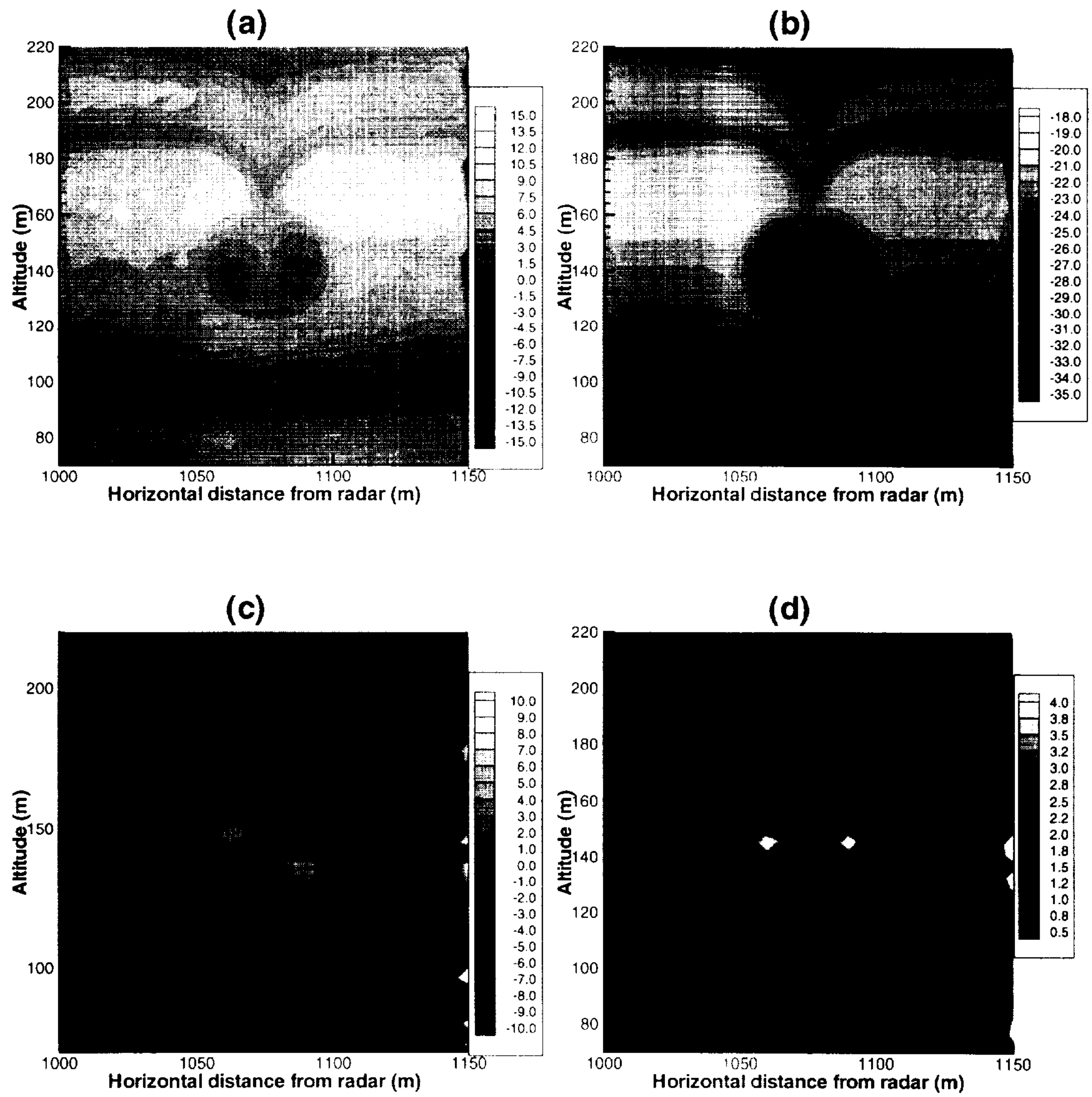

**Estimates of (a) Signal-to-Noise Ratio (dB), (b) Reflectivity (dBZ), (c) Mean Radial Velocity (m/s), and (d) Spectrum width (m/s).**

**C-5A wake, 40 s after rollup, dense fog dataset**
**Waveform-filter = MPS69-MF, $f_o$ = 35 GHz, $P_t$ = 500 W**
**Wake released at 210 m altitude**



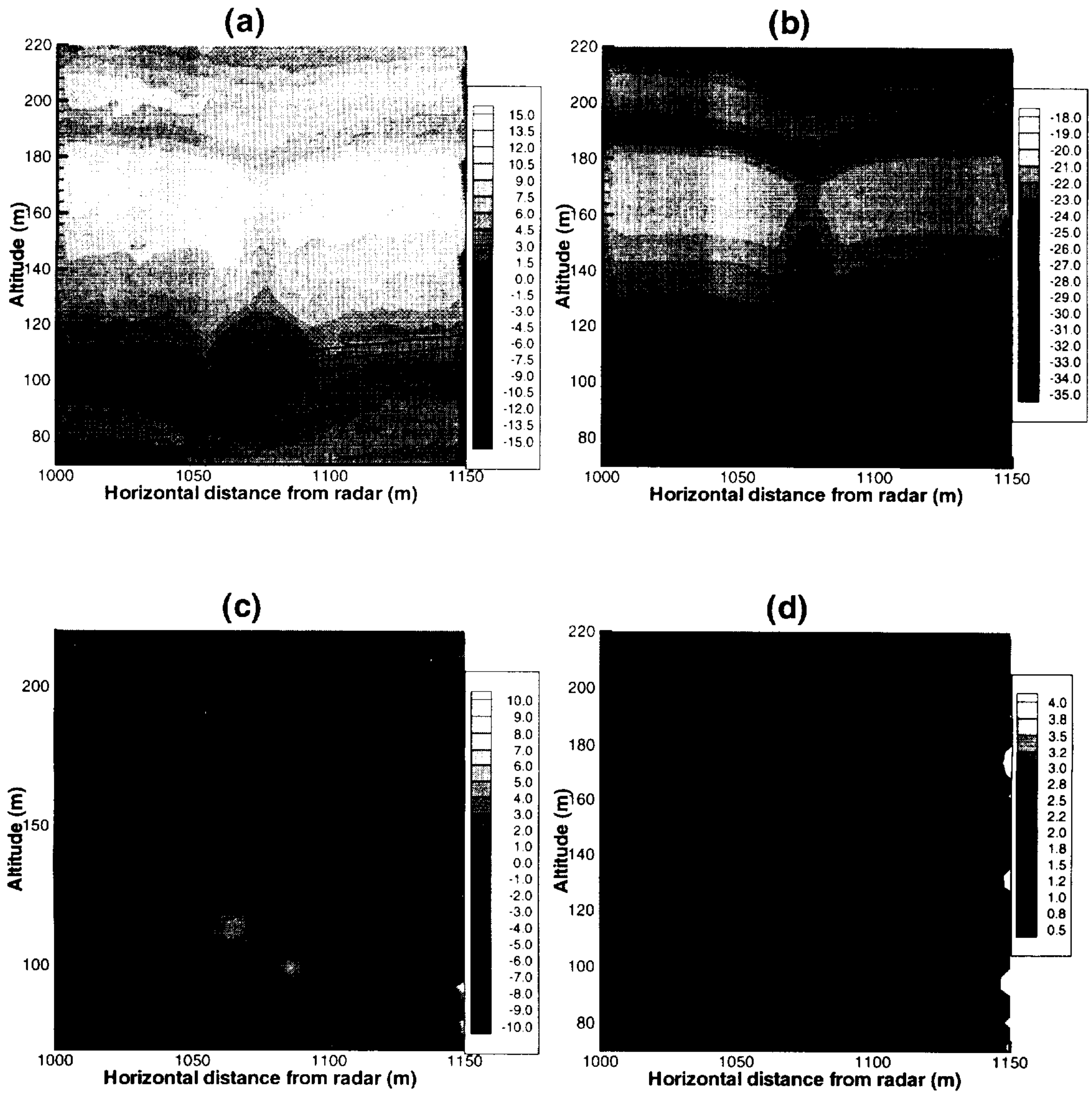

**Estimates of (a) Signal-to-Noise Ratio (dB), (b) Reflectivity (dBZ), (c) Mean Radial Velocity (m/s), and (d) Spectrum width (m/s).**

## C-130 wake, 20 s after rollup
## Waveform-filter = MPS69-MF, $f_o$ = 35 GHz, $P_t$ = 500 W




**Estimates of (a) Signal-to-Noise Ratio (dB), (b) Reflectivity (dBZ), (c) Mean Radial Velocity (m/s), and (d) Spectrum width (m/s).**

**C-130 wake, 40 s after rollup**
**Waveform-filter = MPS69-MF, $f_o$ = 35 GHz, $P_t$ = 500 W**




**Estimates of (a) Signal-to-Noise Ratio (dB), (b) Reflectivity (dBZ), (c) Mean Radial Velocity (m/s), and (d) Spectrum width (m/s).**

# Future Plans

- Incorporate the statistical fluctuations of the signal into the power spectrum model.
- Test various signal processing algorithms that yield "best" estimates of radial velocity, spectrum width, reflectivity.
- Develop algorithms to estimate vortex location, average circulation, and core radius from basic radar measurements.
- Study the tradeoff between SNR vs range resolution, i.e., how estimates of wake vortex characteristics degrade by increasing size radar resolution volume.

**Questions and Discussions Following Rob Marshall's & Ashok Mudukutore's Presentations (RTI)**

Yuh Lang Lin (North Carolina State University)
At end of your simulation it looks like this pair of vertices came together. Have you been able to detect, Crow instability?

Mudukutore
No, we haven't gone that far in our modeling.

Zheng (U. of South Alabama)
Could you please explain how Kolmogorov microscale is determined from TASS code?

Marshall
It is a function of kinematic viscosity and turbulent kinetic energy dissipation rate, both of which are TASS outputs.

Zheng
As I understand TASS, it is large eddie simulation model and the best you can do with large eddie simulation is model something at the Kolmogorov microscale, but you cannot resolve.

Marshall
That is correct. He uses a parameterization in order to get closure, in order to predict turbulent kinetic energy dissipation rate. I am not familiar with details of TASS and how they do that.

Pal Arya (North Carolina State Univ.)
You had an equation for converting Taylor microscale and Kolmogorov scale. There you had velocity scale; as I understand that velocity scale is part of Reynold's number. It should be an autonomous turbulence velocity scale, not the mean velocity of the actual. I thought you were using 8 meters per second which is more of the mean velocity of the wake vortex, not a turbulence velocity scale. The relationship should have a turbulence velocity scale, not mean velocity.

Marshall
We took that as a first pass at it and hoped when we did 10 times the log, dB wise we would not see a lot of difference. But we could refine that velocity scale and that parameterization.

Alexander Proskovsky (NCAR)
Could you show your plot with spectra? Your plot where you show turbulence spectra? First, I want to make a comment. Taylor microscale has nothing to do with the age of inertial range. It might be anywhere within inertial range. And now a question. It is written in any text on turbulence that viscous scale lower atmosphere is something

between 0.3 to 1 or 2 millimeters, so inertial range starts lets say 20 or 25 Kolmogorov scales, which would be about 3 centimeters. What was the reason to make any estimates if you knew you had 1 millimeter wavelengths? So you cannot see inertial range a priori.

Marshall
I didn't get the full question, but we used Tatarski's equations which are only valid for the inertial subrange.

Proskovsky
Yes, but as I said because it was a priori known from any book on turbulence, that turbulence of Kolmogorov scale I repeat is about between 0.3 and 1 millimeter in lower atmosphere and may reach 5 to 10 millimeters at 5 kilometers height. So 1 millimeter wavelength cannot work in inertial range a priori and Tatarski relation is not applicable here a priori. My question is what was the reason to use this equation?

Marshall
Are you asking the reason we made the assumption that we had to work in inertial subrange?

Proskovksy
Yes

Marshall
We based that on fact that we looked at previous work by Cone, and Morris Hill Radars, and papers he put out where he talked that the first step is that we use the equations of Tatarski that assumed you were in inertial subrange.

Proskovksy
Yes

Marshall
The other thing is if you increased your radar frequency too high, you are well into the dissipated range where there was not enough turbulent kinetic energy and you end up having to design a radar with exorborant antenna diameter and transmitter power. So there were two reasons we were interested in what the eddie sizes were in the vortex in this area.

Proskovsky
As first I said, that was known. And second question. In inertial range you can easily derive equations in this range very similar to Tatarski. They are in any book on turbulence. They would be different than Tatarski. For example, structure functions would not be to 1/3 but would be 2nd power, but it does matter. Why was this not done?

Ben Barker (Langley)
In the interest of time, may I suggest we do have a number of breakout rooms. Dr. Marshall and Dr. Mudukutore, I am sure would be glad to meet with you and any other interested party would be welcomed to join the discussion. One more question.

Steve Lewellen (West Virginia Univ.)
Did I understand you right that the leading contribution to the structure function is the humidity fluctuation? Does the TASS simulation you are using include the engine exhaust which are a big contribution to humidity fluctuation?

Marshall
By the engine exhaust I assume you mean the aerosols in the engine exhaust.

Lewellen
The humidity coming in.

Marshall
The humidity. No, that is not included in the TASS model, is my understanding.

Lewellen
Then what you are getting around the vortices could be quite different.

Marshall
Possibly. But that is beyond the capability of TASS at this point.

Klaus Sievers (German Cockpit Assoc.)
Your simulation seems to be done in dense fog up to 300 meters height. That would be Cat 2 or Cat 3 weather where we have fairly long spacing due to other requirements than wake vortex. So my question, under these questions we would not really need your radar. Have you done any simulation in conditions where we might profit from it like when we have 600 feet overcast?

Marshall
Well number one, our NASA administrator has indicated that within 10 years, we will be flying in all fog. We consider this to be a potential sensor for that situation.

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# Wake Sensor Evaluation Program
and
# Results of JFK-1 Wake Vortex Sensor Intercomparisons

NASA *First* Wake Vortex
Dynamic Spacing Workshop
*Day 2 - May 14, 1997*

Ben C. Barker, NASA Langley Research Center
David C. Burnham, Volpe Center/SESI
Robert P. Rudis, Volpe Center

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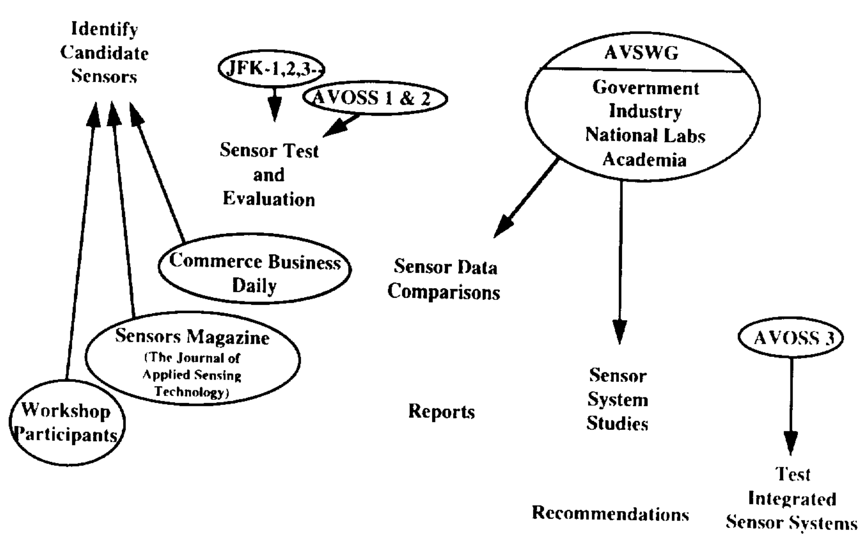
# Outline of Presentation

- Program Objectives
- Program Plan
- Volpe Center's JFK Test Facility
- November 1996 Test Program (JFK-1)
  - Participants
  - Description of Items Tested
  - Final Report Availability
  - Comparative Results (David Burnham)
- Plans for Additional Testing
  - JFK-2 (DFW Prep): May 27 thru June 6, 1997
  - JFK-3: Fall 1997
  - JFK-4 and Beyond
- Conclusions

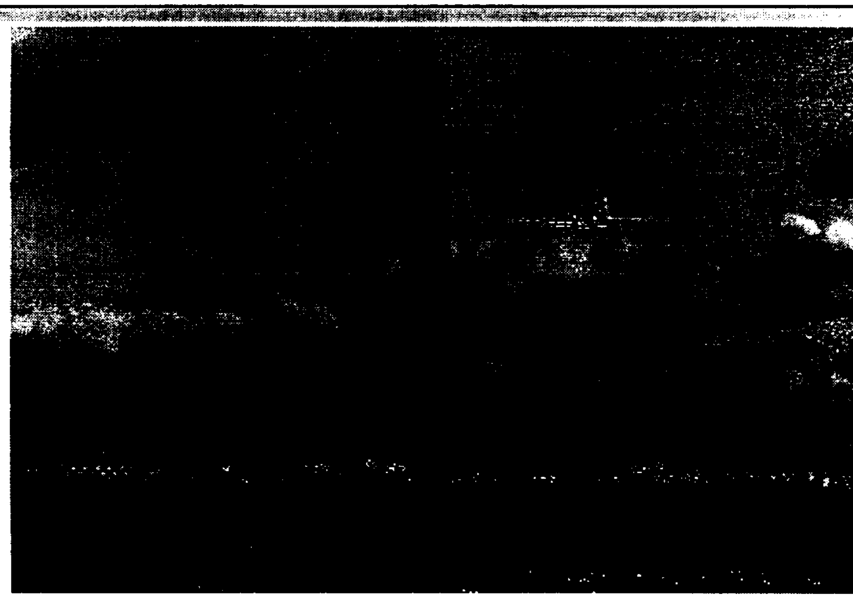
# Program Objectives

- **Identify** new concepts for wake vortex sensors which can individually or collectively fill the wake sensor requirements envelope for AVOSS.
- **Leverage** meteorological sensor technologies for wake vortex detection, tracking and strength measurements.
- **Characterize** sensor performance capabilities over the range of AVOSS environments and deployment configurations.
- **Develop** concepts for integrated sensor systems which satisfy the AVOSS requirements envelope for both weather and wake measurements.

# Program Plan



# Volpe Center's JFK Test Site



# JFK-1 (November 1996)

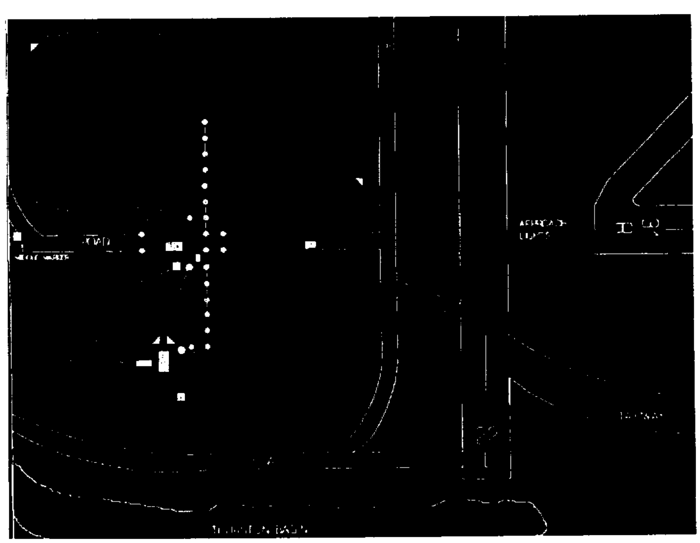
- Test Participants
- Description of Items Tested
- Final Report Availability
- Comparative Test Results (D. Burnham/SESI)

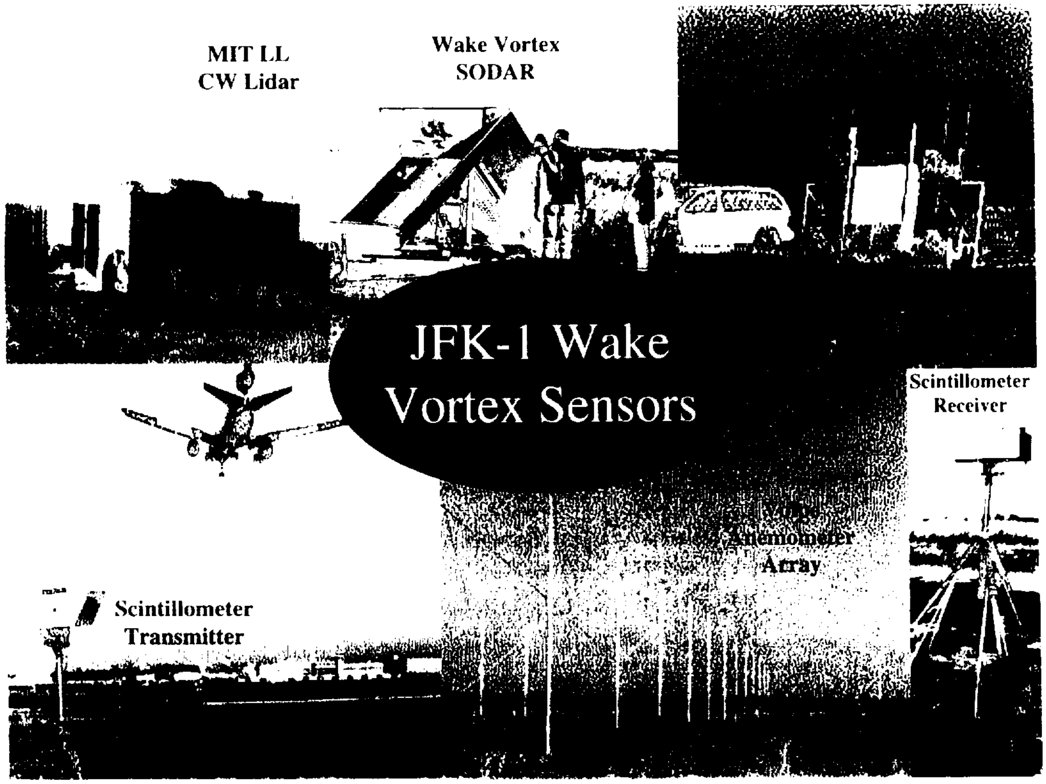
# JFK-1 Test Participants

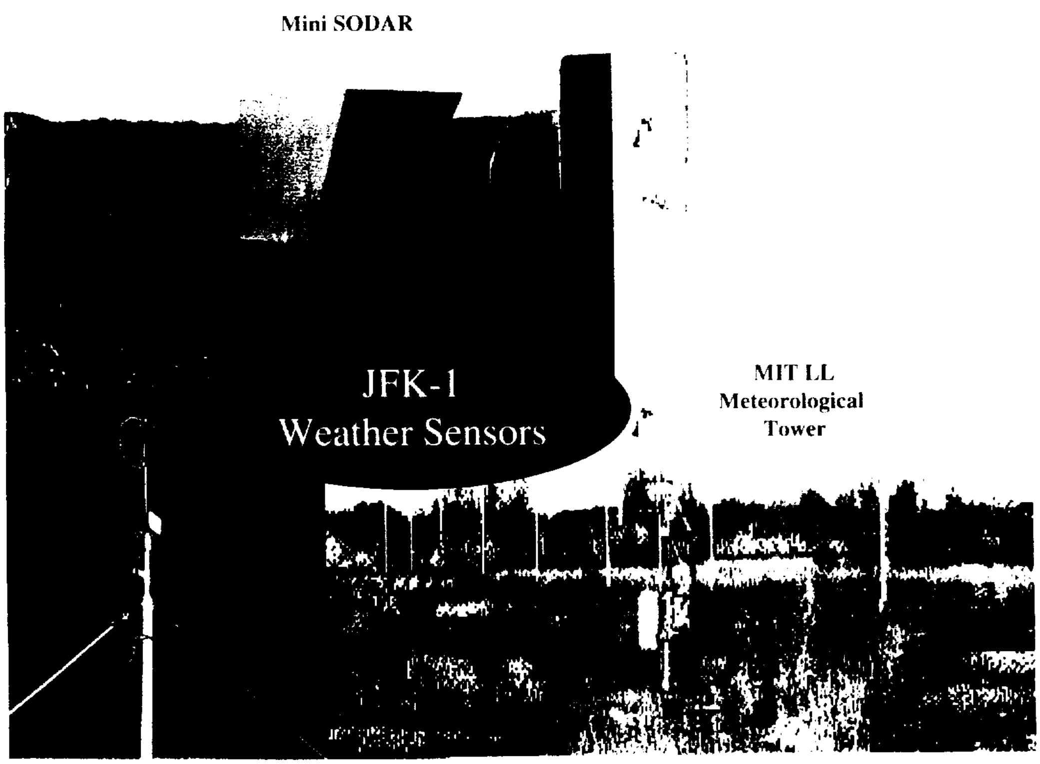
- **Volpe Center:** Steve Abramson (Volpe Center), Leo Jacobs (SRC), Phil McCarty (UNISYS), Bennet Cohen (Rannoch)
- **LaRC:** Ben Barker, Bill Stevens, George Greene, Anne Mackenzie
- **MIT Lincoln Laboratory:** Rick Heinrichs, Tim Dasey, Michael Matthews, Glenn Perras
- **WLR Research:** William L. Rubin
- **BFG Tech Integration:** George Succi, David Dumais
- **ScTI:** Ting-I Wang, Richard Cronkite*
- **Aerovironment:** Ken Underwood

***Photo Credits**

# Volpe Center's JFK Test Facility (JFK-1 Configuration)




MIT LL
CW Lidar
Wake Vortex
SODAR
JFK-1 Wake
Vortex Sensors
Scintillometer
Receiver
Anemometer
Array
Scintillometer
Transmitter


Mini SODAR
JFK-1
Weather Sensors
MIT LL
Meteorological
Tower

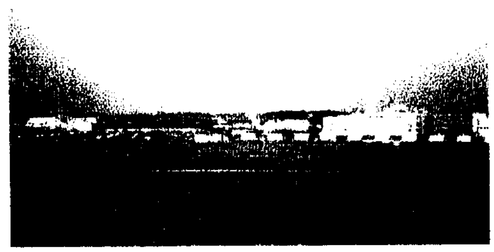
# JFK-1 Final Report

- Availability
  - Six Final Draft Copies Available for Review in the "Bell" Room.
  - Final Report to Be Printed in Mid-June 1997.
- Distribution
  - Please Sign Log Sheet if You Wish A Copy of The Final Report to Be Mailed to You.
  - Report Will Also Be Available From the National Technical Information Service (NTIS).

# Analysis of JFK-1 Data

- Two time periods were selected for data analysis & comparison based on the greatest number of sensors operating properly and availability of multiple aircraft landings:
  - Afternoon of November 13, 1996 (All sensors operating except WLR RASS)
  - Afternoon of November 20, 1996 (All sensors operating except BFG Tech Integration SODAR)
- Data has been reduced for these time periods to support performance comparisons among Volpe's wind line, MIT LL's CW lidar, and each of the other sensors in the test.

## Results of JFK-1 Wake Vortex Sensor Inter-Comparisons



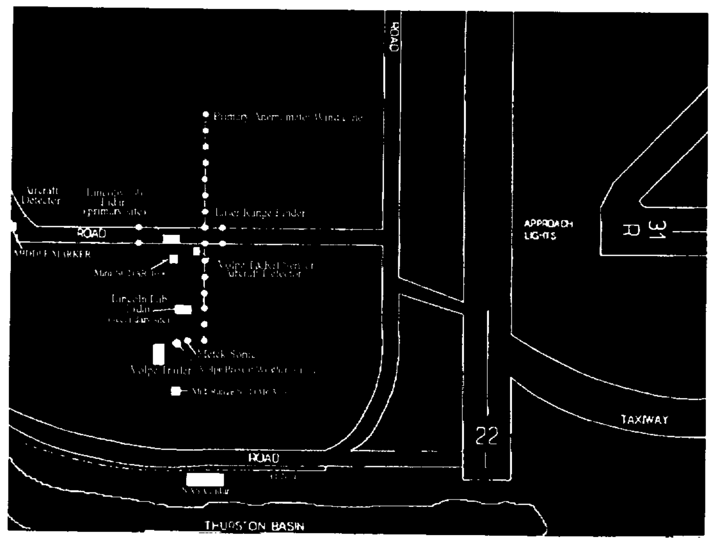
"New York, New York"

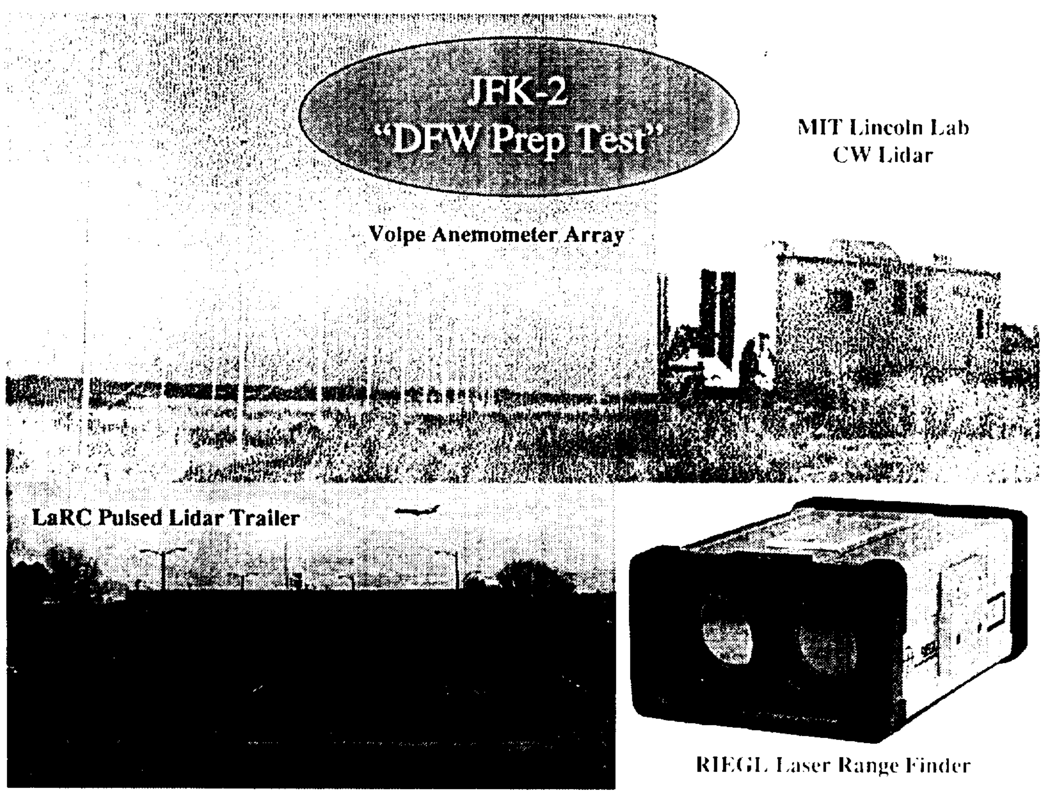
David C. Burnham
Scientific & Engineering Solutions, Inc.

## Plans for Additional Testing

- JFK-2 (DFW Prep) - Comparison of LaRC Pulsed Lidar Performance With that of MIT LL CW Lidar - May 27 thru June 6, 1997.
- JFK-3 - Comparison of All Available Sensors Including Improvements Since JFK-1 - Fall 1997.
- JFK-4 and Beyond - JFK Test Facility Available for Testing New Sensor Concepts As They Reach Maturity.

# Volpe Center's JFK Test Facility (JFK-2 Configuration)




MIT Lincoln Lab
CW Lidar

RIEGL Laser Range Finder

# Conclusions

- Overall Approach Should Be To:
  - Seek Simplest, Sufficiently Robust, Integrated Ground Based Sensor Systems (Wakes and Weather) for AVOSS.
  - Expand all Sensor Performance Cross-comparisons and Data Mergings in On-going Field Deployments.
  - Achieve Maximal Cost Effectiveness Through Hardware/Info Sharing
- An Effective Team is In Place to Accomplish The Above Tasks.

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# JFK-1 Wake Vortex Sensor Intercomparisons

D. C. Burnham

R. P. Rudis

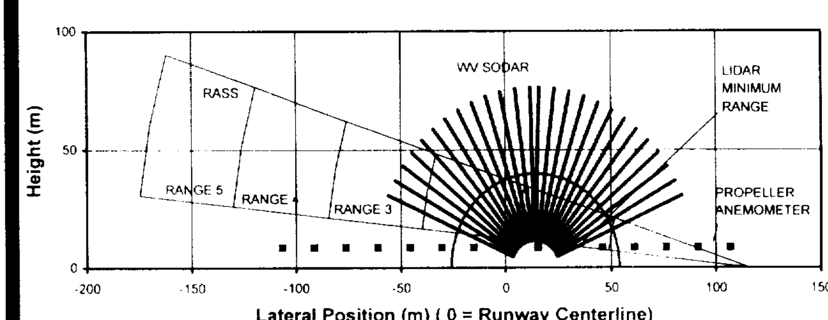
## Vortex Sensors - Status

- Volpe Anemometer Array
  - Height, circulation need validation
- MIT/LL CW Lidar
  - Relatively mature
- WLR RASS
  - Height, circulation need validation
- Wake Vortex Sodar
  - First wake vortex data from final system

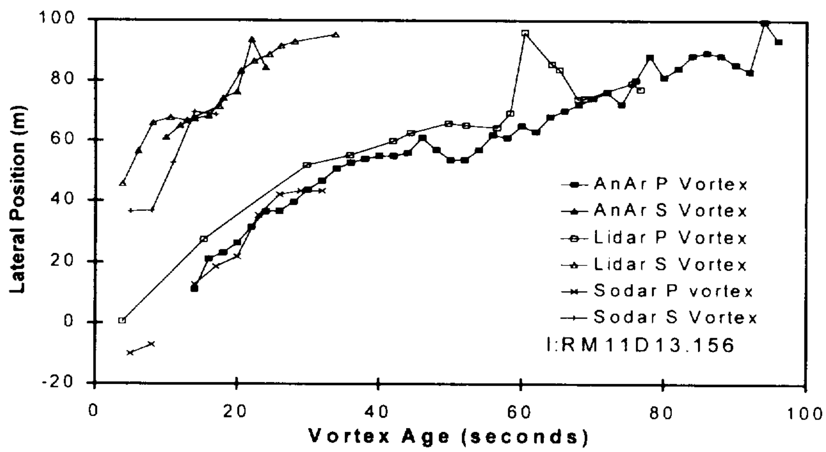
# Reference Sensors

- Lateral Position
  - Lidar, Anemometer Array
- Height
  - Lidar
- Circulation
  - Lidar

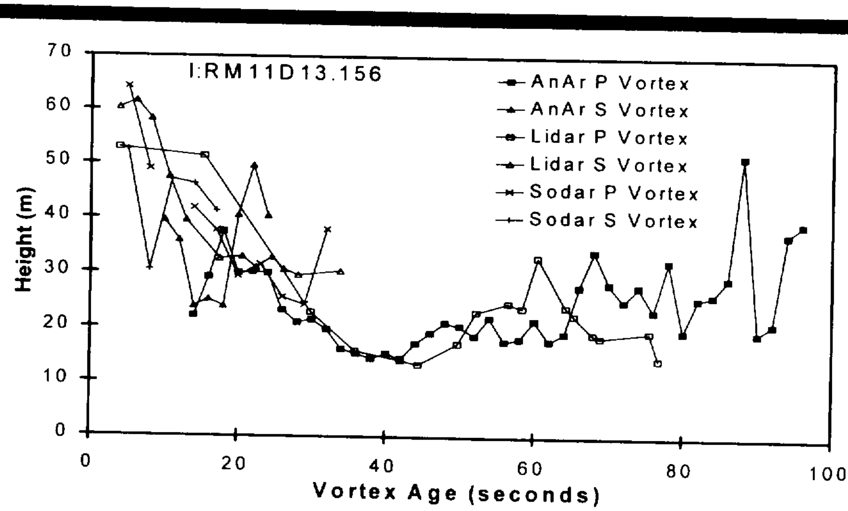
# Wake Vortex Sensor Coverage



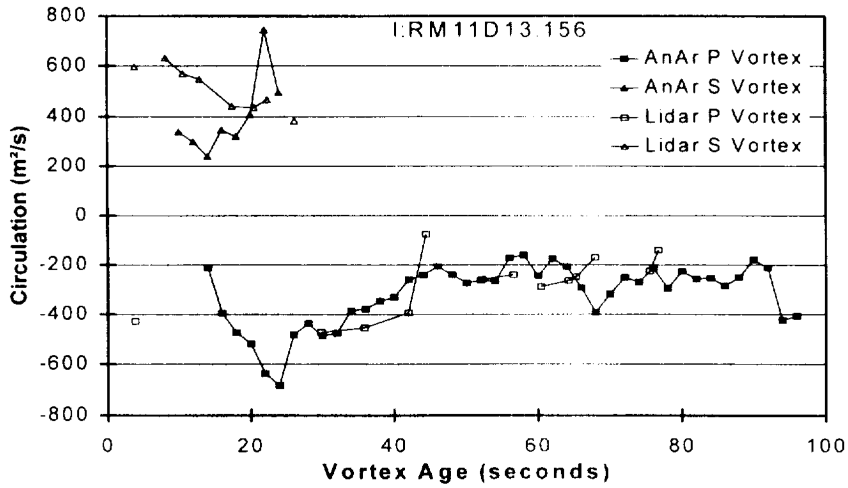
## Lidar - Anemometer Array - Sodar - Lateral Position




## Lidar - Anemometer Array - Sodar - Height



# Lidar - Anemometer Array - Circulation




# Amemometer Array Results

- Height measurements low before vortex age 20 seconds
- Generally agrees with lidar after 20 seconds
- Lateral positions sometimes disagree
- Heights sometimes much lower than lidar values
- Circulations comparable when heights agree

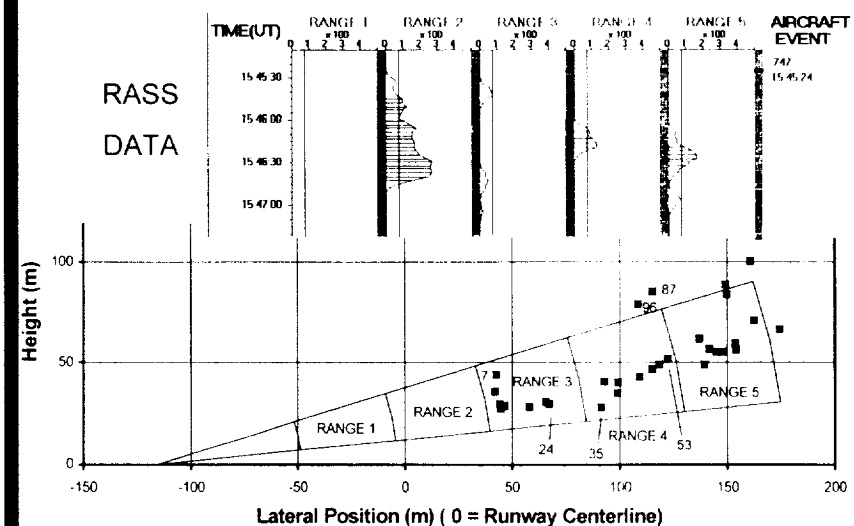
# Lidar Results

- Vortex identification problems for few runs
- Picks up secondary vortex rather than other vortex in a few cases

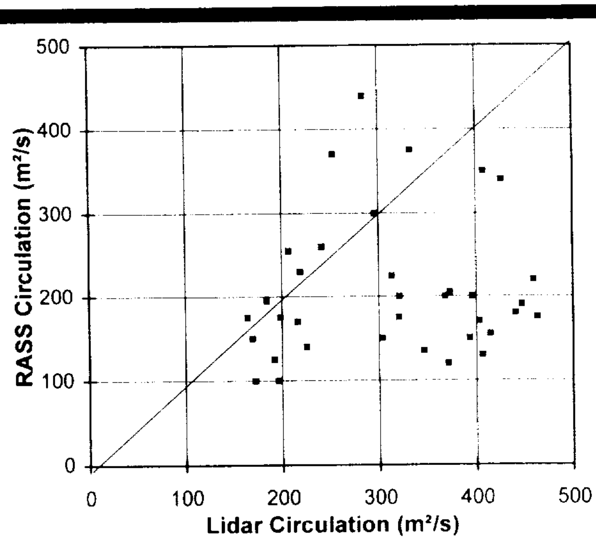
# Wake Vortex Sodar Results

- Hardware improvements needed to permit automatic vortex detection, analysis
- Manual vortex tracking generally consistent with other sensors

# RASS - Lidar: Locations




# RASS-Lidar: Circulations



# RASS Results

- Vortex detection generally consistent with lidar vortex trajectories
- Peak circulation values correlate with but generally lower than lidar values.

# AVOSS Utility

| Vortex Sensor: | An-Ar | Lidar | RASS | Sodar |
|---|---|---|---|---|
| Max. Height (m) | 40 | 250 | 500 | 100 |
| Resolution | Medium | High | Low | Medium |
| Strength Accuracy | Medium | High | Medium | Medium? |
| Automatic? | Yes | No | Yes | Yes |
| All Wx | Yes | No | Yes | No |

# Future Work Needed

- Consider secondary vortices
- Test maximum range of RASS
- Model RASS circulations
- Improve sodar hardware & software
- Test pulsed lidar

**Questions and Discussions Following Ben Barker's (NASA LaRC) and D.C. Burnham's (SESI) Presentations**

Al Zak (Vigyan)
About the JFK-II testing, your focus is going to be on the two lidars. Are you also planning to look at the comparison of wind vector determination outside of the vortex and compare to other sensor in wind mode?

Ben Barker (NASA LaRC)
We are going to do scans of wind information as will Lincoln with their lidar and will compare that with meteorological instruments.

Leonard Credeur (NASA Langley)
The assessment about the lidar and its range and its hardening capabilities, was that for the CW and would you have the some assessment for the NASA lidar?

Ben Barker (NASA LaRC)
The test is to find that out. We believe we will get accurate information that will compare favorably with the Lincoln lidar but that is the reason we are going to JFK to find out.

Klaus Sievers (German Pilot Association)
You have a lot of equipment in a small space. Have you noticed interference between your equipment and the air traffic control radar or air traffic control equipment.

Ben Barker (NASA LaRC)
There was some indication of interference with RASS operation. Dr. Ruben, who is in the audience and who is responsible for development of wake vortex RASS, has taken some instrumentation on site to see where the interference is coming from. As far as our instrumentation interfering with other equipment on airport, we have no indication that is occurring. The airport authority or the FAA has not descended upon us.

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# CURRENT STATUS AND APPLICATION OF HAZARD DEFINITION TECHNOLOGY

9p.

GEORGE C. GREENE

NASA First Wake Vortex Dynamic Spacing Workshop
May 13-15, 1997

# OUTLINE

- Why are we doing this research?
- What are we doing?
- What have we learned?

# WHY

- To define a "non encounter"
- To define a "hazard"
- To provide requirements for sensors
- To obtain input from the user community

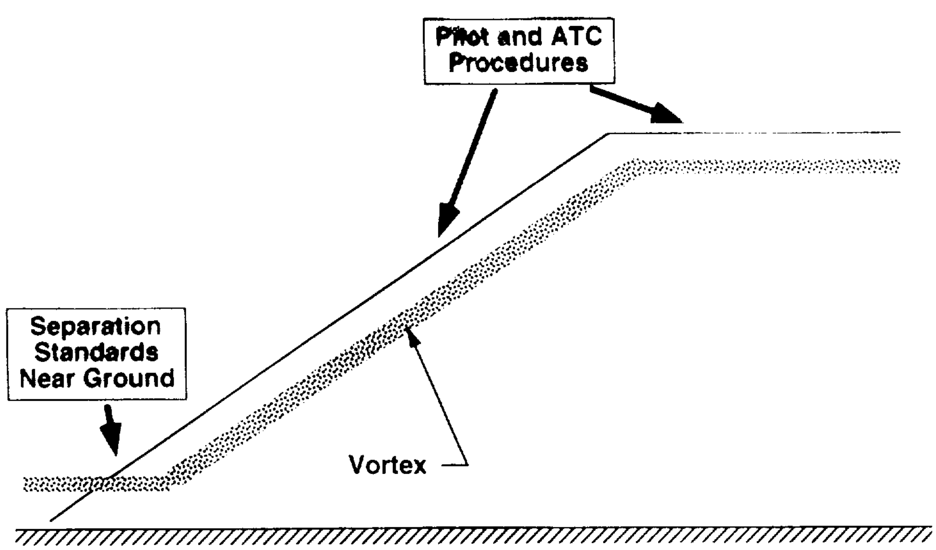
# WHAT

- Validate wake encounter simulation models
- Establish a metric to quantify the upset potential of a wake encounter
- Apply hazard metric and simulation models to the commercial fleet for development of candidate acceptable encounter limits
- Apply technology to near term problems to evaluate current status of technology

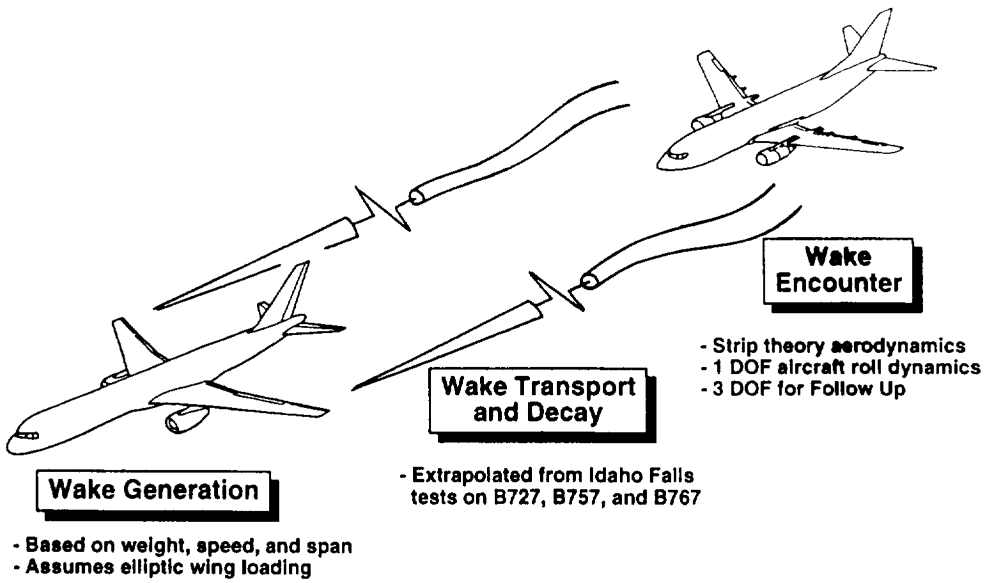
# SEPARATION STUDY

- Conducted for government/industry team
- Used existing technology
- Considered fleet with 27 aircraft types
- Modeled wake generation, decay, encounter

# VORTEX ENCOUNTER FACTORS



# AIRCRAFT SPACING ANALYSIS



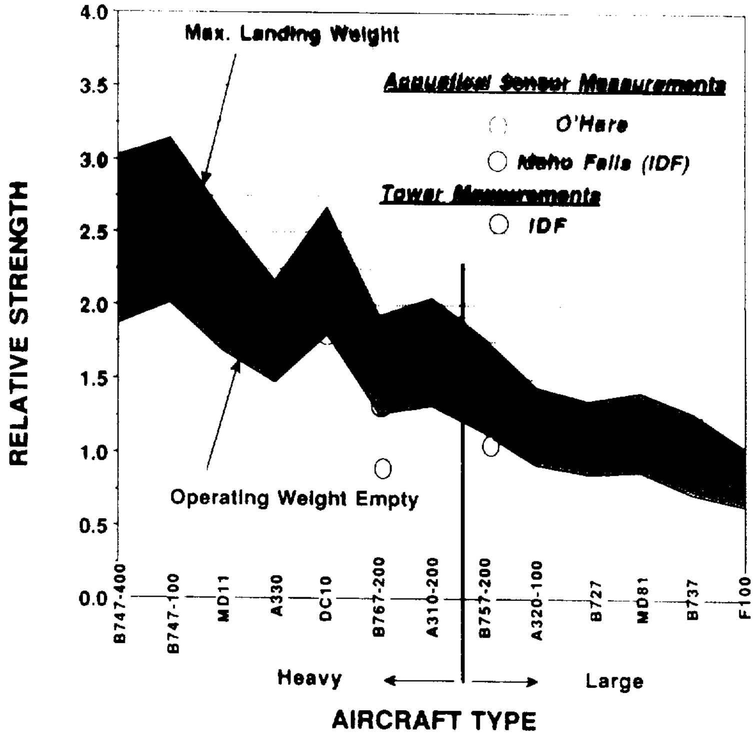

# INITIAL VORTEX STRENGTH

+ Initial vortex strength (circulation) $= k \times \dfrac{\text{Lift (or weight)}}{\text{Density x Speed x Span}}$

+ Initial vortex strength predictions agree well with data

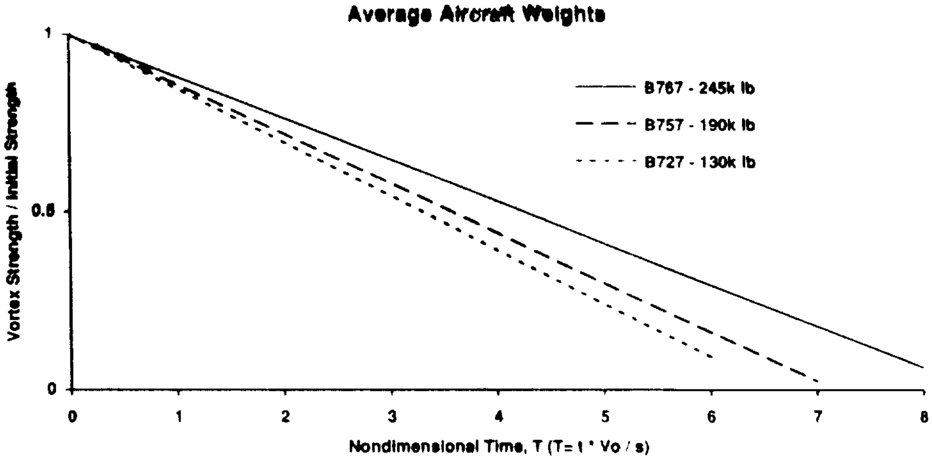
## CALCULATED INITIAL VORTEX STRENGTH

DATA NORMALIZED TO 737 AT MID WEIGHT




## IDF VORTEX DECAY DATA

Average Aircraft Weights



# WAKE DECAY CORRELATION

+ Correlation time, $T = \dfrac{\text{Real time}}{\text{Aircraft characteristic time}}$

+ For wings with Elliptical lift distribution:

$$T = \text{Real time} \times \frac{32}{(\text{pi})^4} \times \frac{\text{Weight}}{(\text{Density}) \times (\text{Speed}) \times (\text{Span})^3}$$

| REC# | NAME | T.O.Wt.( | Ldg.Wt.( | Span(ft) | Area(ft^ | A.R. | C sub L | CLalpha | T.R. | Vias(kts) | Vias(ft/s | Clp(/rad) | T.O.Wt.Ixx( | Ldg.Wt.Ixx(sl-ft^2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Beech Bonanza 36 | 3400 | 3400 | 33.5 | 181 | 6.2 | 1.1 | 4.69 | 0.5 | 72 | 121 | -0.425 | 1900 | 1900 |
| 2 | Beech Baron 58 | 5500 | 5400 | 37.8 | 199 | 7.2 | 0.8 | 4.86 | 0.42 | 98 | 165 | -0.469 | 5400 | 5200 |
| 3 | Cessna 208A Caravan | 7300 | 7300 | 52.1 | 279 | 9.7 | 1.3 | 5.17 | 0.62 | 78 | 132 | -0.548 | 9600 | 9600 |
| 4 | Beech King Air B100 | 11800 | 11200 | 45.8 | 242 | 8.7 | 1.2 | 5.06 | 0.5 | 108 | 182 | -0.5 | 22000 | 19000 |
| 5 | B.Ae. Super 31 | 15300 | 14500 | 52 | 271 | 10.0 | 1.3 | 5.19 | 0.38 | 112 | 189 | -0.58 | 33000 | 31000 |
| 6 | Beech 1900C | 16600 | 16100 | 54.5 | 303 | 9.8 | 1.2 | 5.17 | 0.42 | 113 | 191 | -0.543 | 35000 | 34000 |
| 7 | LearJet 35a | 18300 | 15300 | 39.5 | 253 | 6.2 | 1.1 | 4.69 | 0.58 | 125 | 211 | -0.44 | 20000 | 16700 |
| 8 | Cessna 750 Citation | 31000 | 29000 | 64 | 630 | 6.5 | 0.9 | 4.75 | 0.28 | 126 | 213 | -0.394 | 88700 | 83000 |
| 9 | DHC-8 Dash 8 | 41100 | 38400 | 90 | 605 | 12.0 | 1.9 | 5.43 | 0.48 | 99 | 168 | -0.65 | 155000 | 150000 |
| 10 | Fokker F-50 | 41900 | 43000 | 95.1 | 754 | 12.0 | 1.4 | 5.35 | 0.4 | 110 | 186 | -0.585 | 200000 | 200000 |
| 11 | Saab 2000 | 48500 | 47400 | 81.2 | 600 | 11.0 | 1.9 | 5.28 | 0.38 | 110 | 185 | -0.585 | 260000 | 250000 |
| 12 | GulfStream IV | 69700 | 58500 | 77 | 950 | 6.2 | 1.1 | 4.7 | 0.31 | 131 | 221 | -0.414 | 289000 | 242000 |
| 13 | Fokker F-100 | 95000 | 88000 | 92.1 | 1006 | 8.4 | 1.5 | 5.03 | 0.2 | 131 | 221 | -0.463 | 380000 | 324000 |
| 14 | B737-200 | 115500 | 103000 | 93 | 1098 | 7.9 | 1.7 | 4.96 | 0.34 | 129 | 218 | -0.498 | 469000 | 449000 |
| 15 | McD MD-81 | 140000 | 139500 | 107.8 | 1270 | 9.2 | 1.7 | 5.11 | 0.16 | 139 | 235 | -0.451 | 740000 | 676000 |
| 16 | A320-100 | 162000 | 142200 | 111.3 | 1317 | 9.4 | 1.7 | 5.14 | 0.25 | 135 | 228 | -0.512 | 1500000 | 1100000 |
| 17 | B727-200 | 190500 | 154500 | 108 | 1700 | 6.9 | 1.5 | 4.81 | 0.3 | 133 | 225 | -0.41 | 1061000 | 877000 |
| 18 | B757-200 | 230000 | 210000 | 124.5 | 1951 | 7.9 | 1.7 | 4.97 | 0.23 | 137 | 231 | -0.462 | 3500000 | 3000000 |
| 19 | A310-200 | 313000 | 273400 | 144 | 2357 | 8.8 | 1.8 | 5.07 | 0.26 | 139 | 235 | -0.48 | 6200000 | 5200000 |
| 20 | B767-200 | 345000 | 285000 | 156.1 | 3050 | 8.0 | 1.4 | 4.98 | 0.27 | 139 | 235 | -0.447 | 8500000 | 4600000 |
| 21 | McD DC-10 | 455000 | 421000 | 155.3 | 3861 | 6.2 | 1.5 | 4.7 | 0.3 | 145 | 245 | -0.407 | 10100000 | 6000000 |
| 22 | Lockheed L1011 | 496000 | 368000 | 155.33 | 3456 | 7.0 | 1.4 | 4.83 | 0.3 | 149 | 252 | -0.423 | 14000000 | 8000000 |
| 23 | A330 | 467400 | 383600 | 195.4 | 3908 | 9.8 | 1.5 | 5.17 | 0.23 | 137 | 232 | -0.458 | 10900000 | 9000000 |
| 24 | B777-200 | 590000 | 445000 | 199.92 | 4605 | 8.7 | 1.5 | 5.06 | 0.2 | 138 | 233 | -0.421 | 20000000 | 13000000 |
| 25 | McD MD-11 | 603000 | 430000 | 169.5 | 3648 | 7.9 | 1.6 | 4.96 | 0.26 | 148 | 250 | -0.44 | 20000000 | 10000000 |
| 26 | B747-100 | 735000 | 564000 | 195.8 | 5500 | 7.0 | 1.5 | 4.83 | 0.25 | 141 | 238 | -0.408 | 18399000 | 15671000 |
| 27 | B747-400 | 850000 | 630000 | 211 | 6360 | 7.0 | 1.3 | 4.83 | 0.25 | 153 | 258 | -0.384 | 24710000 | 19599000 |

Figure C 1

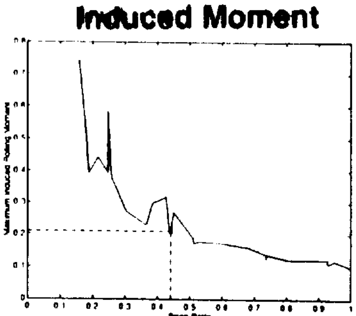
# MODELS AND ASSUMPTIONS

| AIRCRAFT RESPONSE | FLOW FIELDS | VORTEX CORE | AIRCRAFT LOCATION | HAZARD DEF | WAKE DECAY | TRAFFIC MIXES |
|---|---|---|---|---|---|---|
| 1 DOF IMPULSE WITH & WO CONTROLS | SINGLE VORTEX | FUSELAGE DIAMETER | MAXIMUM UPSET | $\Phi = 15°$ | | |
| 1 DOF IMPULSE WITH CONTROLS | VORTEX PAIR | $0.02B_0$ | MAXIMUM UPSET | $\Phi = 7.5 + 500/b$<br>$\Phi = 1000/b$ | 1 - T/8<br>1 - T/5 | 4 MIXES |
| 3 DOF WITH CONTROLS | VORTEX PAIR | $0.02B_0$ | POSITION LOOP CLOSED ON GLIDE SLOPE | | | |

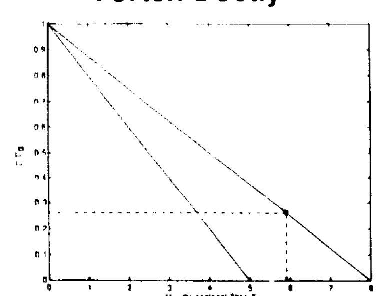
## Methodology

### B737 following B747

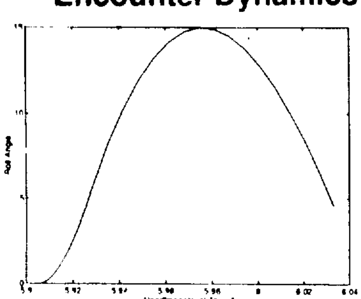
**Induced Moment**



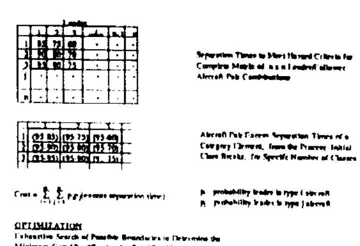
**Vortex Decay**



**Encounter Dynamics**



**Classification Process**



**Classifications based on Weight**
**Position Loop Closed**
**Bank Angle Limit = 15 degrees, 1-T/8 Decay**
**27 Planes, Uniform Distribution**

| Max. Landing Weights | Separation Matrix | | | | | Cost | AC/Hr. |
|---|---|---|---|---|---|---|---|
| $3400 \le W \le 630000$ | 237 | | | | | 157.8 | 12.8 |
| $128000 \le W \le 630000$ | 158 | 50 | | | | 77.8 | 17.9 |
| $3400 \le W \le 107000$ | 237 | 180 | | | | | |
| $271200 \le W \le 630000$ | 125 | 50 | 50 | | | 37.7 | 22.4 |
| $40000 \le W \le 198000$ | 186 | 85 | 50 | | | | |
| $3400 \le W \le 29000$ | 237 | 180 | 94 | | | | |
| $383600 \le W \le 630000$ | 106 | 61 | 50 | 50 | | 27.9 | 24.2 |
| $198000 \le W \le 368000$ | 135 | 84 | 50 | 50 | | | |
| $40000 \le W \le 160000$ | 186 | 130 | 81 | 50 | | | |
| $3400 \le W \le 29000$ | 237 | 170 | 180 | 94 | | | |
| $383600 \le W \le 630000$ | 106 | 61 | 50 | 50 | 50 | 20.7 | 25.1 |
| $271200 \le W \le 368000$ | 125 | 74 | 50 | 50 | 50 | | |
| $85500 \le W \le 198000$ | 169 | 117 | 77 | 50 | 50 | | |
| $40000 \le W \le 58500$ | 186 | 130 | 85 | 50 | 50 | | |
| $3400 \le W \le 29000$ | 237 | 170 | 120 | 180 | 94 | | |
| | 27 x 27 Matrix | | | | | 0 | 29.3 |

**Classifications based on Weight**
**Position Loop Closed**
**Bank Angle Limit = 1000/Span degrees, 1-T/8 Decay**
**27 Planes, Uniform Distribution**

| Max. Landing Weights | Separation Matrix | | | | | Cost |
|---|---|---|---|---|---|---|
| $3400 \le W \le 630000$ | 225 | | | | | 141.6 |
| $198000 \le W \le 630000$ | 159 | 65 | | | | 66.5 |
| $3400 \le W \le 160000$ | 225 | 153 | | | | |
| $271200 \le W \le 630000$ | 155 | 72 | 50 | | | 34.4 |
| $40000 \le W \le 198000$ | 191 | 88 | 50 | | | |
| $3400 \le W \le 29000$ | 225 | 153 | 76 | | | |
| $383600 \le W \le 630000$ | 146 | 102 | 59 | 50 | | 24.7 |
| $198000 \le W \le 368000$ | 159 | 109 | 65 | 50 | | |
| $40000 \le W \le 160000$ | 191 | 134 | 85 | 50 | | |
| $3400 \le W \le 29000$ | 225 | 162 | 153 | 76 | | |
| $383600 \le W \le 630000$ | 146 | 102 | 59 | 50 | 50 | 18.5 |
| $198000 \le W \le 368000$ | 159 | 109 | 65 | 50 | 50 | |
| $40000 \le W \le 160000$ | 191 | 134 | 85 | 50 | 50 | |
| $11200 \le W \le 29000$ | 208 | 148 | 98 | 50 | 50 | |
| $3400 \le W \le 7300$ | 225 | 162 | 153 | 76 | 56 | |

**Classifications based on Span**

**Position Loop Closed**

**Bank Angle Limit = 1000/Span degrees, 1-T/8 Decay**

**27 Planes, Uniform Distribution**

| Span | Separation Matrix | | | | | Cost |
|---|---|---|---|---|---|---|
| $34 \le b \le 211$ | 225 | | | | | 141.6 |
| $111 \le b \le 211$ | 161 | 62 | | | | 66.2 |
| $34 \le b \le 108$ | 225 | 153 | | | | |
| $156 \le b \le 211$ | 153 | 96 | 50 | | | 33.0 |
| $81 \le b \le 155$ | 186 | 111 | 50 | | | |
| $34 \le b \le 77$ | 225 | 153 | 80 | | | |
| $195 \le b \le 211$ | 146 | 106 | 59 | 50 | | 22.6 |
| $124 \le b \le 170$ | 159 | 110 | 65 | 50 | | |
| $81 \le b \le 111$ | 186 | 130 | 81 | 50 | | |
| $34 \le b \le 77$ | 225 | 162 | 153 | 80 | | |
| $195 \le b \le 211$ | 146 | 106 | 59 | 50 | 50 | 17.5 |
| $124 \le b \le 170$ | 159 | 110 | 65 | 50 | 50 | |
| $90 \le b \le 111$ | 186 | 130 | 81 | 50 | 50 | |
| $54 \le b \le 81$ | 202 | 143 | 94 | 64 | 50 | |
| $34 \le b \le 52$ | 225 | 162 | 153 | 94 | 59 | |

# SUMMARY

- Technology is not adequate to determine absolute spacing requirements
- Time, not distance, determines the duration of the wake hazard
- Optimum standards depend on the traffic
- Wing span is an important parameter for characterizing both generator and follower
- Short span "biz jets" are easily rolled

# Piloted Simulation Study of Wake Encounters

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by

Eric Stewart

NASA Langley Research Center

presented at

1st Wake Vortex Dynamic Spacing Workshop May, 1997

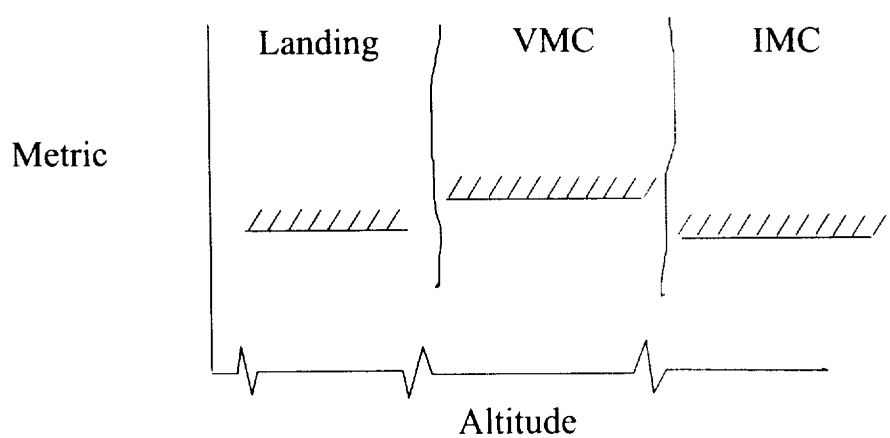
# Outline

- Background
- Simulator description
- Worst-case approach
- Phase I results
- Phase II plans
- Discussion issues
- Concluding remarks

# Objective

- To determine an acceptable level of vortex roll disturbance for worst-case encounter geometries during normal, routine operations
  - Determine boundary
  - Determine metric(s)
  - Define evaluation factors
  - Define evaluation procedures

# Anticipated Results



# Contrast to Previous WV Simulations

Using a more conservative criteria:

(a) "Acceptable" for <u>routine</u> operations for <u>all</u> pilot groups for <u>worst-case</u> encounter geometries

rather than

(b) "Non hazardous" for typical encounter geometries

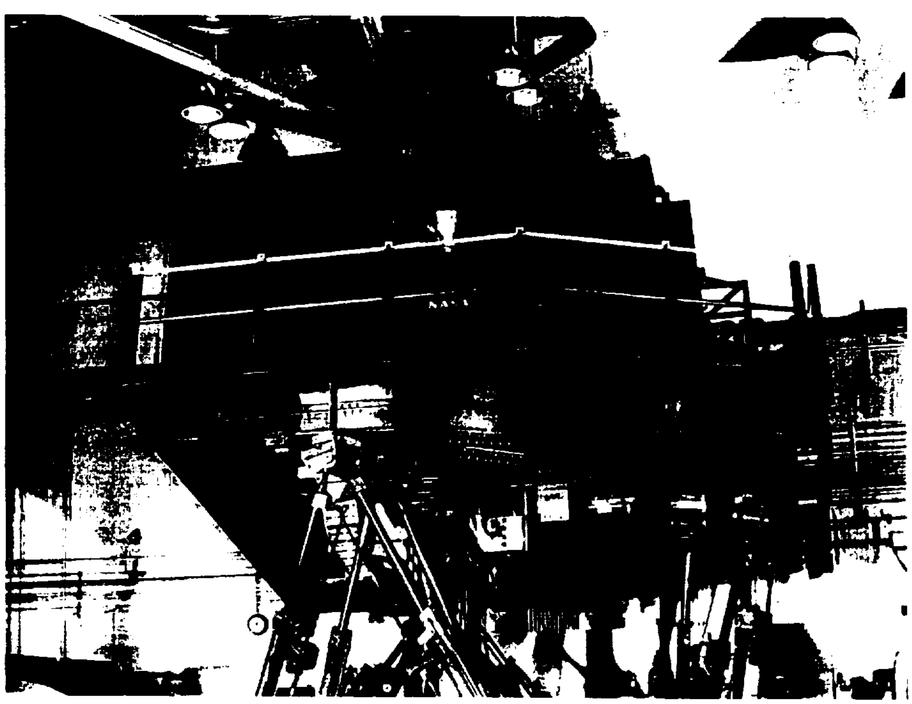
# Limitations of Study

- Generic result in a research simulator
- Pilots will not be surprised by the wake encounters
- Results must be checked in training simulators with a better surprise factor

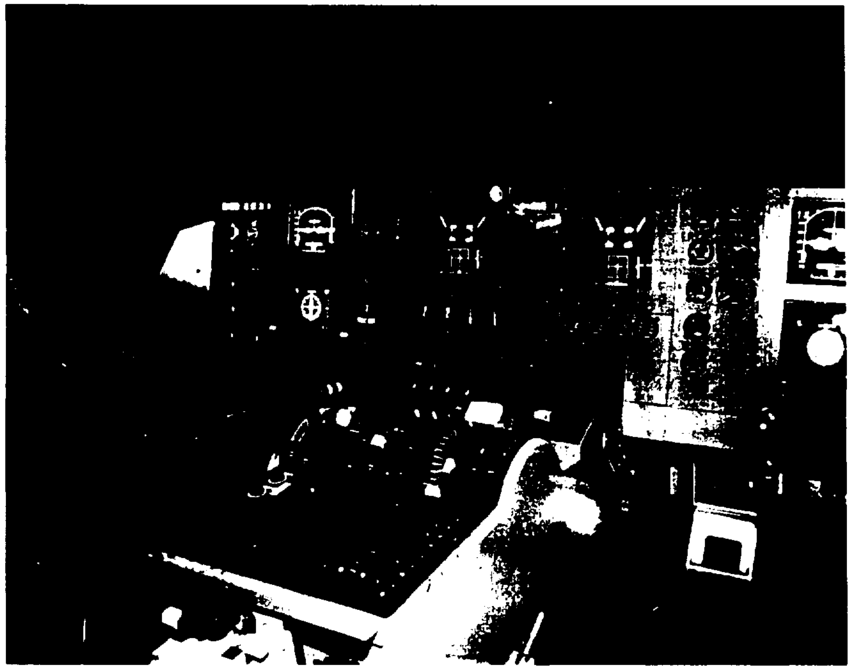
# Simulation Hardware

- Visual Motion Simulator (VMS)
  - Glass cockpit
  - Sidestick controller (with rate limit)
  - Take-Off Go-Around buttons
  - Event marker

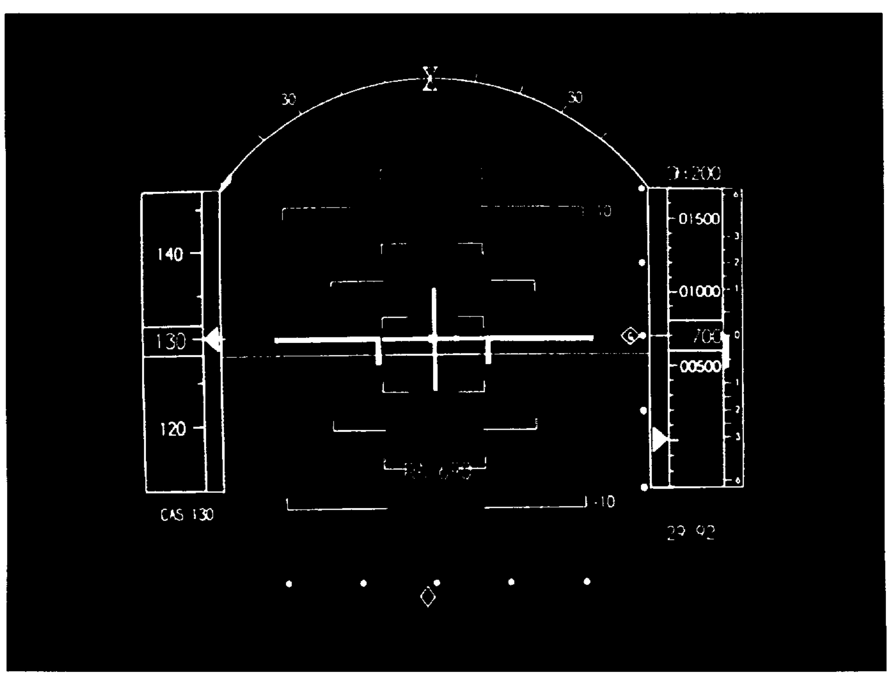
# VMS Exterior Photo



# VMS Interior Photo



# PFD Photo



# Research Simulator Software

- B737-100 characteristics (forward cockpit)
- Autothrottle
- Flight Director
- Yaw Damper
- Manual control system
- Wing scrapes @ $\phi = 8$ degrees
- Passenger comfort calculations
- Drink slosh calculations

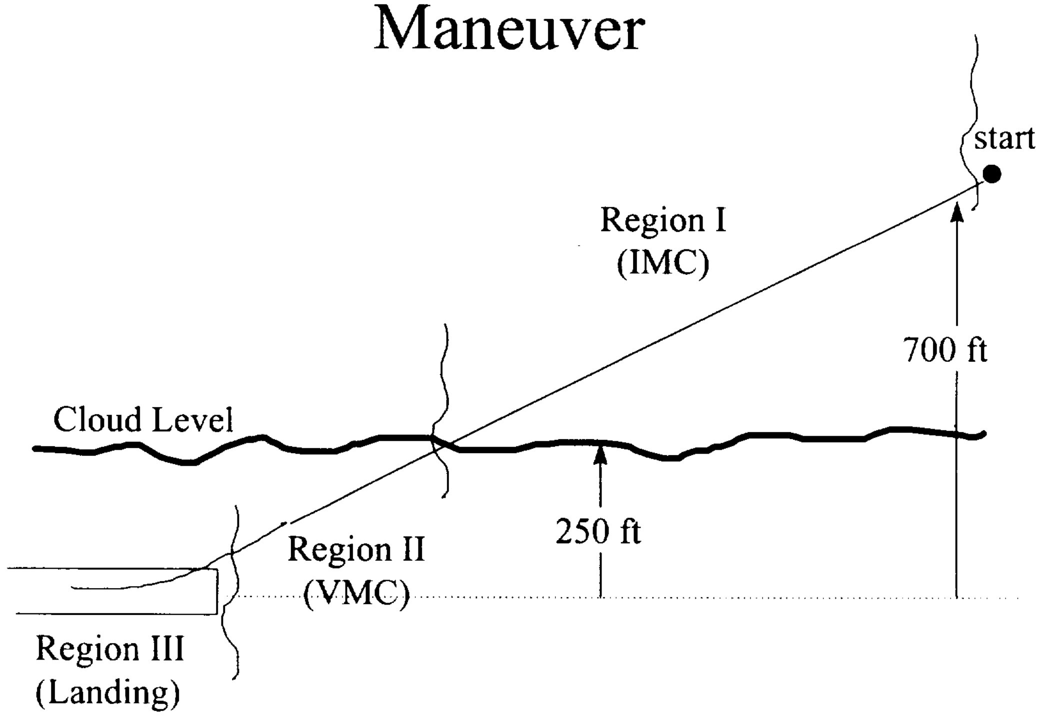
# Worst-case Conditions

- Approach/Landing maneuver
- Roll encounter
- IMC down to 250 ft
- Manual control
- No airplane system failures
- Does not include deliberate pilot mistakes
- Worst-case geometry?

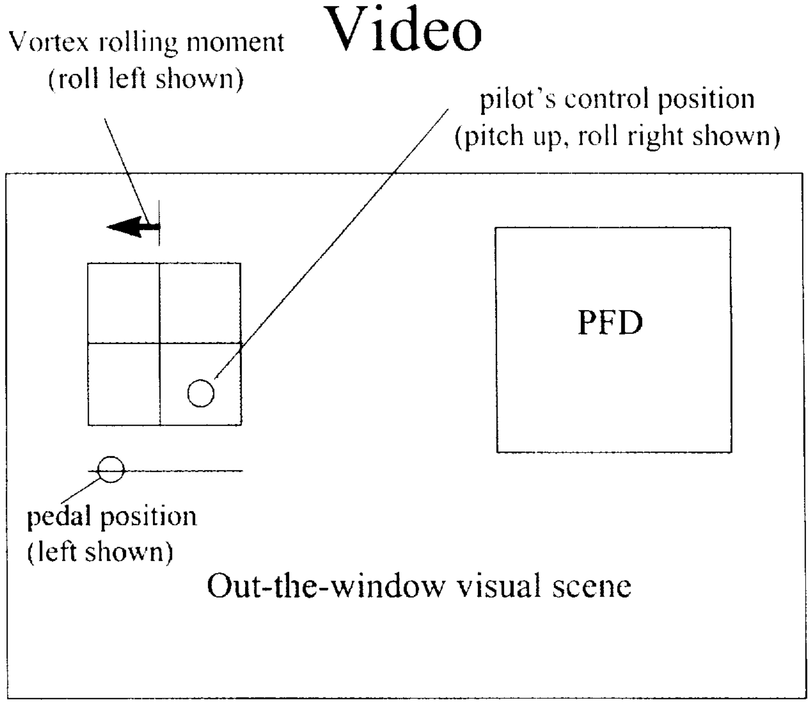
# Approach

- Phase I (completed) determined worst-case geometry at a moderate vortex strength level -- NASA pilots
- Phase II (in final planning stages) to determine acceptable vortex strength level for worst-case geometry--Airline pilots

# Maneuver

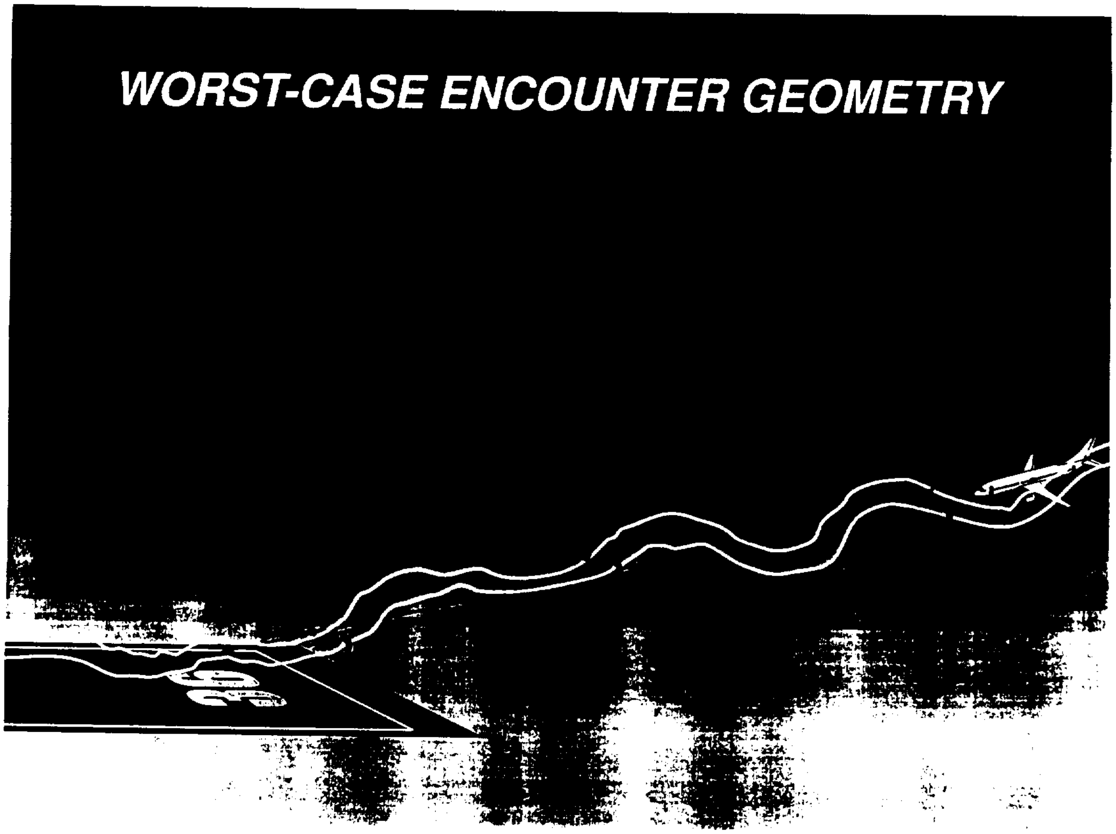


# Video



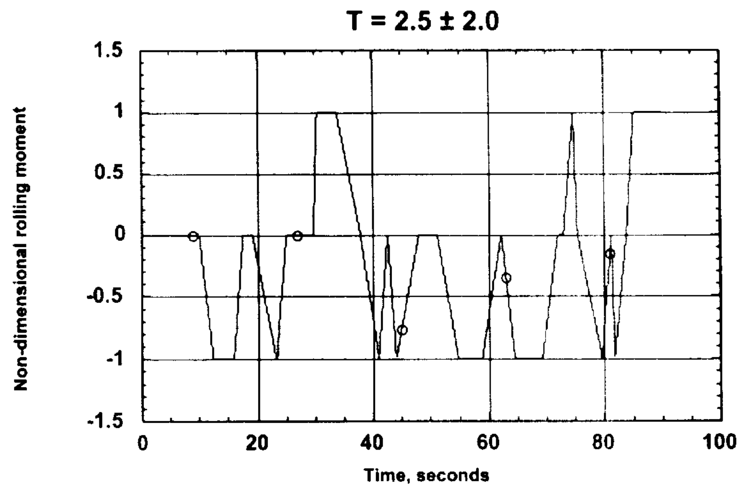

# Phase I Observations

- Encounter geometry is a first-order effect as important as vortex strength
- Worst-case encounter geometry is a "20-year" wake encounter and not a typical encounter
- Worst-case geometry produces a randomly varying rolling moment with fast onsets and multiple reversals




# B-727 Wake Vortex Pattern

# Random Vortex Rolling Moment




# Phase I Observations (continued)

- Acceptable vortex strengths have rolling moments much less than the pilot's roll control authority
- Pilot inputs are potentially more dangerous than wake effects
- Landing is most susceptible to vortex encounters

# Phase I Observations (concluded)

- Maneuvering close to the ground to correct lateral displacements/drifts often leads to wing scrapes
- Pilot reaction times from first vortex influence are often greater than 1.0 second
- Yaw damper increases acceptability of wake encounters

# Phase II (plans)

- Use worst-case geometry determined in Phase I
- Vary vortex strength and roll control power
- Use airline pilots

# Strawman Encounter Metric

(Non-dimensional, applicable to all aircraft pairs)

$$\delta_v = \frac{(\text{MaxVortex Rolling Moment})^x}{(\text{Max Control Rolling Moment})}$$

$$x > 1$$

(Max Vortex Rolling Moment) = f ( generator wake characteristics, wake decay, follower response to wakes)

(Max Control Rolling Moment) = g( follower control characteristics )

# Research Variables

- Max vortex rolling moment, $M_v$
- Max control rolling moment, $M_\delta$

$$\delta_v = \frac{(M_v)^x}{M_\delta}$$

$$x > 1$$

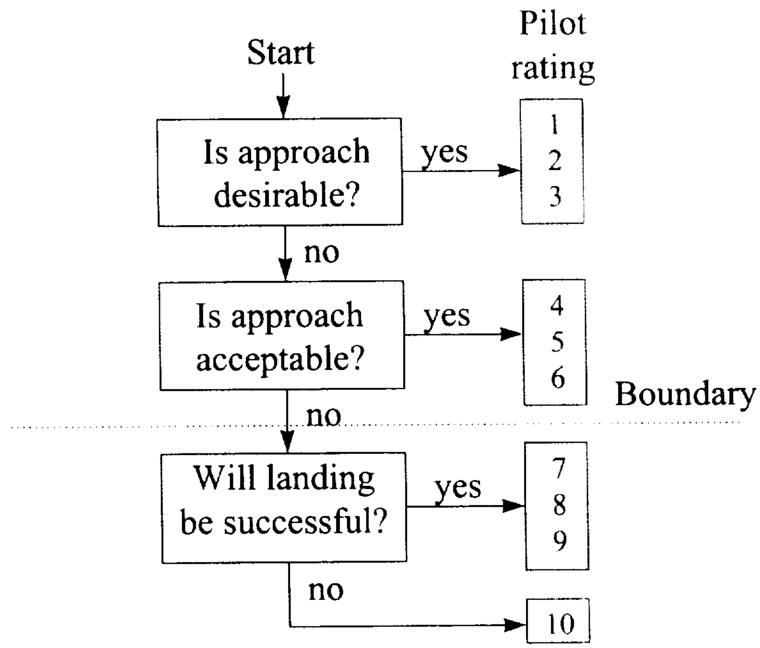
# Evaluation Factors

- Initial list of factors
  - Safety
  - Equipment damage (e.g. wing scrape)
  - Roll attitude
  - ILS tracking precision
  - Pilot workload/anxiety
  - Passenger comfort/anxiety
  - Landings
- Test subjects will be asked to specify/suggest additional factors

# Pilot Rating System

- Primary data is pilot judgment of "acceptable" or "unacceptable" encounter
- Pilot will give 3 ratings for each maneuver based on a "chief company pilot" mind-set
  - IMC portion
  - VMC portion
  - Landing
- Motivation for accepting a non-zero vortex upset is increased safety and company profits from AVOSS

# Pilot Rating Scale




# **Quantitative Data Types**

- Angular (angles, rates, accelerations)
- Linear (positions, rates, accelerations)
- Flight path (Glideslope, localizer, flight director)
- Controls (Positions, forces, rates, aerodynamic)
- Configuration (Engine, flaps, gear, YD, AT)
- Air Data (Airspeed, flow angles)
- Rolling moment (Level, shape)
- Ride quality (% Passengers satisfied, drink slosh)
- Audio-Video

# Discussion Issues

- Suggest evaluation factors/criteria
- Should we use intentional pilot mistakes as part of the worst-case scenario?-- what kind?
- Are pilot controller rate limits required/important training simulator characteristics?

# Concluding Remarks

- Piloted simulation effort started
- Phase I research has defined a worst-case encounter geometry
- Phase I research has identified some fundamental observations
- Phase II will identify a tentative acceptable strength

**Questions and Discussions Following Eric Stewart's Presentation (NASA LaRC)**

Mary Kay Higgins (Mitre Corp.)
With phase one, when you found the worst case geometry, did you do that with a couple of airplanes? And if so, what was the leading airplane doing, and what was the following airplane doing?

Eric Stewart
We have only been using the B737 as the following airplane, the generator produced a rolling moment which was marginal to start with and then we varied the encounter geometry. This could have been a wake from a B757 that decayed in 10 minutes or it could have been B727 that was less. The net result was rolling moment on following aircraft which was a B737,

Frank Cheshire (American Airlines)
One question two comments. The question has to do with the same parameters she mentioned. Are you using the 20-year worst case to knowingly get outside the bounds of acceptable and then try to establish where inside the bound the acceptability really rests?

Stewart
The so-called 20-year encounter is just a descriptive phrase we use; it's just a worst case that we have tried. We have tried single encounters, we tried encounters with slower onset rates that stay a long time, but we have no statistics basis for saying that is really a one in twenty year encounter. Most of the pilots that get in say they have had encounters before and it's in and out, but this is different and it is worse. If you just have in and out it is not as bad. So we are looking for a worst case and if acceptable for this encounter, then it will be acceptable for the more normal encounter.

Cheshire
I asked the question because I suspect if you had one of those encounters with the AVOSS system operating it would, effective that day, be deemed unsatisfactory.

Stewart
We don't want to give the impression that what we are flying is what we are saying AVOSS would allow you to fly in. In this study, we are having the pilots tell us what is acceptable. AVOSS we are assuming can predict those levels and you tell what level is acceptable, but we will never operationally give you anything you are uncomfortable with. We have tried to set up the rating scale so that is something for routine operation for any pilot. It is not something barely on the edge of being unsafe. But to bound the problem, in the test we give them something unacceptable like that I showed you. That was probably bad judgment to show you that because I don't want you going away with the impression that we are proposing the kind of maneuver you saw in the film.

Cheshire
I know Brad Perry has heard this comment before. You mentioned 15 degrees as a possible limit to acceptability. That all depends, if I have full control throw to the left and a 15 degree bank to the right, that is unacceptable.

Stewart
Yes, I don't think the ones we consider acceptable have that big an upset. What we need for AVOSS is something that can be measured by these sensors we talked about earlier. They cannot measure roll attitude. The parameter we need must include wake vortex strength. That is a response. But like you say, I think 15 degrees is too much.

Kenny Kaulia (Airline Pilots Association)
I don't know where to start. I could probably talk for a half-hour just based on your presentation. Obviously, we will need to talk a little more after the session today. First, with the so-called 20-year encounter, I don't think you are going to get a real world feel for it. The incidents I have heard about lately have been the in and out variety, especially with the turbo-prop aircraft where you have roll angle in excess of 60 degrees. Things such as that, I have been working with George Greene on the industry team, and I feel more comfortable with that work rather than the simulation you have where they are encountering the wake numerous times. Again, from the information I have got from the pilots I represent, that most encounters are of the in and out variety.

Stewart
Absolutely, and I want to emphasize that this is not a typical encounter. We want one that is your worst nightmare. So if the wake strength limit is set for this worst nightmare encounter, then your in and out encounter for this same strength will not cause a problem.

Kaulia
What I am saying is that in and out is not nothing.

Stewart
It will be, if we get the level of the vortex strength for the in and out encounter to be defined by the so-called nightmare encounter.

Kaulia
Well, by the second rule I would hope the pilot would go around. Otherwise, I would not be buying a ticket on that airline.

Stewart
The only encounter you hear about are the ones that are totally unacceptable. We will be getting encounters that will be non-events.

Leonard Credeur (NASA LaRC)
Let me say something that might clarify the situation. There are two things going on here. One is the frequency and wave shape of the wake encounter, and the other is the strength of the wake itself. Perhaps those factors are getting confused.

Stewart
Yes. What we are assuming is that AVOSS can predict the level of the wake, but it cannot predict the detail geometry or sequence of the encounter. And that is the only thing we can set standards on is the wake strength which is the level. We have come up with the so-called 20 year encounter which may be somewhat unrealistic, but it is unrealistic on the conservative side to be safe.

Kaulia
OK, let us discuss this some more later. With your strawman encounter metric for phase 2, you talk about roll moment. Does it take into account roll due to rudder also, or just ailerons?

Stewart
It is just ailerons at this point but that is just a strawman and we look at others.

Kaulia
Understood, on the simulator you have now, you have a side stick controller. My suggestion before you use any airline pilots in this country, you go ahead and outfit it with a normal control wheel. I think you would get more realistic results unless you use pilots that were used to sidestick.

Stewart
We have had considerable discussion about the controller. Some of our in-house pilots say that is not an issue, others say it is.

Unknown
(Part of question was not captured on tape) ...penetration aircraft simply because I would think the response characteristics would have a great deal to do with how comfortable a pilot is with a penetration.

Stewart
I don't think we plan, at Langley, to do any other airplane because it is too big a job to get such a simulation going for a particular airplane. That is why I said up front, this is the preliminary work we need to get with industry who have the simulators for the wide fleet of aircraft where these results will be checked. I expect to get a conservative answer here using the so-called "worst case" encounter geometry that we are using. That is, there will be a built-in safety margin relative to the more traditional in-out encounter.

Klaus Sievers (German Cockpit Association)
I have a few comments. Landing is most critical that is what said, I agree. I would hope any colleague flying your pattern there would do a go-around the latest at least a 100 ft above ground and would not try landing.

Stewart
I want him to tell me to reduce the strength level until he doesn't feel he needs to go around.

Sievers
A wing scrape, that is a lot of paperwork.

Stewart
The test subject pilot is in the driver's seat and will tell us what is acceptable and what isn't. And we will reduce it to that level.

Sievers
Coming to 1 second delay time. I think Boeing has a little problem with reversers going open in flight. They did a study and found out 3 seconds was typical reaction time to unexpected events during flight. So maybe it is not surprising that pilots take a little time and think of what they do. And now the vortex simulated by random rolling moments, I believe I saw a research paper where a wing was in a wind tunnel following another wing and was exposed to the wake. It was found that not only rolling moment was present, but also some lift loss due to vortex. Maybe that would be a refinement for your simulator.

Stewart
Yes, that will be refined and is what Dan Vicroy will talk about next.

Sievers
Lift loss at 200 ft. I don't like that. And your approach seems to be flown manually, I suggest that you look at autopilot flown approaches.

Stewart
Dan is doing that.

Sievers
And also what happens when a human pilot determines that whatever action the autopilot is taking at 100 ft is not OK. It is difficult if you are suddenly faced with the task of flying manually at low level. Not trivial.

Stewart
I agree completely. There are other studies that are being considered.

Rocky Stone (United Airlines)
I think this is a great study. One concern that I had, basically you are measuring the gain of the pilot in a feedback problem where he is trying to level the aircraft. One of the statements there is that you accept zero upsets and what I am worried that you will drive the pilots into an artificial high gain roll control situation. Some people fly like that all the time, but most probably don't. They are with Frank's airline, just kidding, I didn't say that. But I am wondering if you should put in other statements such as to emphasize smoothness in control rather than accepting zero upset, just to lower gain to what would be a normal gain in normal situation, then you will get even more conservative results.

Stewart
Yes, that follows in what I was saying. I was hoping to get feedback from our test subjects on what other factors to consider. Maybe one of these is smoothness of control.

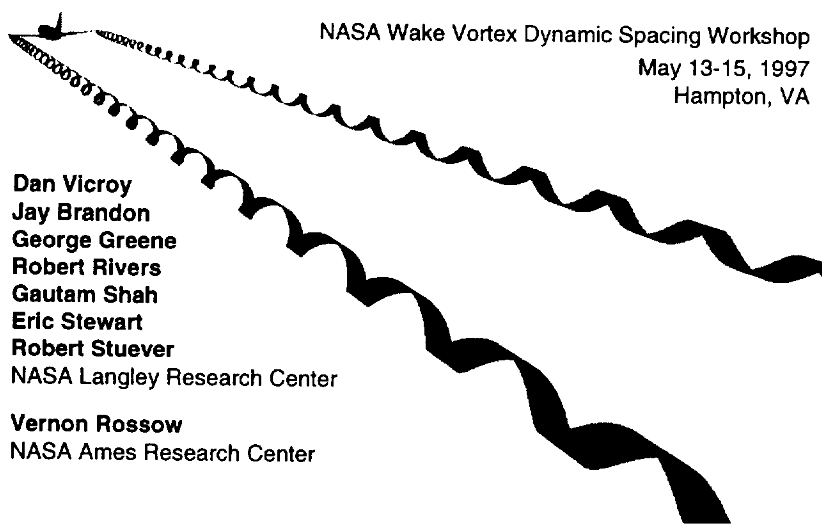
Stone
That is something you can quantitatively measure.

Stewart
That data will be measured. That is part of the rate limit thing that I mentioned. Because of the way it was initially implemented, they could put essentially infinite rates in with the side arm controller, which you can't physically do on a B737. You can't move it faster than actuators can move control surface, so we fixed that. That is part of the smoothness of control and may be a factor we need to evaluate.

Dave Hinton (NASA LaRC)
I would like to clarify one misunderstanding that may be creeping into all this. In that the AVOSS is either a transport or decay system. We can turn off the decay part so we are basing separation only on transport. I fully expect that will be the initial AVOSS implementation. Therefore, what you are seeing here is not relevant to a transport only system. I am not suggesting that you go out and start subjecting American and United and everybody to these encounters. Only after we as a community have come to an agreement to what is acceptable and what is not acceptable, and that is what Eric is starting into in this process, would we even consider turning on the decay part of AVOSS. Everybody in this room and everybody in community gets a say on whether that will work or not. Whether decay can be turned on or not.

# Wake Vortex Encounter Model Validation Experiments

NASA Wake Vortex Dynamic Spacing Workshop
May 13-15, 1997
Hampton, VA



**Dan Vicroy**
**Jay Brandon**
**George Greene**
**Robert Rivers**
**Gautam Shah**
**Eric Stewart**
**Robert Stuever**
NASA Langley Research Center

**Vernon Rossow**
NASA Ames Research Center

## Presentation Outline

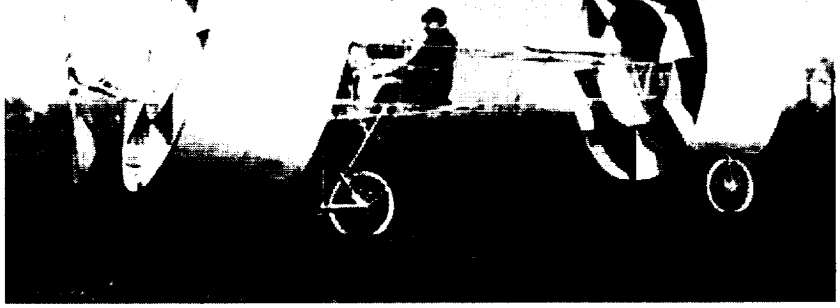
- Why are we doing this?
  - Goal
- What are doing?
  - Approach
  - Wind Tunnel Tests
  - Flight Tests
- How are we doing?
  - Current Status

Wake_97

## Why are we doing this?

**Goal**

- Establish a database to:
  - validate / calibrate wake encounter analysis methods for fleet-wide application
  - measure / document atmospheric effects on wake decay



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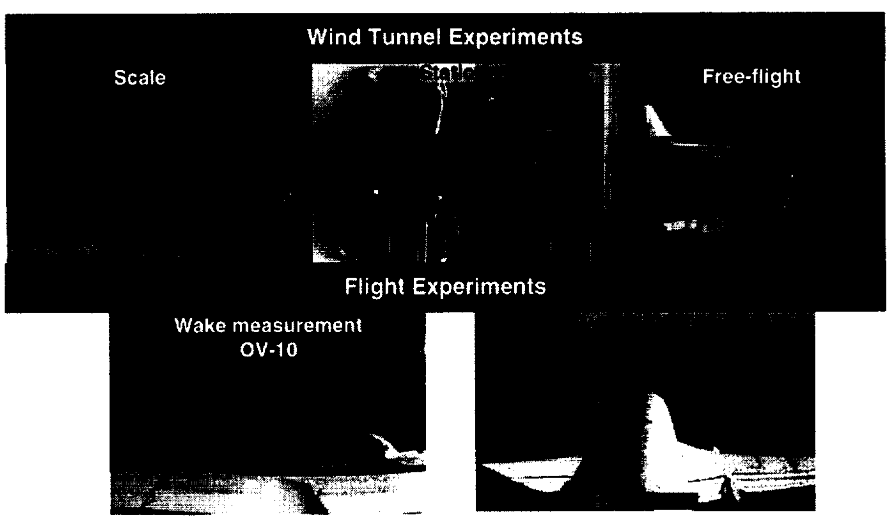
## What are we doing?

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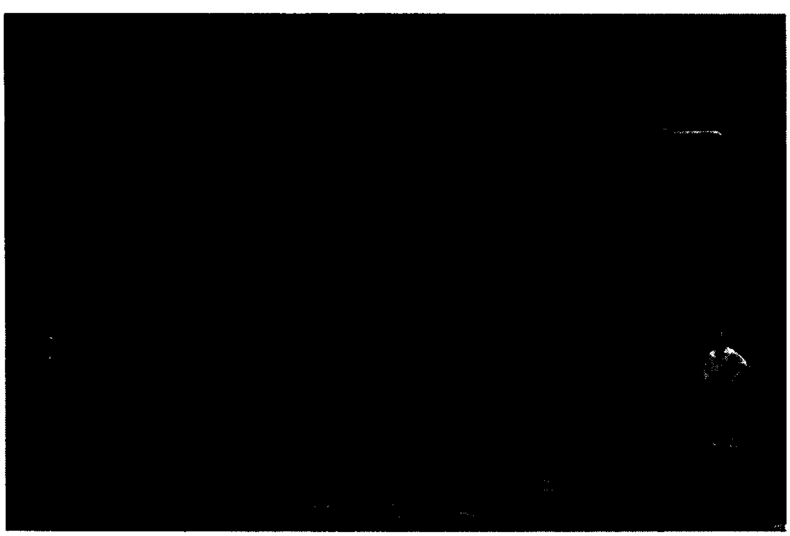
## Tunnel Tests

- Scaled Static Test (Ames 80 x 120 ft)
  - Measure effect of span ratio on encounter upset
  - Compare measured and computed encounter loads
- Free-flight and Static Test (Langley 30 x 60 ft)
  - Determine feasibility and utility of conducting controlled free-flight wake-vortex encounters
  - Compare static and dynamic measurements
  - Assess airplane/vortex interaction
  - Compare wind tunnel, flight test and simulated encounter trajectories

Wake_97

## 3%-Scale Static Test (Ames 80x120)



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80x120 Test Results Slide

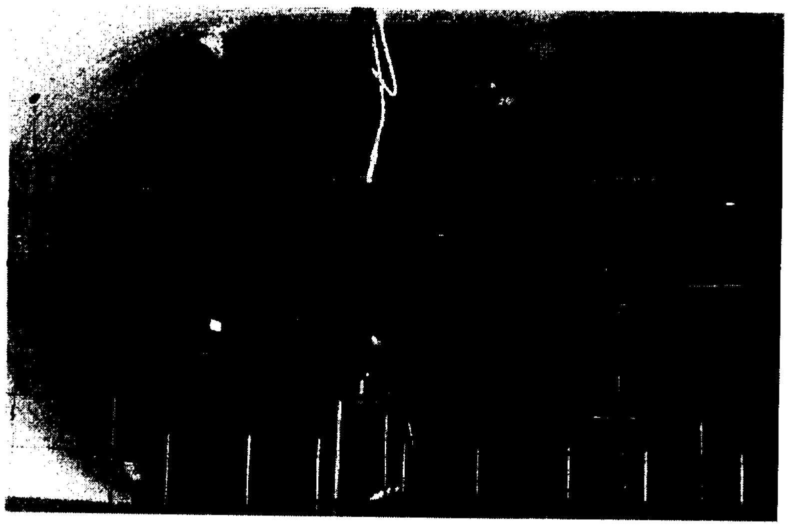
## Free-flight Test (Langley 30x60)

- 10%-Scale B737-100
- Dynamically Scaled
  - –80,000 lbs @ 13k ft
  - –140 KCAS
- Flaps: 0, 15, 30

- Generating Wings
  - –NACA 4112
  - –AR = 8
  - –Span 9.3', 18.6'

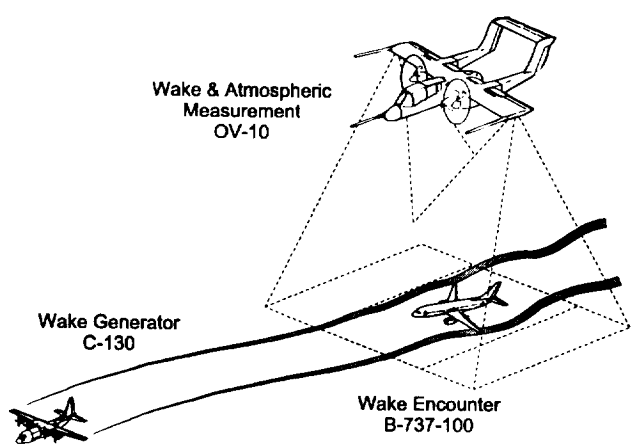
Wake 97

## Static Test (Langley 30x60)

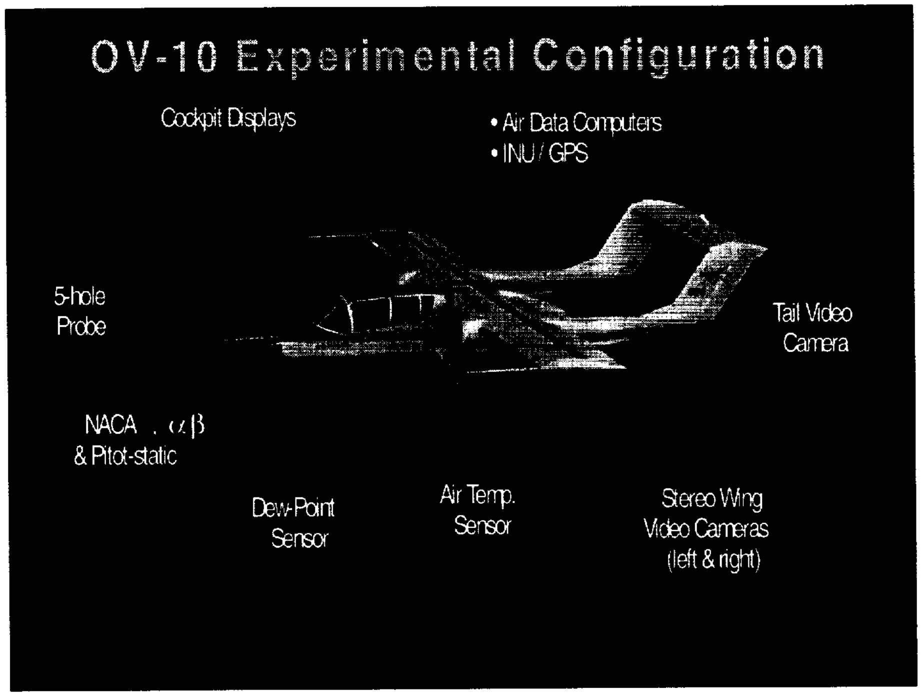


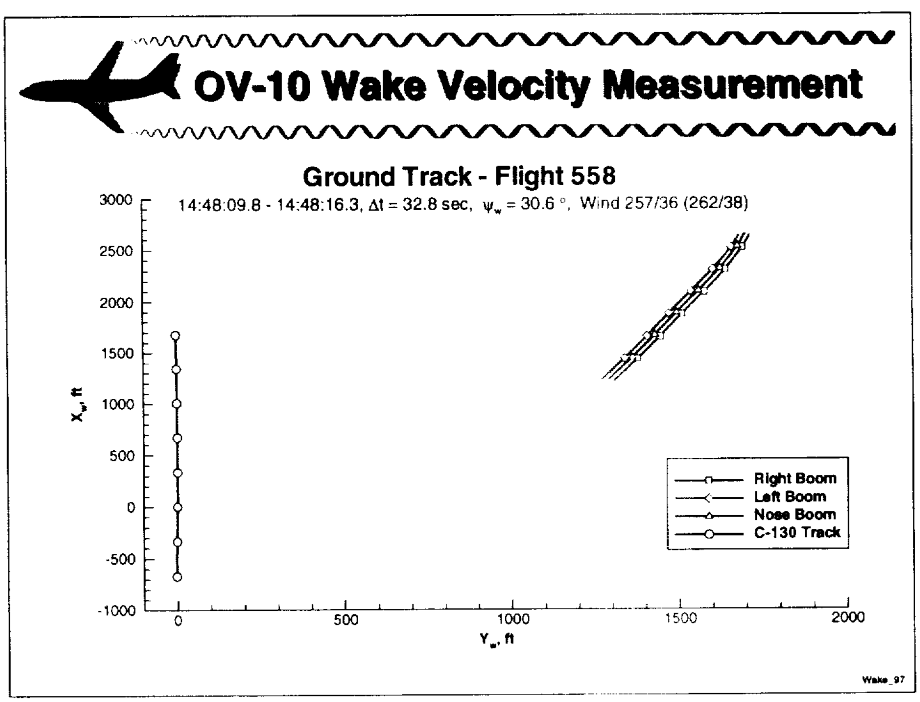
Wake_97

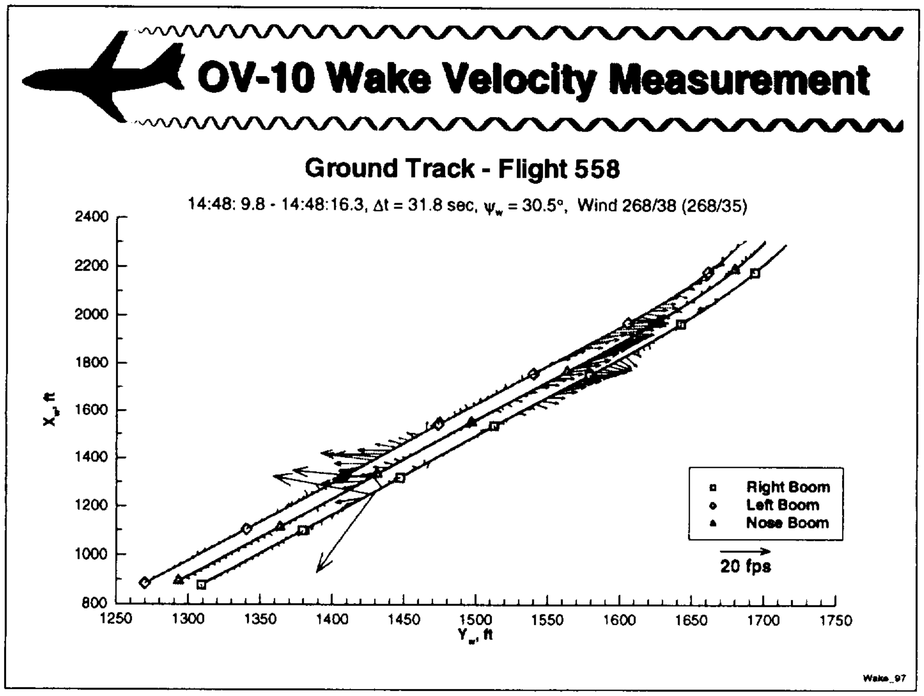
## Flight Test Setup

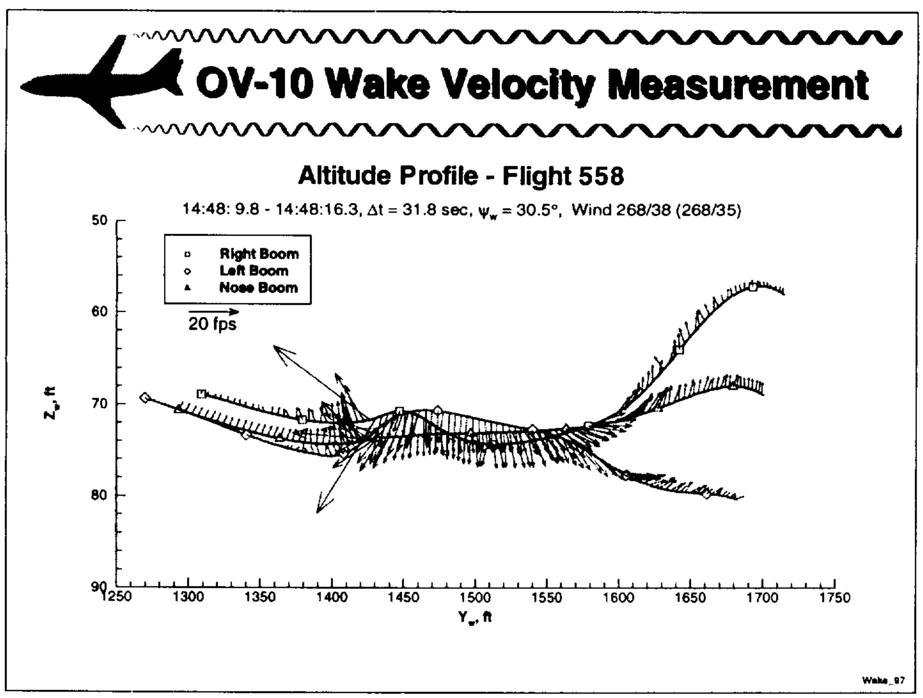


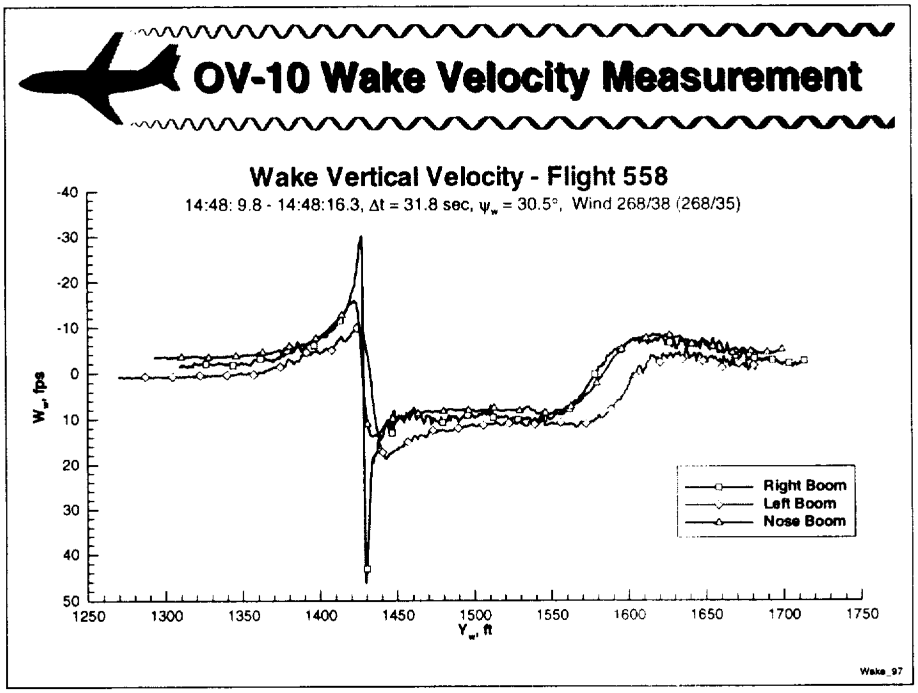

Wake_97

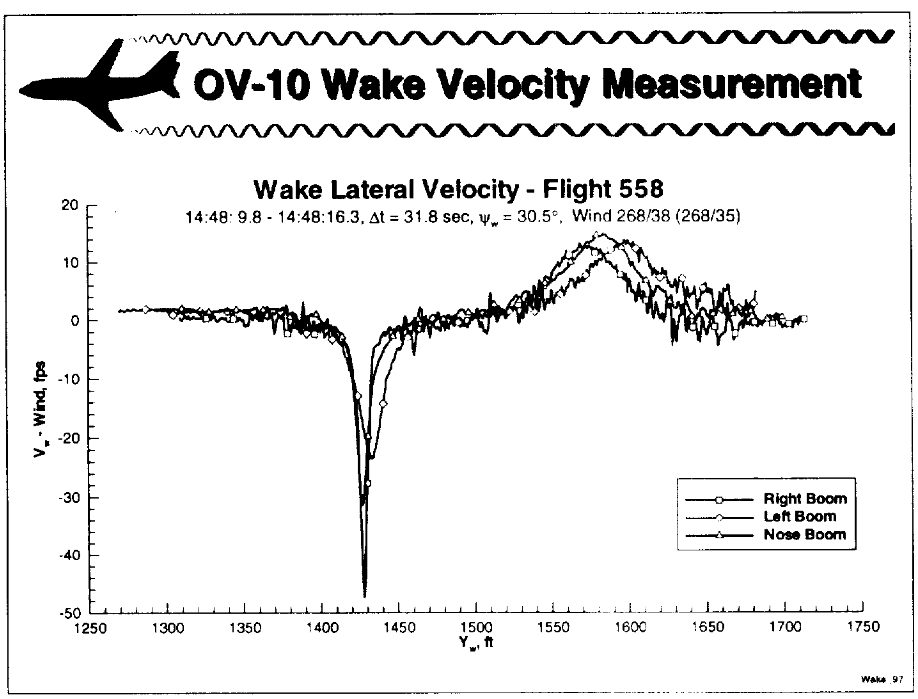

OV-10 Experimental Configuration
Cockpit Displays
• Air Data Computers
• INU / GPS
5-hole Probe
Tail Video Camera
NACA , α β & Pitot-static
Dew-Point Sensor
Air Temp. Sensor
Stereo Wing Video Cameras (left & right)


OV-10 Wake Velocity Measurement
Ground Track - Flight 558
14:48:09.8 - 14:48:16.3, Δt = 32.8 sec, ψw = 30.6 °, Wind 257/36 (262/38)
Xw, ft
Yw, ft
Right Boom
Left Boom
Nose Boom
C-130 Track
Wake_97

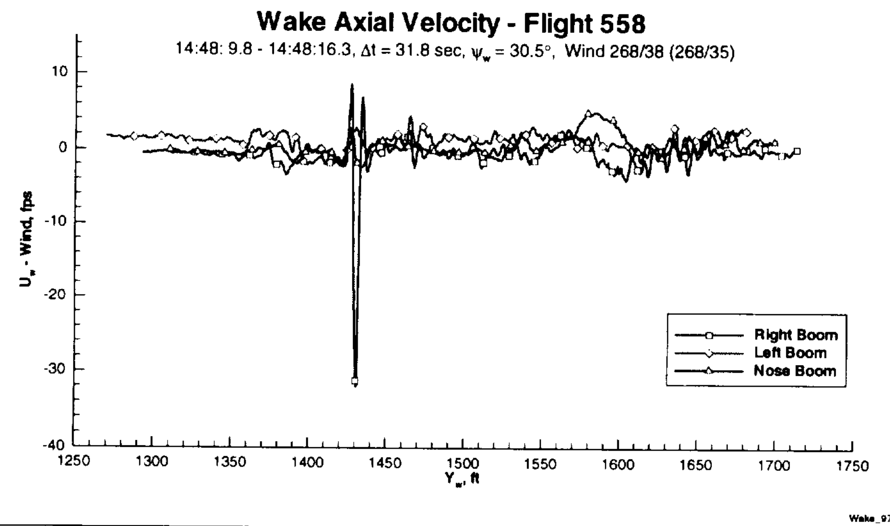

OV-10 Wake Velocity Measurement
Ground Track - Flight 558
14:48: 9.8 - 14:48:16.3, Δt = 31.8 sec, ψw = 30.5°, Wind 268/38 (268/35)
Xw, ft
Yw, ft
Right Boom
Left Boom
Nose Boom
20 fps
Wake_97


OV-10 Wake Velocity Measurement
Altitude Profile - Flight 558
14:48: 9.8 - 14:48:16.3, Δt = 31.8 sec, ψw = 30.5°, Wind 268/38 (268/35)
Right Boom
Left Boom
Nose Boom
20 fps
Zw, ft
Yw, ft
Wake_97

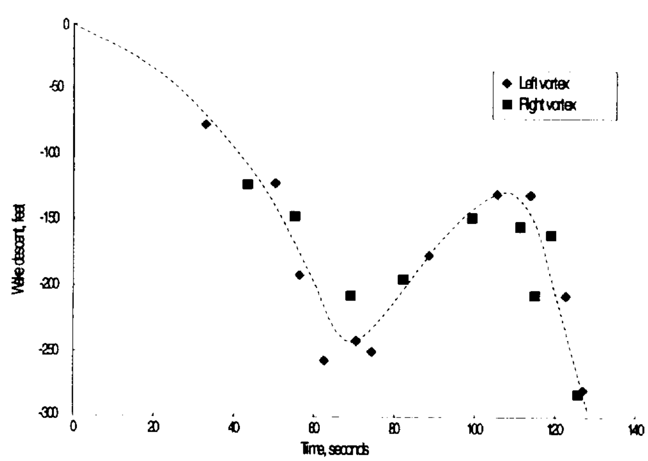

OV-10 Wake Velocity Measurement
Wake Vertical Velocity - Flight 558
14:48: 9.8 - 14:48:16.3, Δt = 31.8 sec, ψw = 30.5°, Wind 268/38 (268/35)
Ww, fps
Yw, ft
Right Boom
Left Boom
Nose Boom
Wake_97


OV-10 Wake Velocity Measurement
Wake Lateral Velocity - Flight 558
14:48: 9.8 - 14:48:16.3, Δt = 31.8 sec, ψw = 30.5°, Wind 268/38 (268/35)
Vw - Wind, fps
Yw, ft
Right Boom
Left Boom
Nose Boom
Wake_97

## OV-10 Wake Velocity Measurement




## OV-10 Wake Descent Measurement



# How are we doing?

**Current Status**

- Wind tunnel tests are complete and under analysis and documentation
- 16 OV-10 hours of flight test remaining for wake encounter and decay testing
- Task in place with Boeing to assist in flight test data analysis and documentation

Wake_97

**Questions and Discussions Following Dan Vicroy's Presentation (NASA LaRC)**

Myron Clark (FAA, Flight Standards) - You said that encounter that you showed us was 70 ft below the generating altitude. The fine print was too small. What was distance behind the generator, was it plotted in time?

Vicroy
Yes, it was plotted in time, and that was about 32 seconds.

Clark
32 seconds, translated to what?

Vicroy
It was flying about 150 knots.

Clark
150 knots, I will do arithmetic myself.

Vicroy
Bob says about a mile and half.

Frank Cheshire (American Airlines)
Could you put the slide back up that showed the vertical velocity skew. You get the impression that was picked up by the right boom only.

Vicroy
That is correct.

Cheshire
How do you explain that?

Vicroy
Possibly, we have 40 ft between the right and left, so 20 ft between that and nose and generally you don't get all three going through the same space. The booms are tracing three lines in space, which are different. So the right boom hit the core in this region and other booms are not seeing the same airspace.

Unknown
Dan did you say that there is more video. Are you going to show that?

Vicroy
I can show that encounter real quick. It only lasts 10 seconds, but you will see slightly under the one and way under the other.

Charles Zheng (University of South Alabama)
Could you show the slide on OV-10 vortex descent measurements? This is the same cross-section of wake vortex which you measured at different times. Is that true?

Vicroy
This is as we are falling further and further back. Each time we fly through the wake we compute altitude and what time, how far back we were from the time it was generated.

Zheng
What is the spatial location of the vortex that you measured?

Vicroy
The spatial location?

Zheng
You measured at different times, right?

Vicroy
Yes, and we are drifting back, relative to generator, and every time we hit the core we record what our altitude is and what was the altitude of the C130 when it passed that location basically. If you figure in the wind, you have to add winds.

Pal Arya (North Carolina State University)
I had a question about wind tunnel free flight tests. You had very violent response to wake vortices which you did not see in flight test, what is mismatch here?

Vicroy
We were not looking to get those kinds of upsets in the flight test. From the flight safety standpoint you probably would not be allowed to do test, but can do in the tunnel. What I showed in the tunnel was fairly dramatic, but we looked at lower angle of attack on the generating wing, lower circulation strengths. In terms of modeling, we are not interested in modeling a 60 degree upset. We want to model something more subtle because that is the calculation we are trying to get right. What you saw was the high end of what we looked at.

Arya
So the wind tunnel tests were not representing the real flight test conditions?

Vicroy
We could change angle of attack of the generating wing to give you anything you wanted. That was a high strength vortex; we also looked at low strength.

Phil Hogg (United Airlines)
Do you have any plans to conduct any flight testing of aircraft in landing configuration? In other words with gear down and flaps in landing configuration?

Vicroy
I didn't mention that in both wind tunnel and flight we looked at flaps 30, we didn't go to flaps 40 because from flight safety, margins are less. We did do flaps 30, but did not do gear down.

Hogg
I notice that distance was roughly a mile and a quarter.

Vicroy
We went back as far as 7 miles, as far back as we could find a marked wake.

Susan Ying (McDonnell Douglas)
How do your wind tunnel results correlate with your flight results with encounters of similar strength. How do the Reynolds numbers correlate?

Vicroy
That is a good question, we haven't got there yet. That is one of the things we will try and answer. We are still reducing the flight data to the same point where we can compare with wind tunnel stuff. We just haven't got there yet. That is why we did the two tests and did them similar.

528-47

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318721

21p.

# Meteorological Instrumentation at the Memphis and DFW Airports

Michael P. Matthews
MIT Lincoln Laboratory

1st Wake Vortex Dynamic Spacing Workshop

May 14, 1997



## Outline

- Overview
- Sensor Descriptions
- Memphis Operations and Analysis
  - Wake Vortex Research Community
- Dallas/Fort Worth Meteorological Systems
  - Wake Vortex Research Community
  - AVOSS Prototype Operations (Build 1)
- Algorithm Development
- Summary

# Overview

## Lincoln Lab's AVOSS Tasks

- Conduct field measurements which measure atmospheric conditions and vortex information with high fidelity
- Provide wake vortex and meteorological data analysis
- Provide real–time system design support
- Construct algorithms for diagnosing and predicting airport wind, temperature, and turbulence profiles

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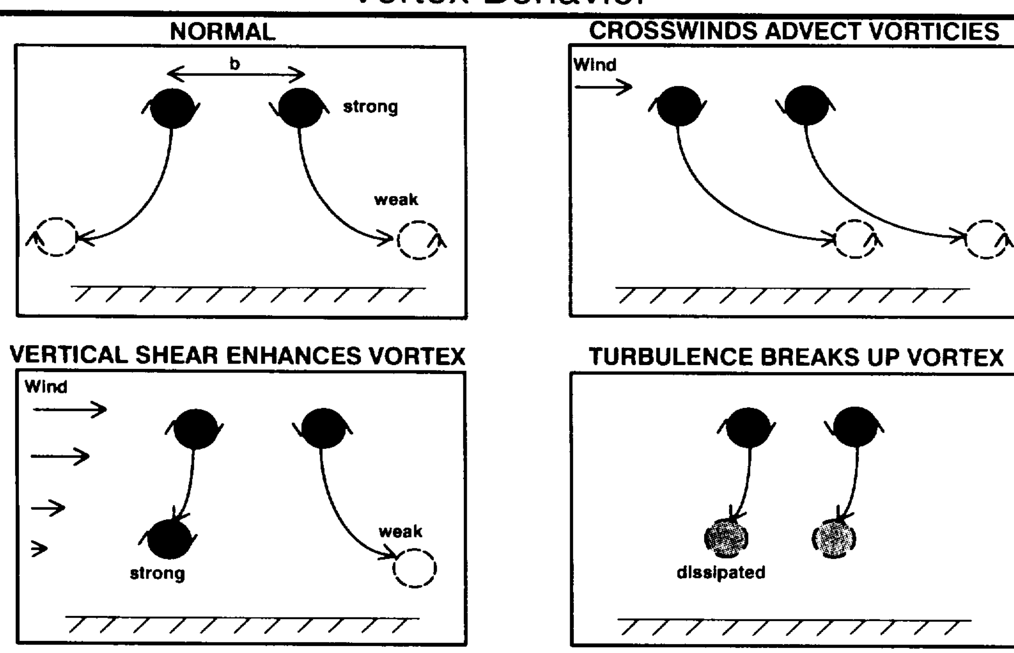
# Meteorological Conditions Affect Vortex Behavior

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## Data Users

### Wake Vortex Research

- Wake vortex modelers (NASA Langley,NWRA,etc.)
  - Compare wake vortex models with real world atmospheric conditions and wake vortex behavior
- Atmospheric modelers (NCSU,UQAM)
  - predict atmospheric conditions several hours in advance at a high fidelity

### AVOSS Prototype Demonstration (Build 1)

- AVOSS wind profile algorithm (Lincoln)
  - merge multiple wind measuring sytems in to one vertical profile, providing means and variances.
- COBEL column model (UQAM)
  - diagnose atmospheric stability and turbulence from limited atmospheric measurements
- Real–time vortex prediction algorithms (NASA Langley)
  - Apply wake vortex models to real–time atmospheric conditions



## System Requirements

### Wake Vortex Research

- High fidelity measurements of atmospheric conditions (temperature, turbulence, winds)
- Significant amounts of post–processing to ensure HIGH quality measurements

### AVOSS Prototype Demonstration

- Highest fidelity measurements possible with sensors that have a high probability of being available in a real–time system
- Automated algorithms to diagnose atmospheric conditions (temperature, turbulence, winds)
- Automated data quality editing
- Real–time data access by AVOSS algorithms

## Timeline of Lincoln Meteorological Systems

| Memphis Wake Vortex Research | | Year | Dallas/Fort Worth AVOSS Prototype Demo Wake Vortex Research | |
|---|---|---|---|---|
| FUNDING STARTED | MAR | 94 | | |
| EQUIPMENT PURCHASED | APR | 94 | | |
| SITE INSTALLED | NOV | 94 | | |
| '94 DEPLOYMENT | DEC | 94 | | |
| '94 DATA DELIVERY | MAY | 95 | | |
| REAL-TIME DATA DELIVERY | JUN | 95 | | |
| DEPLOYMENT | AUG | 95 | | |
| POST-DATA DELIVERY | SEP | 95 | | |
| | | 96 | MAR | PLANNING BEGUN |
| | | 96 | JUL | EQUIPMENT PURCHASE |
| HAND TRUTHED PROFILES | NOV | 96 | | |
| SITE DISMANTLED | FEB | 97 | FEB | CONSTRUCTION BEGUN |
| | | 97 | MAY | SENSOR INSTALLATION |
| | | 97 | JUN | SYSTEM OPERATIONAL |

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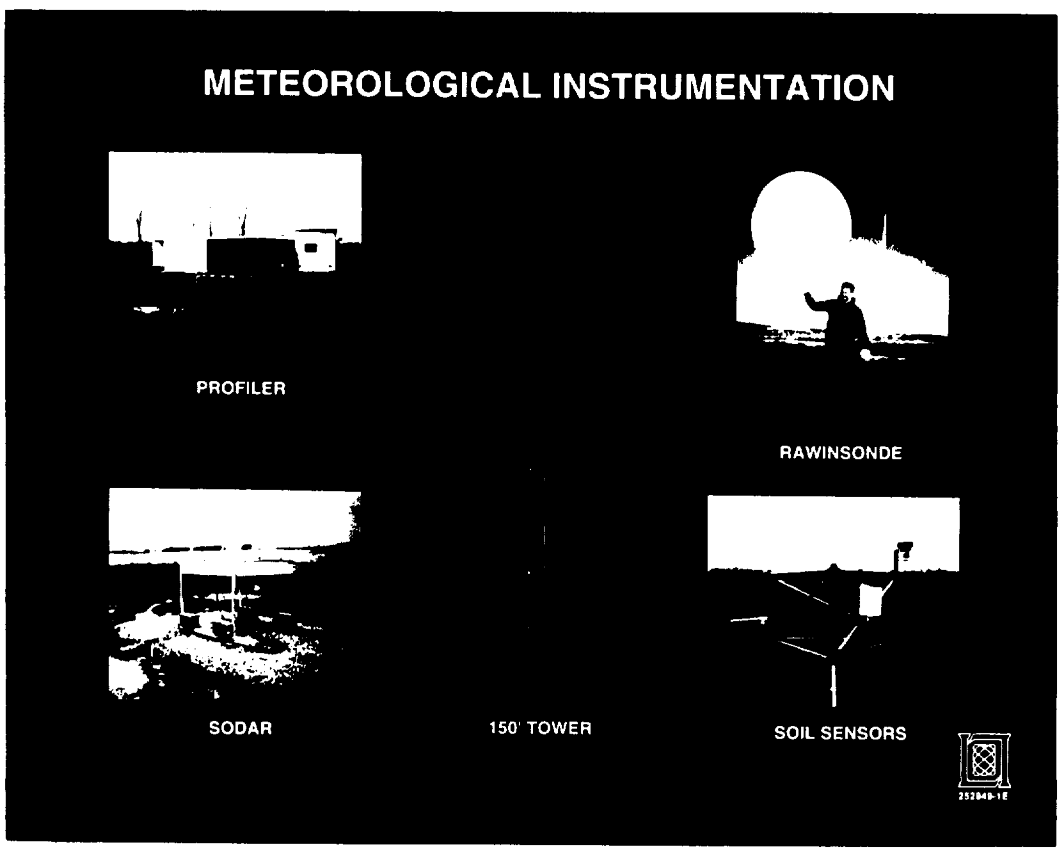


## 150' Instrumented Tower

### R.M. Young Instrumentation

| | |
|---|---|
| Sensors: | 5, 10, 20, 30, 42 m |
| Sample Rate: | 1 Hz |
| Average Period: | 60 sec |

**Temperature, Humidity**

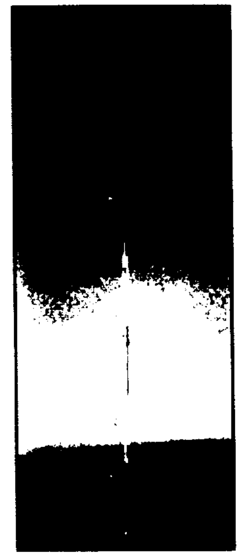
| | |
|---|---|
| Temperature Range: | ±50°C |
| Temperature Accuracy: | 0.3°C |
| Humidity Range: | 0–100% |
| Humidity Accuracy: | 2% |

**Wind**

| | |
|---|---|
| Wind Speed Range: | 0.4–40 m/s |
| Wind Speed Accuracy: | 2% |
| Wind Direction Accuracy: | 3 deg |

**Pressure**

| | |
|---|---|
| Pressure Range: | 800–1100 mb |
| Pressure Accuracy: | 0.15 mb |



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## 150' Instrumented Tower

### Applied Technologies Sonic Anemometers

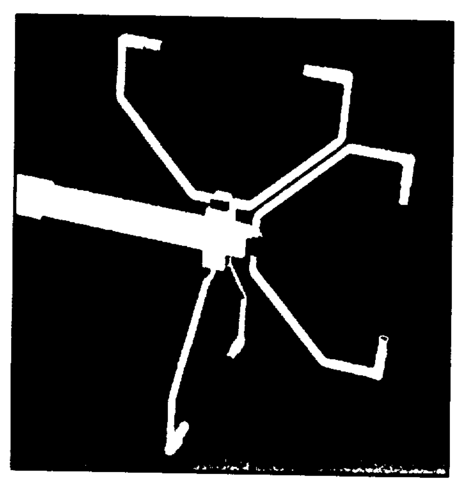
| | |
|---|---|
| Sensors: | 5, 40 m |
| Sample Rate: | 10 Hz |
| Averaging Period: | 60 sec |
| Path Length: | 15 cm |

**Wind**

| | |
|---|---|
| Wind Speed Range: | ±15 m/s |
| Wind Speed Accuracy: | 0.05 m/s |

**Temperature**

| | |
|---|---|
| Temperature Range: | –20 to 50°C |
| Absolute Temperature Accuracy: | 2.0°C |
| Sonic Temperature Accuracy: | 0.05°C |



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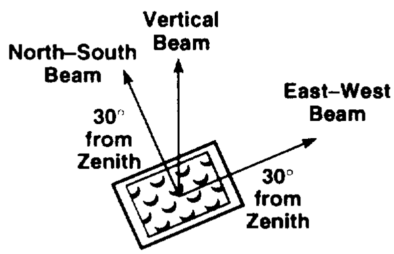
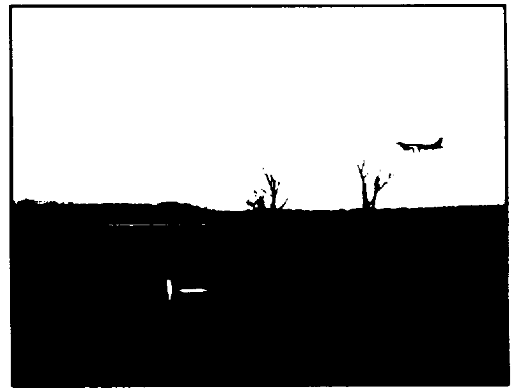
# REMTECH PA2 Sodar

## Phased Array Doppler Sodar

| | | | |
|---|---|---|---|
| Frequency: | 2100 Hz | Averaging Period: | 10 min |
| Peak Power: | 30 W | Wind Speed Range: | 0–40 m/s |
| Vertical Resolution: | 20 m | Wind Speed Accuracy: | 0.2 m/s |
| Vertical Range: | 600 m | Wind Direction Accuracy: | 5 deg |



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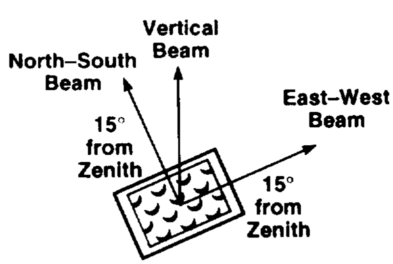
# AEROVIRONMENT M2000

## Phased Array Doppler Sodar

| | | | |
|---|---|---|---|
| Frequency: | 2000 Hz | Averaging Period: | 10 min |
| Peak Power: | 100 W | Wind Speed Range: | 0–35 m/s |
| Vertical Resolution: | 20 m | Wind Speed Accuracy: | 0.3 m/s |
| Vertical Range: | 600 m | Wind Direction Accuracy: | 5 deg |

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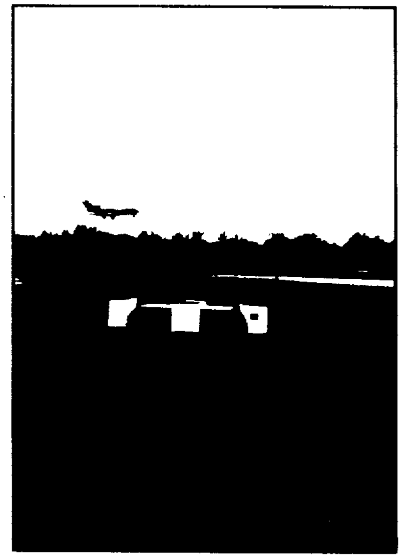
# RADIAN LAP3000 Profiler

## Five Beam Phased Array Antenna

| | |
|---|---|
| Frequency: | 915 MHz |
| Peak Power: | 500 W |
| Vertical Resolution: | 100 m |
| Vertical Range: | 5 km |
| Averaging Period: | 25 min |
| Wind Speed Range: | 0–51 m/s |
| Wind Speed Accuracy: | 1 m/s |
| Wind Direction Accuracy: | 10 deg |



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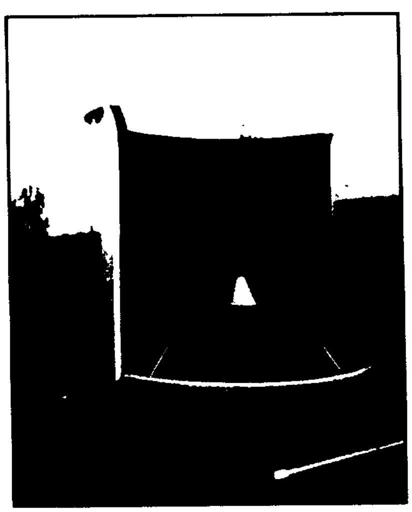
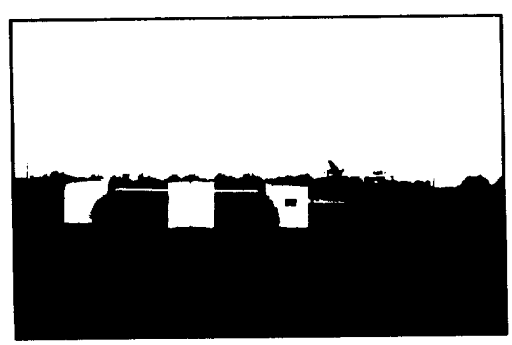
# RADIAN LAP3000 RASS

## Radio Acoustic Sounding System

| | | | |
|---|---|---|---|
| Frequency: | 2000 Hz | Beamwidth: | 10 deg |
| Vertical Range: | 1500 m | Averaging Period: | 5 min |
| Vertical Resolution: | 100 m | Temperature Accuracy: | 1°C |





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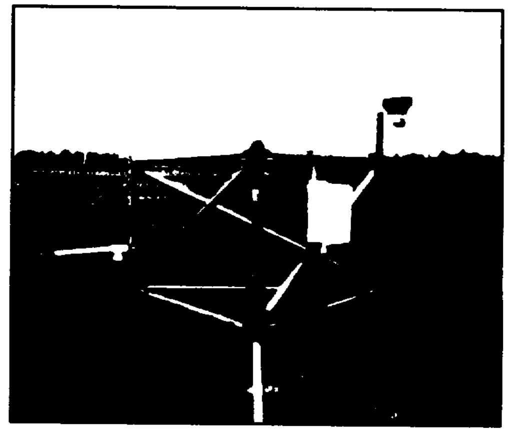
# Soil Sensors

| | |
|---|---|
| Sample Rate: | 1 Hz |
| Averaging Period: | 60 sec |



### Rain Gauge

Texas Electronics TE525MM

| | |
|---|---|
| Increment: | 0.1 mm |
| Accuracy: | 1% at 2 in/hr |

### Soil Temperature / Moisture

REBS STP-1/SMP-1

| | |
|---|---|
| Temperature Range: | ± 50°C |
| Temperature Accuracy: | 0.05°C |
| % Water Content Range: | 0–35% |
| Moisture Accuracy: | N/A |

### Radiometer

REBS THRDS-7

| | |
|---|---|
| Radiation Range: | –1000 to 2000 W/m$^2$ |
| Radiation Accuracy: | N/A |



# LORAN Class Sounding System

## University of Massachusetts at Lowell

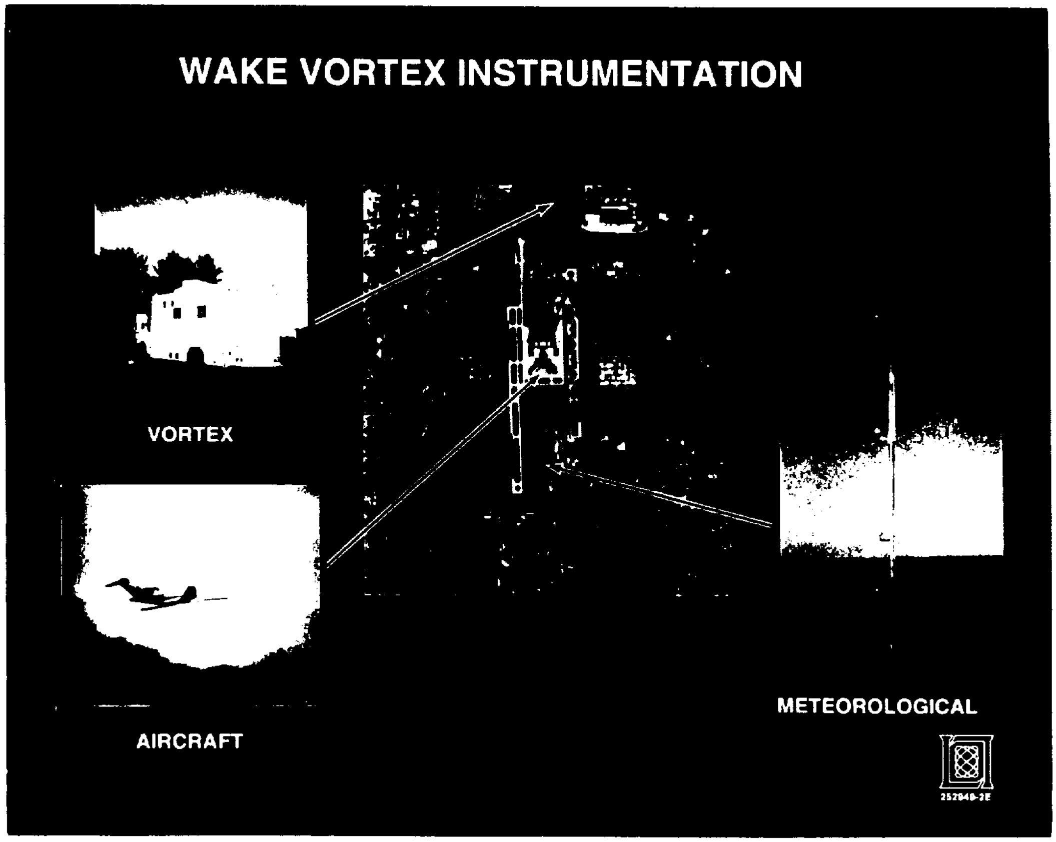
| | |
|---|---|
| Vertical Resolution: | ~50 m |
| Vertical Range: | 50 kft |

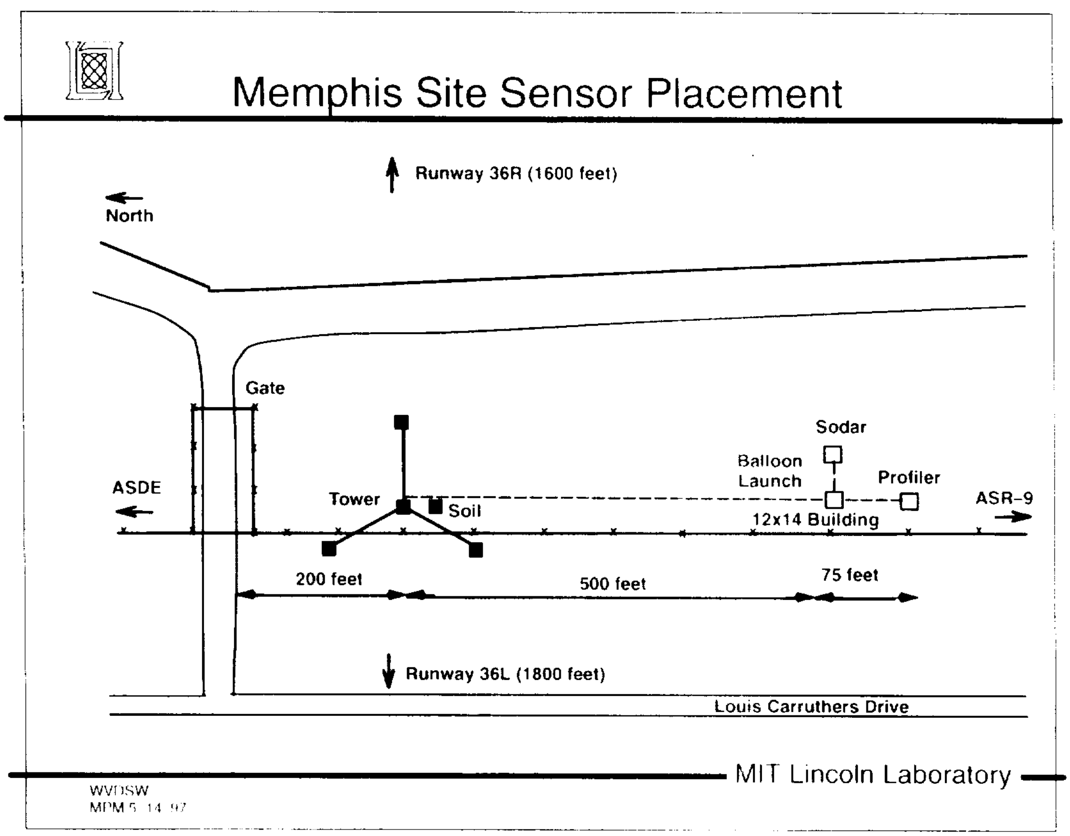
### Pressure, Temperature, Humidity

| | |
|---|---|
| Averaging Period: | 10 sec |
| Pressure Accuracy: | 1 mb |
| Temperature Range: | ±50°C |
| Temperature Accuracy: | 1°C |
| Humidity Range: | 0–100% |
| Humidity Accuracy: | 3% |

### Wind

| | |
|---|---|
| Average Period: | 60 sec |
| Wind Speed Range: | 0–50 m/s |
| Wind Speed Accuracy: | 1 m/s |
| Wind Direction Accuracy: | 10 deg |


WAKE VORTEX INSTRUMENTATION
VORTEX
AIRCRAFT
METEOROLOGICAL


Memphis Site Sensor Placement
Runway 36R (1600 feet)
North
Gate
Sodar
Balloon Launch
Profiler
ASDE
Tower
Soil
ASR-9
12x14 Building
200 feet
500 feet
75 feet
Runway 36L (1800 feet)
Louis Carruthers Drive
MIT Lincoln Laboratory
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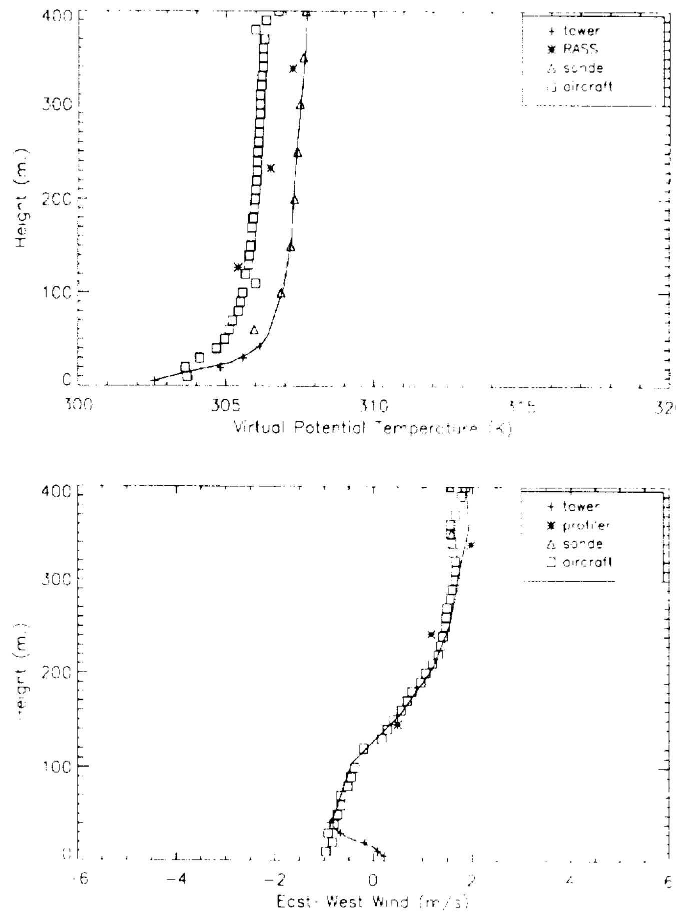
# Memphis Operations and Analysis

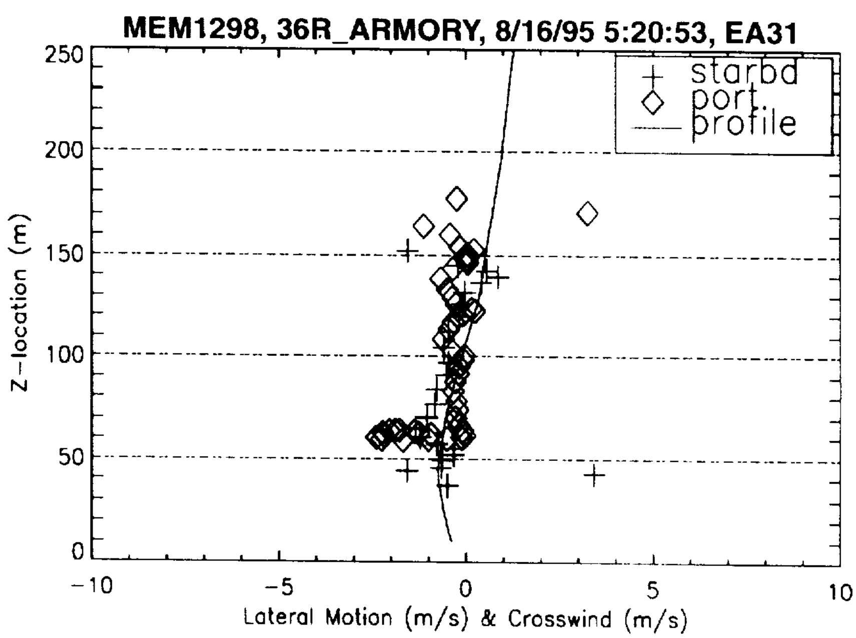
## Operational Statistics

- High quality vortex measurements were made of 572 aircraft on 21 different days during 31 pushes.
- Meteorological systems (tower, profiler, rass, balloons, soil) were operational during 30 of the 31 pushes.
- Doppler sodars were operational on some days, with sensor performance varying during measurement periods.
- Significant amount of data to post–process, analyze, and compare with vortex measurements.

## METEOROLOGICAL DATA ANALYSIS




## Vortex Lateral Motion vs. Crosswind

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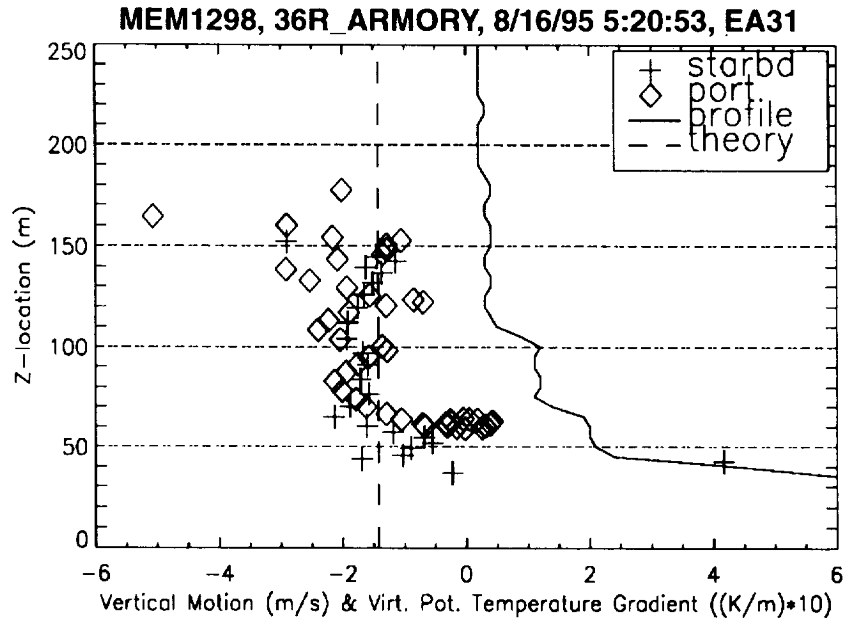
## Vortex Vertical Motion vs. Virtual Potential Temperature Gradient

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## Dallas/Fort Worth Meteorological Systems

- Focus of efforts is to support a real-time AVOSS Prototype Demonstration
  - Automated algorithms to diagnose atmospheric conditions (temperature, turbulence, winds)
  - Automated data quality editing
  - Real-time data access by AVOSS algorithms
- Dallas/Fort Worth is a larger airport than Memphis
  - More spatial variability is possible in measurements

    Sensors MUST be able to capture spatial variabilty
  - Airport operations are continuous during the day

    System MUST be reliable, and operational 95+% of the time

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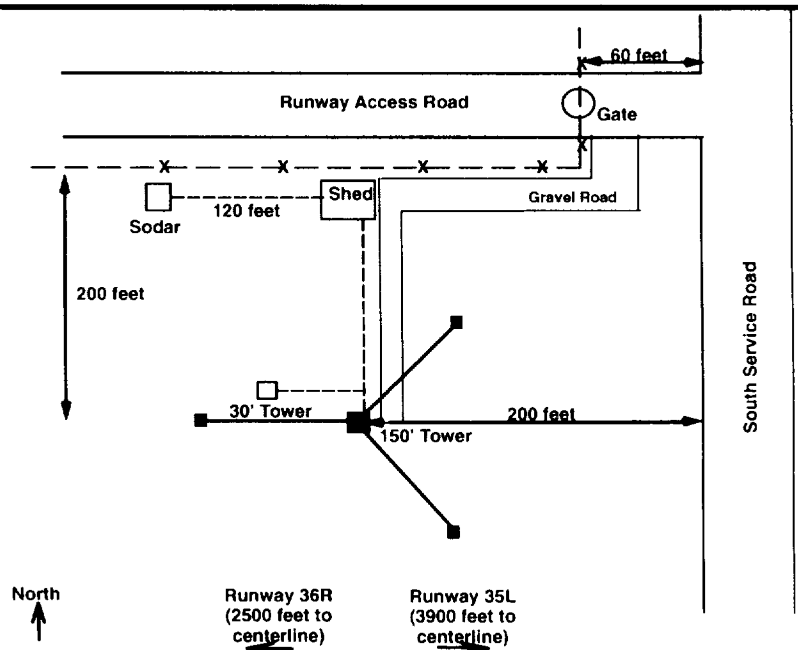
Dallas/Fort Worth International Airport

## DFW South Site Sensor Placement

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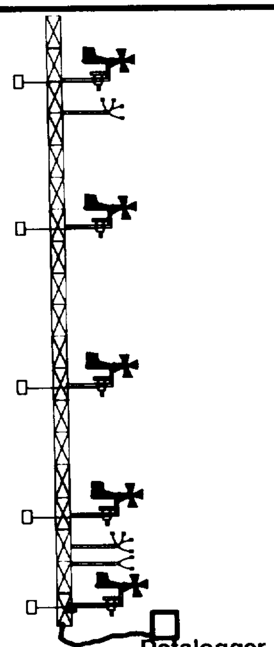
## DFW South Site 150' Tower




**SAVPAK**
2,10,20,32,42 meters
- 1Hz Temperature
- 1Hz Rel. Humidity
- 1Hz Wind Speed
- 1Hz Wind Direction

**FLUXPAK**
5,40 meters
- 10Hz Virtual Temp.
- 10Hz 3D winds
- 20Hz Humidity(5 m.)

**BAROMETER**
2 meters
- 1Hz Pressure

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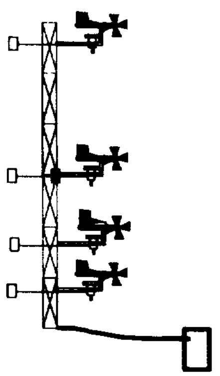
## DFW South Site 30' Tower




**SAVPAK**
1,2,5, 10 meters
- 1Hz Temperature
- 1Hz Rel. Humidity
- 1Hz Wind Speed
- 1Hz Wind Direction

**BAROMETER**
5 meters
- 1Hz Pressure

**FLUXPAK**
8 meters
- 10Hz Virtual Temp.
- 10Hz 3D winds

**RADIOMETER**
2 meters
- 1 Hz Net Radiation
- 1 Hz Radiation IN
- 1 Hz Radiation OUT

**SOILPAK**
2.5,5,10 cm.
- 1Hz Temperature
- 1Hz Moisture
- 0.1 mm Rain

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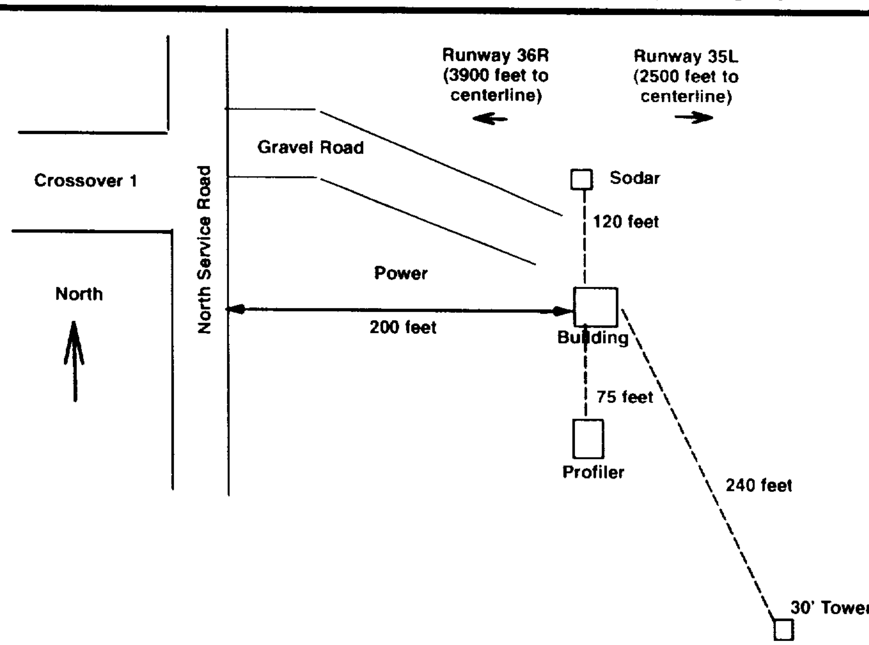
## DFW North Site Sensor Placement

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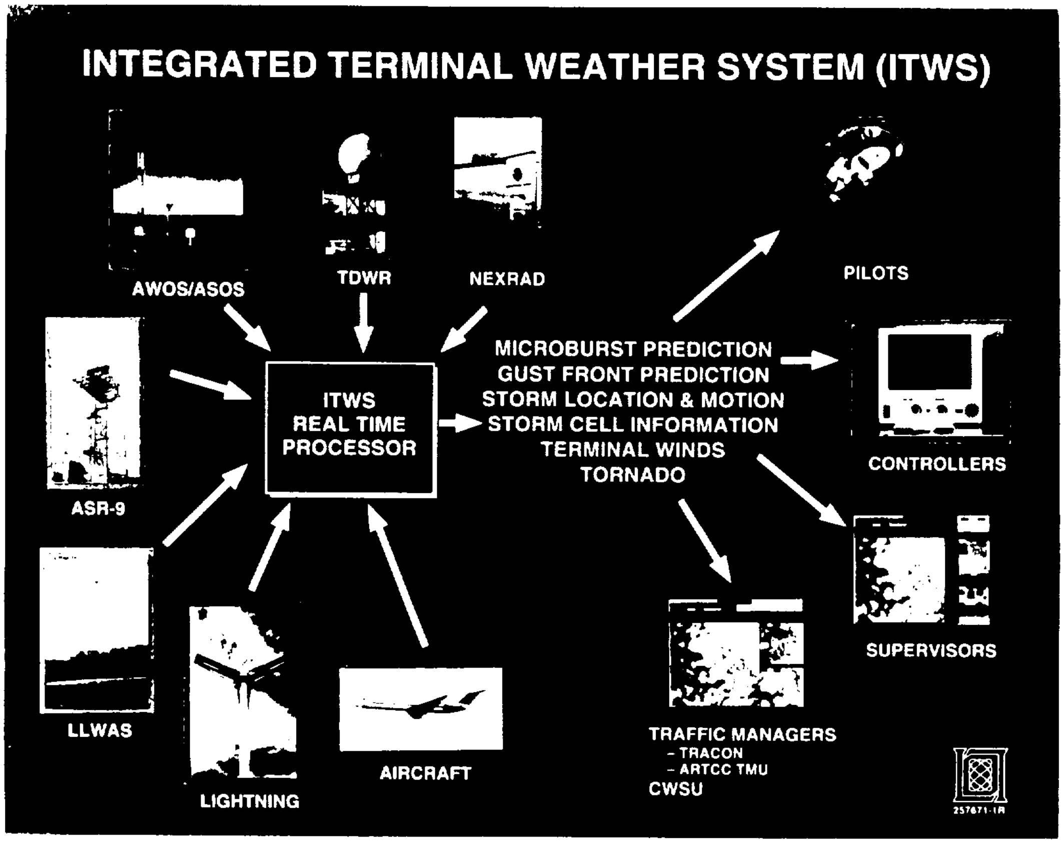
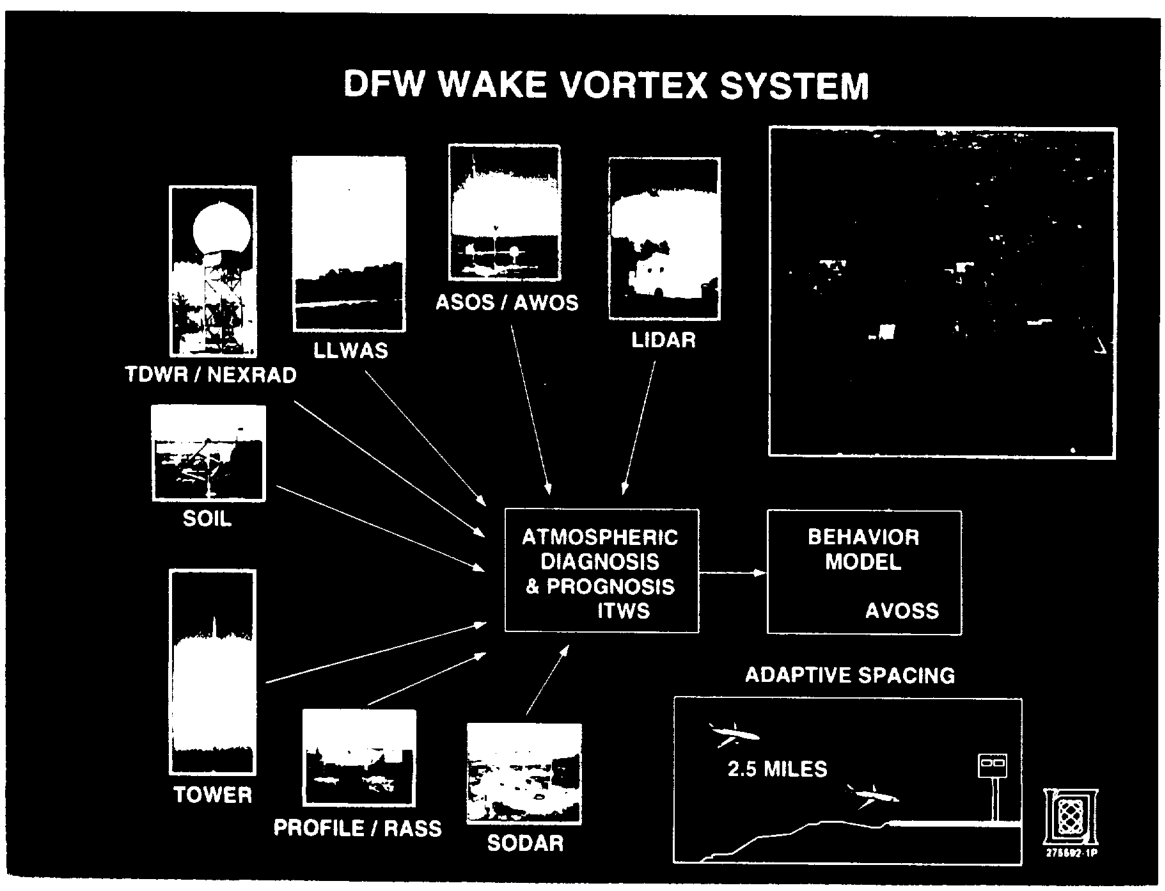
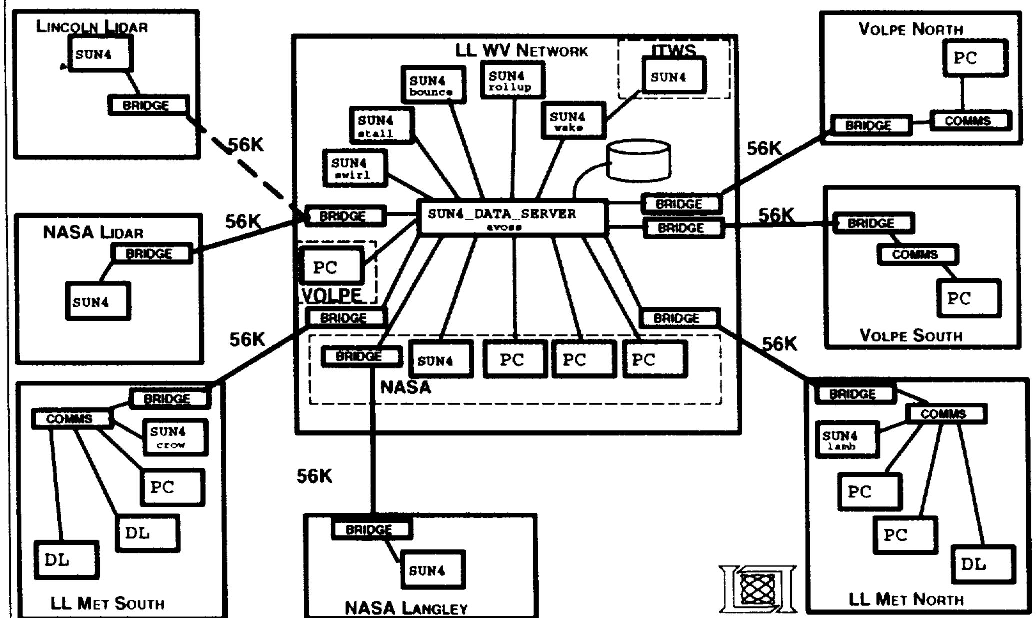
WVDSW
MPM 5 14-97


INTEGRATED TERMINAL WEATHER SYSTEM (ITWS)
AWOS/ASOS
TDWR
NEXRAD
PILOTS
ASR-9
ITWS REAL TIME PROCESSOR
MICROBURST PREDICTION
GUST FRONT PREDICTION
STORM LOCATION & MOTION
STORM CELL INFORMATION
TERMINAL WINDS
TORNADO
CONTROLLERS
SUPERVISORS
LLWAS
LIGHTNING
AIRCRAFT
TRAFFIC MANAGERS
- TRACON
- ARTCC TMU
CWSU


DFW WAKE VORTEX SYSTEM
TDWR / NEXRAD
LLWAS
ASOS / AWOS
LIDAR
SOIL
ATMOSPHERIC DIAGNOSIS & PROGNOSIS ITWS
BEHAVIOR MODEL
AVOSS
ADAPTIVE SPACING
2.5 MILES
TOWER
PROFILE / RASS
SODAR

# Wake Vortex System Design




MIT Lincoln Laboratory

WVDSW
MPM 5-14-97

# Outline

- Overview
- Sensor Descriptions
- Memphis Operations and Analysis
  - Wake Vortex Research Community
- Dallas/Fort Worth Meteorological Systems
  - Wake Vortex Research Community
  - AVOSS Prototype Operations
- Algorithm Development
- Summary

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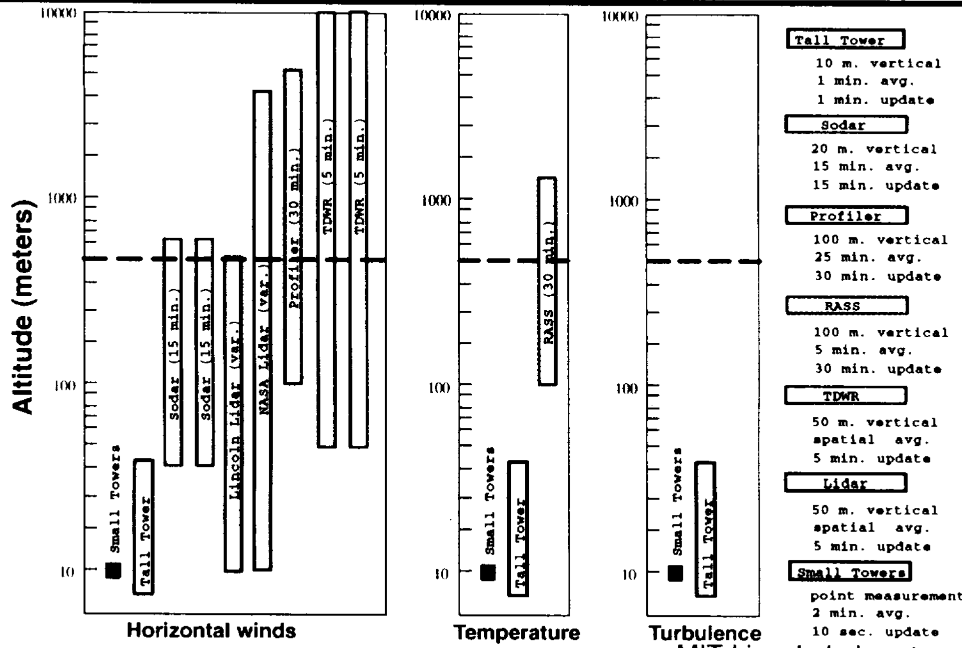
# Wake Vortex Meteorological Data Comparison

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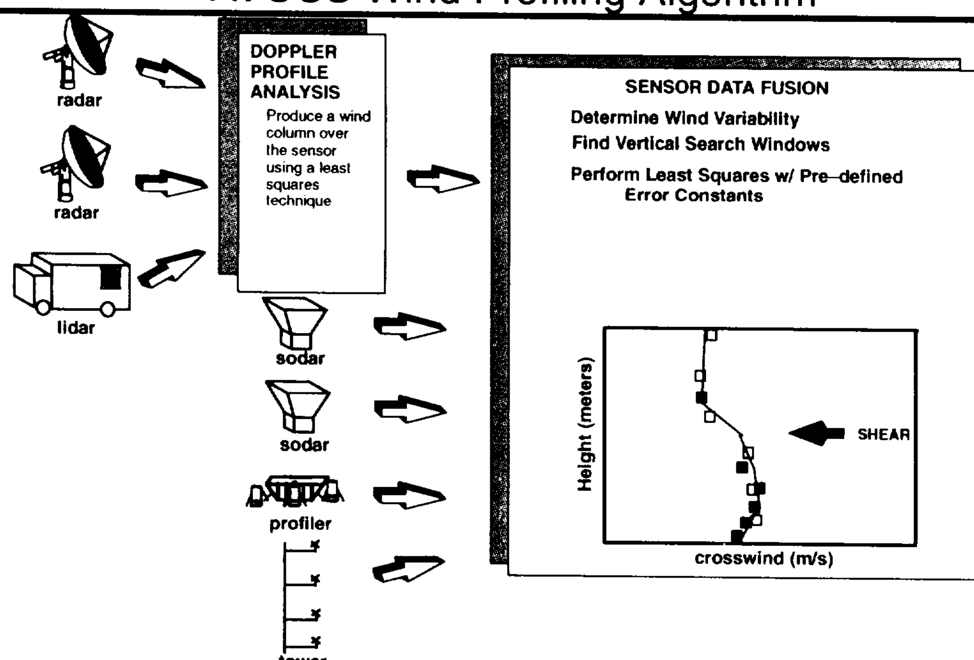
# AVOSS Wind Profiling Algorithm

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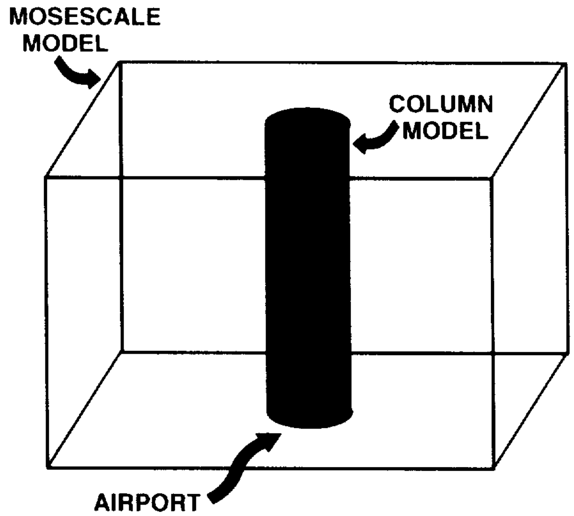
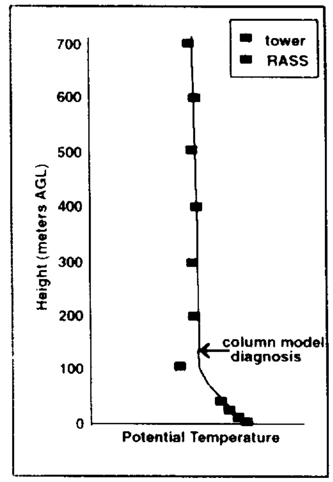
## Column Model Applications

UQAM: R. Tardif, P. Zwack, C. Page; MIT/LL: M. Matthews




Modified COBEL (Meteo France / Paul Sabatier University)

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## Summary

- Conducted field measurements which measured atmospheric conditions in conjunction with vortex information with high fidelity sensors in Memphis, Tenn.
- Provided post–analysis of meteorological data for researchers and scientists
- Developing real–time weather system for AVOSS demonstration
- Continued research in algorithm design for diagnosing and predicting airport wind, temperature, and turbulence profiles

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**Questions and Discussions Following Mike Matthews' Presentation (Lincoln Lab)**

Stephen Hannon (Coherent Technologies, Inc.)
One of your first profile plots showed a temperature profile with a discrepancy on top. I thought the bottom one was just the wind profile at the same time. I was confused as to how that was resolving the ambiguity or discrepancy in the top plot.

Matthews
No, that was just the two viewgraphs I happened to have up. Basically what happened was that as the vortex fell, it reached the top of that inversion and began to spread out, went off to the negative direction I believe, when there was no vertical wind. What happened? It was reaching the top of the inversion, the top of a very strong stable layer.

Hannon
So you have not been able to resolve the difference between the aircraft measurements. In that plot there is a couple of degrees Kelvin difference in the top plot.

Unknown
Why is there a difference in temperature between aircraft measurement and yours?

Matthews
Oh that, well, you can ask an OV-10 person about that. We believe there is a bias of about 1 degree in their sensor, and as you get nearer to the surface here you are getting closer to tarmac which is probably warmer than the open field that our sensors are in.

Hannon
The other question was what kind of turbulence matrix are you going to try and derive or what are the plans regarding either of lidar data to fill in the gaps you showed in the turbulence plot.

Matthews
That is more of a question for Rick. My understanding is that they are providing a basic wind profile, like a UV wind profile of like with 20 meter resolution. They can measure turbulence but I don't think that is in their plan. The way we hope to resolve turbulence is the use of the COBEL model which computes wind profile from which we compute a turbulence profile.

Hannon
Lidars will be able to do turbulence at least pulse lidar to a higher altitude, and give you spatial variability at selected locations throughout the airport.

Matthews
Yes it would be very useful, but the TWR is also providing some information on spatial

variability of the winds so you can use that information to get a feel for wind variability

Yuh Lin (N.C. State University)
I am kind of curious about why you put a tower in north and one in south. When you have east-west crosswinds, the winds measurement at your towers will not represent the upstream conditions.

Matthews
That's a good question. That's hard to say what would agree spatially. If they were landing to the south there might be some difference close to the surface. You want to get the tower as close as you can to the middle of the airport because that is where planes are lowest in altitude. But the winds primarily blow from the south and if they are going to blow across an area that has a lot of buildings and concrete it is certainly going to warm some. You want to get a feel for what is going on with atmospheric conditions before it reaches that. Then we have a shorter tower on the north side to hopefully see what conditions there are. At the top of the tower you hope it would not be too too different. I am talking very low level modification to atmosphere. You can put another 150 ft tower on the north side, it's just coming up with money to do that.

Dave DeCroix (N. C. State University)
One of the things we need to run the TASS model is a good representation of the wind as a function of height. With all the sensors and balloon sounding that you have being deployed at Dallas, do you feel you are going to get an adequate measure of this?

Matthews
I didn't talk about that, there is an effort underway by NASA, Al Zwack and a few others. We are trying to get multiple balloon launches, five balloon launches occurring at the same time, around the Dallas-Fort Worth area to try to get this type of information. I don't think that has been finalized yet. They are still getting permission from the FAA etc. But that information would be very useful.

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# AVOSS Wind Profiling Algorithm

Rodney E. Cole
MIT Lincoln Laboratory

NASA First Wake Vortex Dynamic Spacing Workshop

MIT Lincoln Laboratory

REC 5-14-97

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## AVOSS Wind Profiling Algorithm

### Outline

- Introduction
- Sensors
- System/Algorithm overview
- Development Status and Plans
- Preliminary results
- Summary

## What Is The Problem?

- AVOSS wake vortex behavior algorithm needs a single view of the atmosphere
- Lot of sensors, each provides some of the information required
- Different sensors provide different types of information
- The sensors are not in agreement

The challenge is to build an automated system that puts together the information from the various sensors

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## AVOSS Wind Profiling Goals

- Primary goal is to support real–time AVOSS operations; i.e. support wake vortex behavior predictions
  - What are the possible winds that a wake vortex may encounter?
  - Is a persistence forecast reliable?
- Secondary goal is to support the real--time column model effort
- Lastly, support to off–line scientific studies

Each goal places different requirements on the system. It may not be possible to support all three goals with a single wind profile.

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# AVOSS Wind Profiling Requirements

Provide a vertical profile to support to real–time AVOSS operations

- Information content:
  - Mean head wind and cross wind

    nominally equivalent to a 15 minute running average
  - Variation of the wind about the reported mean

    True variance about the mean + variance of the reported mean about "true mean"
  - Vertical shear in the cross wind
- Extent and resolution:
  - Surface to 500 m, resolution 10–50 m
  - Updated every 1–5 minutes, driven by sensor updates

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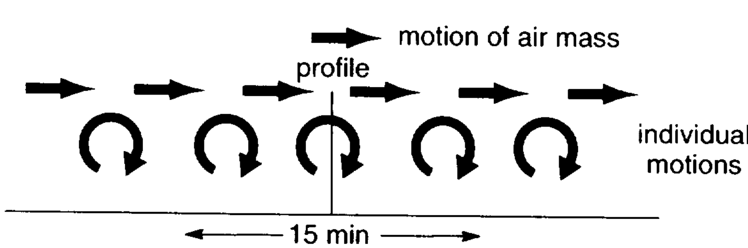
# Design Issues

- Need to avoid introducing artificial vertical shears, for example at the top of the tower
- Need to avoid smoothing over real vertical shears
- Need to better understand the required smoothing to best predict the wind over the next 15 minutes
- Regional statistics ⇔ Temporal statistics

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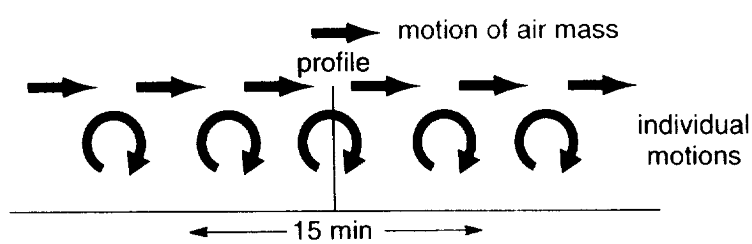


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# Sensors

- Sodars (2)
  - Profile every 15 minutes
- Doppler profiler
  - Profile every 30 minutes
- Tall tower
  - Wind at several heights every minute
- Short towers (several, including FAA wind shear detection anemometers)
  - Wind at one height every minute or less
- TDWR Doppler radars (2)
  - fields of radial velocity every 5 minutes, 120 m x .5$^0$ gates

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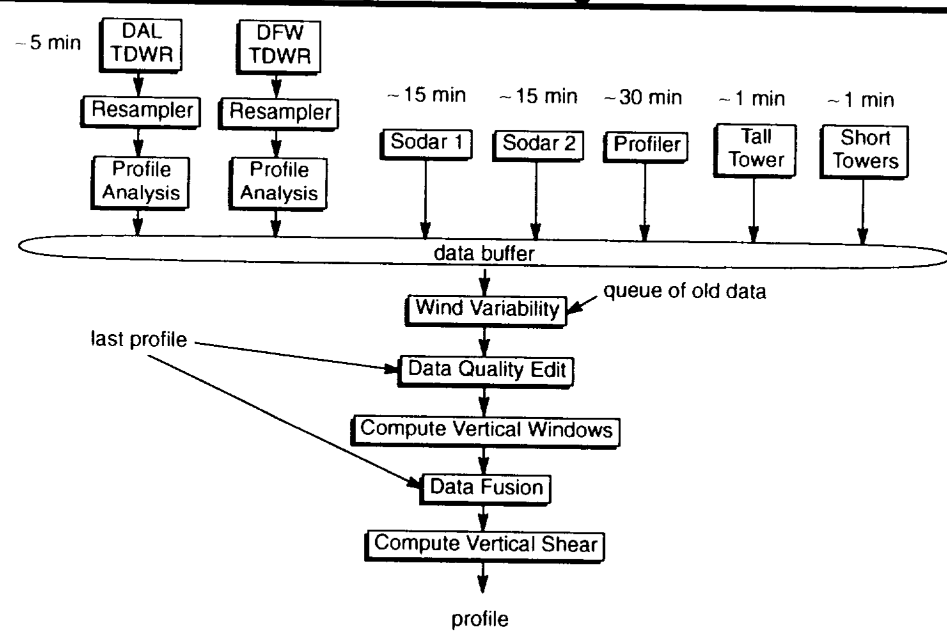
# System Design

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## Simple Example of the Data Fusion

- Given: Relationship between unknown and wind data:

$$\underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ \cos(\theta_1) & \sin(\theta_1) \\ \bullet & \bullet \\ \bullet & \bullet \\ \bullet & \bullet \\ \cos(\theta n) & \sin(\theta n) \end{bmatrix}}_{\text{A}} \underbrace{\begin{bmatrix} u \\ v \end{bmatrix}}_{\text{Unknown}} = \underbrace{\begin{bmatrix} u_0 \\ v_0 \\ u_1 \\ v_1 \\ r_1 \\ \bullet \\ \bullet \\ \bullet \\ r_n \end{bmatrix}}_{\text{Data}}$$

INITIAL EST.

VECTOR OB.

RADAR OBS.

- Given: Estimated error covariance matrix C
- Linear minimum variance unbiased estimate is:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \mathbf{(A^T C^{-1} A)^{-1} A^T C^{-1} Data}$$

- Error covariance of the solution is $(A^T C^{-1} A)^{-1}$

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## Full Set of Equations

- For each analysis point, solve system of equations (in least squares sense):
  - For each vector observation:
    - $u + u_x \Delta x + u_y \Delta y$ = $u$ initial or observed
    - $v + v_x \Delta x + v_y \Delta y$ = $v$ initial or observed
  - For each radar (radial) observation:
    - $(u + u_x \Delta x + u_y \Delta y) \cdot \cos\theta$
    - $+ (v + v_x \Delta x + v_y \Delta y) \cdot \sin\theta$ = radial observed
  - For each derivative:
    - $u_x$ = $u_x$ initial
    - $u_y$ = $u_y$ initial
    - $v_x$ = $v_x$ initial
    - $v_y$ = $v_y$ initial
- Return: $(u, v, u_x, u_y, v_x, v_y)$, and associated errors

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## Modeling Error Covariance

- Sensor (measurement) errors
  - How well does the sensor measure what it is intended to measure?
  - How well does the intended measurement fit the desired measurement?
- Displacement errors
  - What is the error due to the displacement of the observation from the analysis point?
  - Is this needed, since the goal is a regional average wind?

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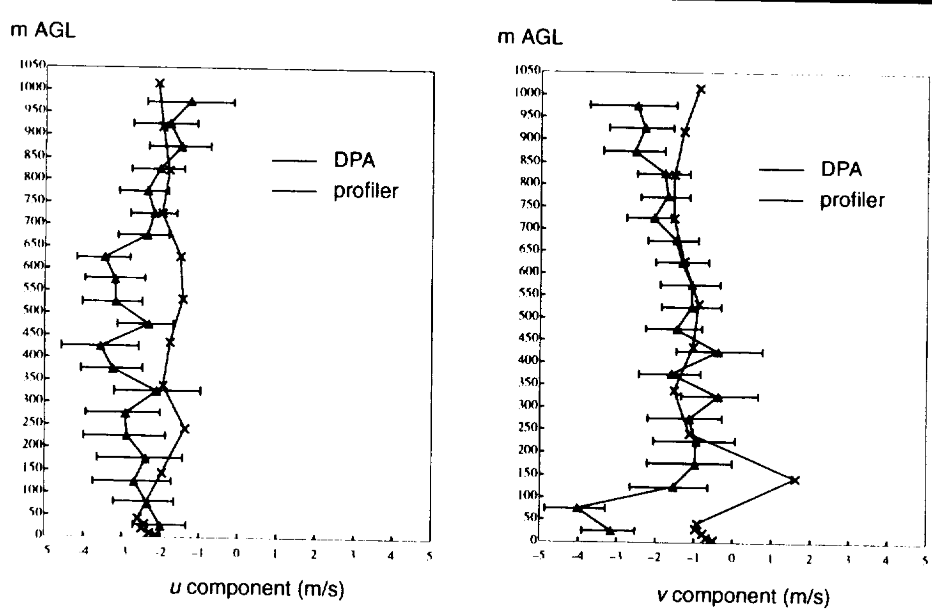
## DPA Preliminary Results

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## Development Status & Plans

- System design done
- Infrastructure coded and running
- Analysis modules coded and running:
  Radar Resampler, Doppler Profile Analysis,
  Wind Variability, Data QC, Data Fusion
- Analysis modules stubbed or waiting to be coded:
  Compute Vertical Windows, Compute Vertical Shear
- Expect to be running real–time in DFW shortly after sensors are providing data
- Expect iterative evaluation/refinement cycle
  - evaluation by humans and vs. balloon soundings

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## Summary

- AVOSS wind profiling system developed primarily to support real–time AVOSS operations
- Initial system is running (off–line) and an upgrade path is identified pending testing with DFW data
- Initial results are promising

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**Questions and Discussions Following Rod Cole's Presentation (MIT Lincoln Lab)**

David Burnham (SESI)
Have you got any plans to use the sodar intensity returns to help you identify inversion layers?

We have discussed that and we have had mixed comments on how well it correlates with the inversion layer. And so we do not have any current plans to do that.

Jim Evans (Lincoln Lab)
I think we also have to be careful on understanding in this 30 minutes that winds are going to be the principal focus in an initial AVOSS in the sense that winds get vortex out of correction. We are going to have to be careful in identification of the changes in the wind. You may recall that was one of the problems that happened at O'Hara was that the thing kept going from red to green, the fact that it was stable for awhile kept changing on you. We have to understand there have been systems like ITWS, TWS for the FAA that identify wind changes, but those are a little better than the change we are talking about here. As you push down to even smaller changes, the difficulty is if it is really windy, no problem. Unfortunately, it is not really windy that much of the time. So you are going to have to get down closer and closer to the threshold to find greater fractions of time where just a wind alone algorithm will work. When you do that it means you are going to have to push on this business of spotting changes. Now you have an advantage, you got a lot of sensor down there, you can see change coming, but there are a lot of funny little quirks out there in the field. I think that people should understand though we have systems that are fairly good at identifying runway shifts, there may be a class of shifts that we are talking about which are a lot smaller than that.

**FIRST WAKE VORTEX DYNAMIC SPACING WORKSHOP**
**NASA LANGLEY RESEARCH CENTER**
**MAY 13-15, 1997**

**Peter Zwack**

**Robert Tardif**

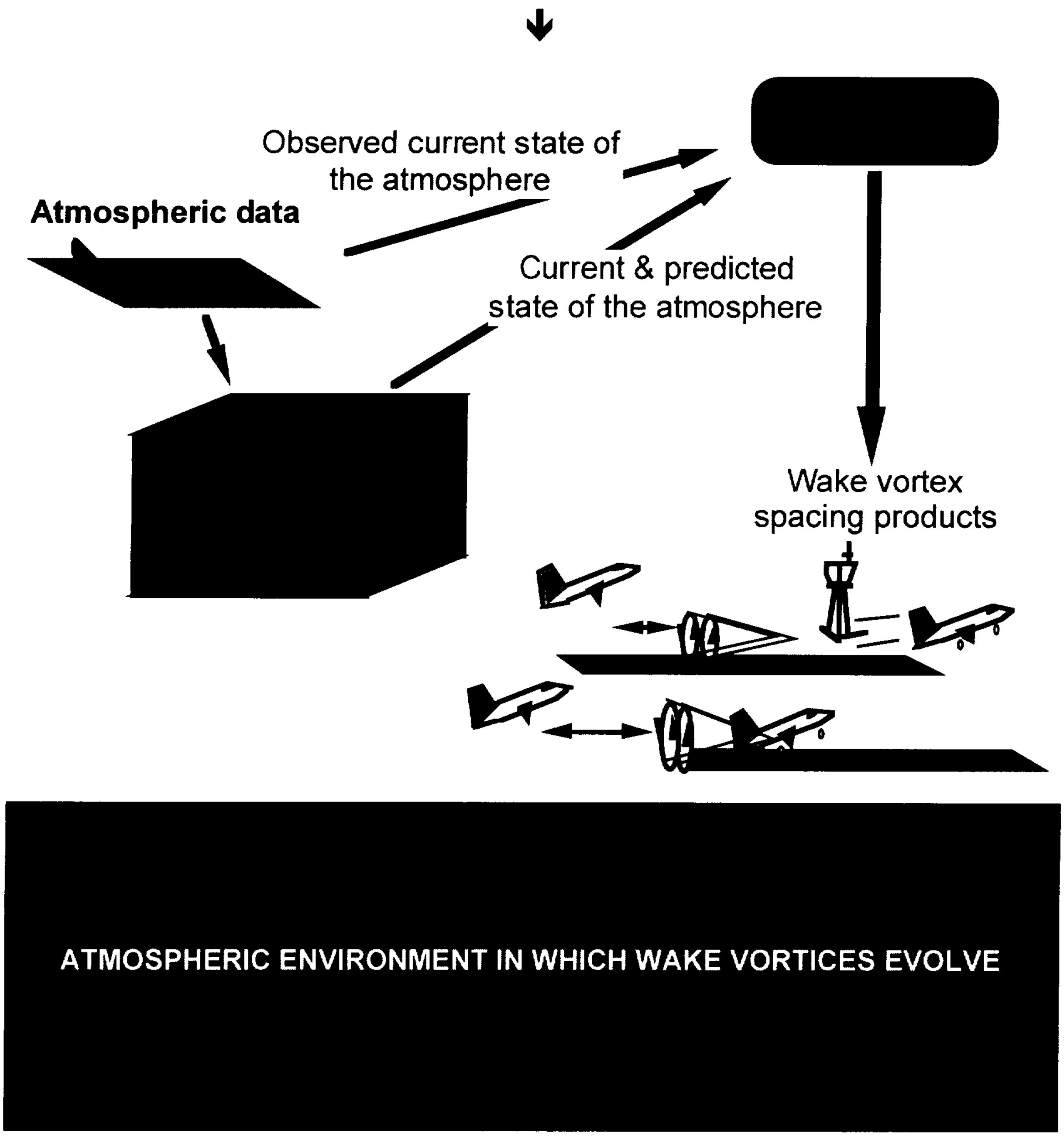
**Université du Québec à Montréal**
**Atmospheric Sciences**

**&**

**Montreal Cooperative Center for Research in Mesometeorology**

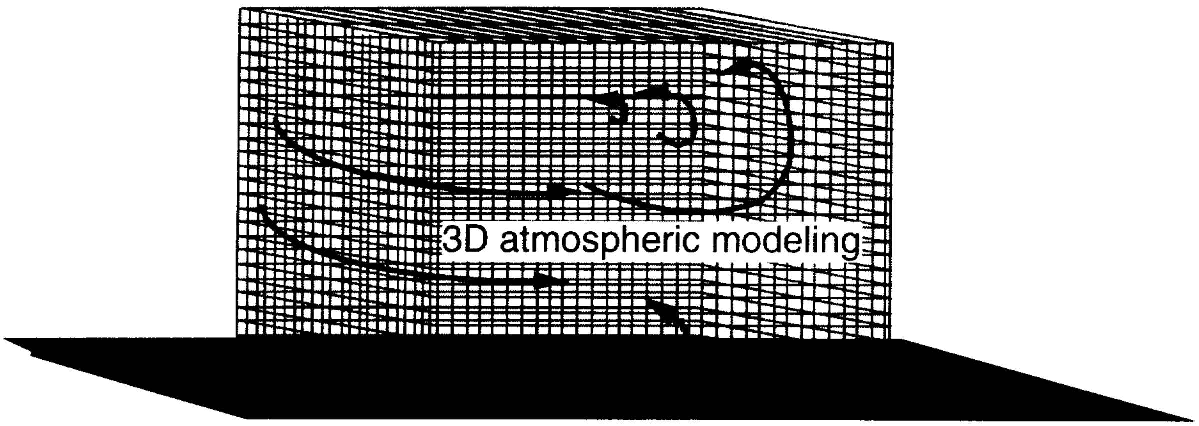
## • 1 INTRODUCTION

### Providing meteorological support to AVOSS



## • 2 ONE-DIMENSIONAL MODELING CONCEPT

**Ideal solution:** Models resolving all relevant physical phenomena




requires :

- very high-resolution
- detailed physics (not all of which is known)
- very accurate numerical methods
- efficient data assimilation techniques
- "super-supercomputers"

↓

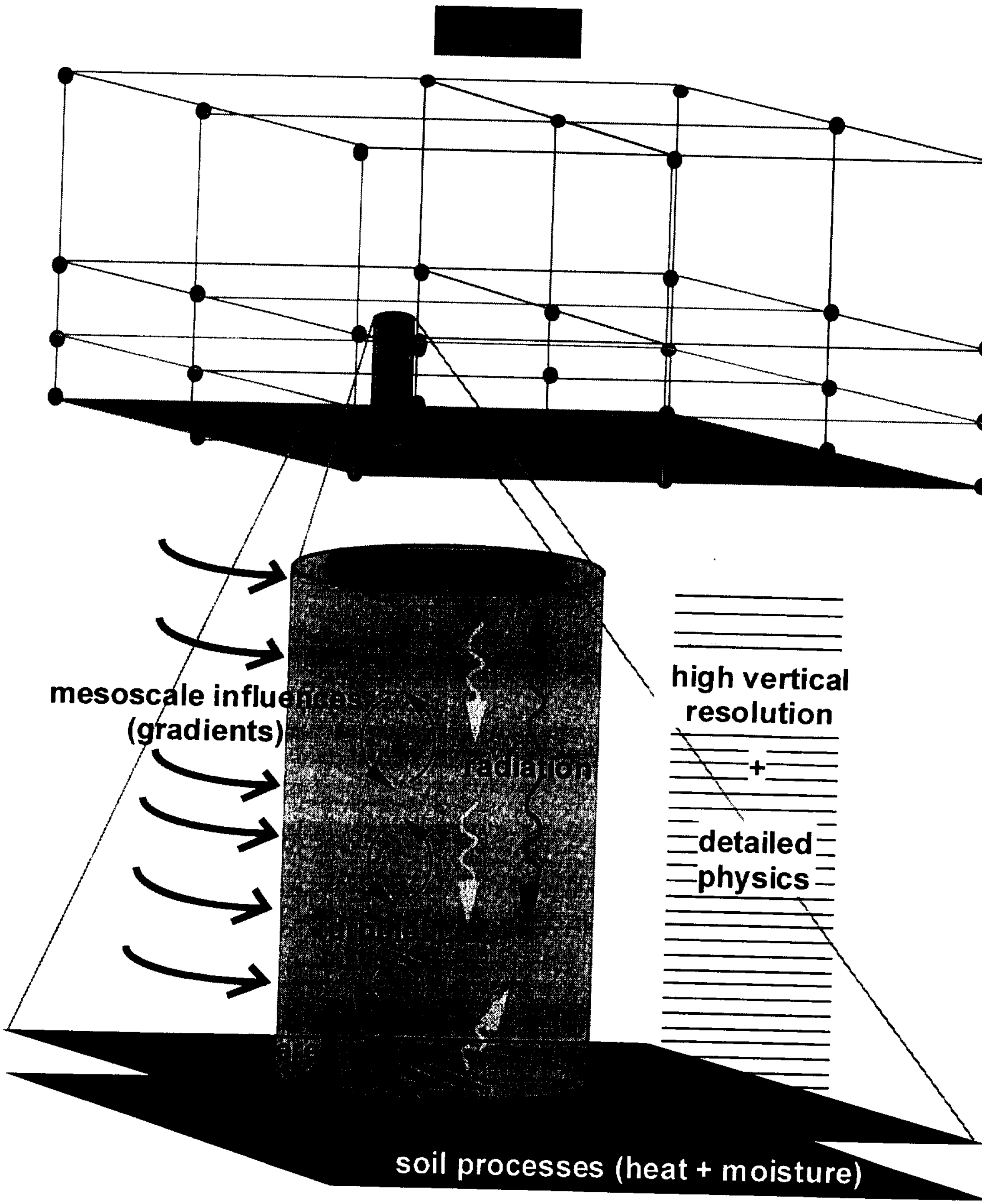
currently the topic of basic research

**Operational alternative ➔**

**Use of existing state-of-the-art 3D mesoscale models**

**with a nested detailed 1D model**

# Column model approach



## • 3 Overview of COBEL

### Historical perspective

1982

[redacted]

◆ COBEL prototype developed at Laboratoire d'Aérologie, Université Paul Sabatier, Toulouse, France (study of dry nocturnal boundary layer, Estournel and Guédalia, Bound. Lay. Met.)

1987

◆ COBEL prototype used to study the formation of radiation fog (Monneris, Ph.D. thesis)

1988

[redacted]

1991

◆ Development of a numerical fog forecasting method based on COBEL (Bergot and Guédalia, Mon. Wea. Rev.)

◆ Extending COBEL to include a wider range of phenomena (UQAM, 1993 ...)

1994

◆ COBEL tested in pre-operational mode, with a 90% success rate over 229 cases, with 54 cases of observed fog -> 3 winters worth of data (Bergot and Guédalia, La Météorologie)

◆ Operational adaptation of COBEL for fog forecasting at Météo-France for the Nord-Pas de Calais region (1995...) 1995

[redacted]

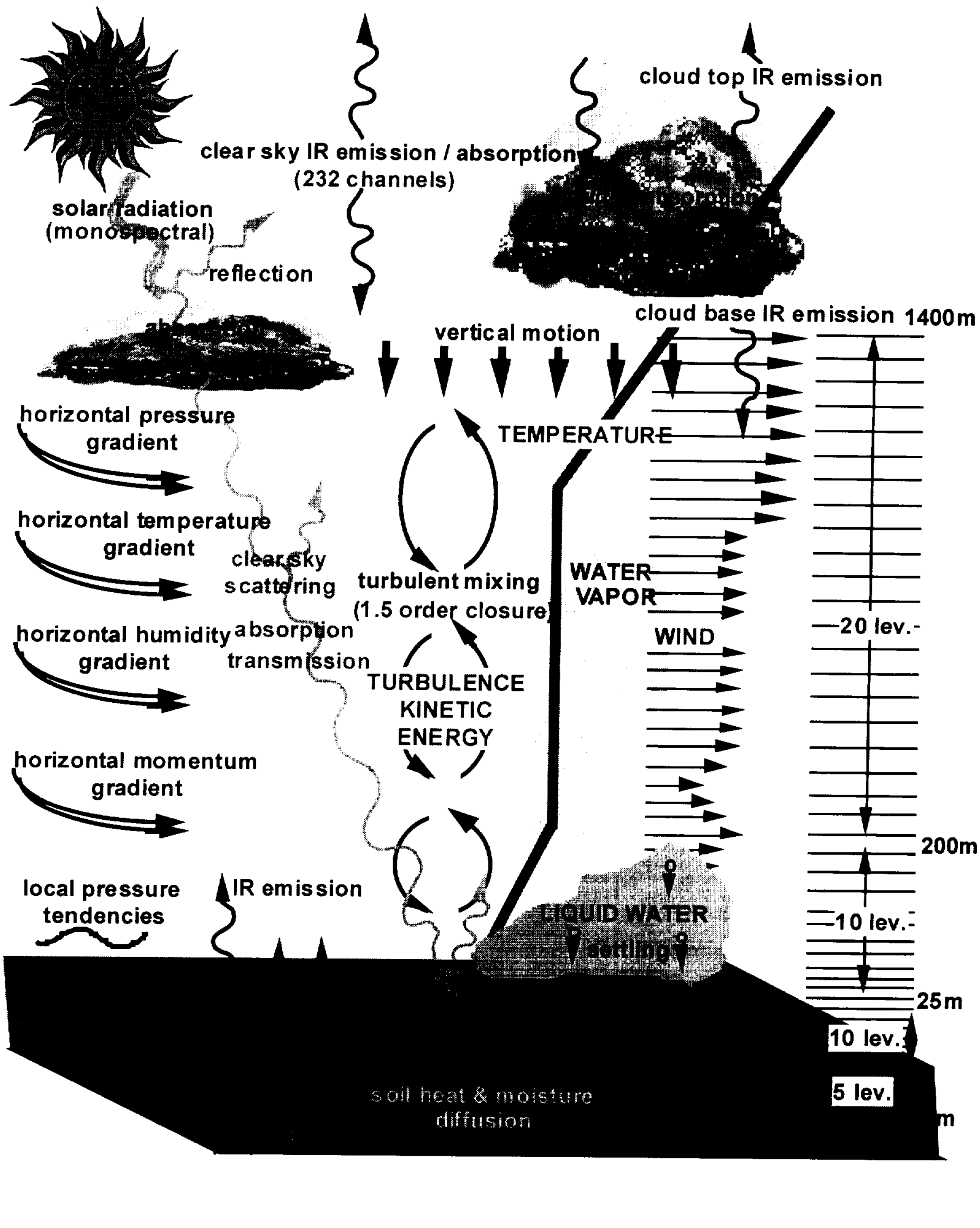
1996

◆ COBEL validated in daytime situations using Memphis data

◆ Adapt COBEL to support AVOSS

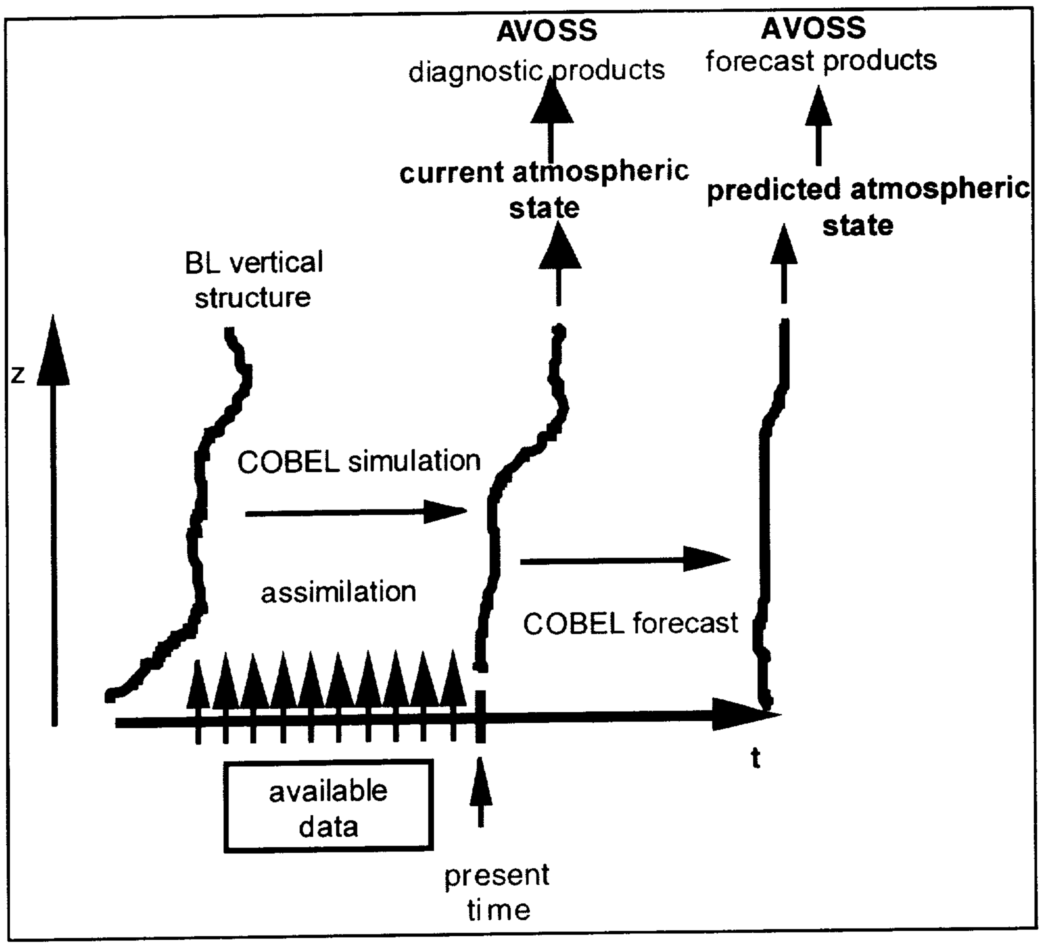
•
•
•

## COBEL & physical processes



## • 4 COBEL CONFIGURATION FOR DFW

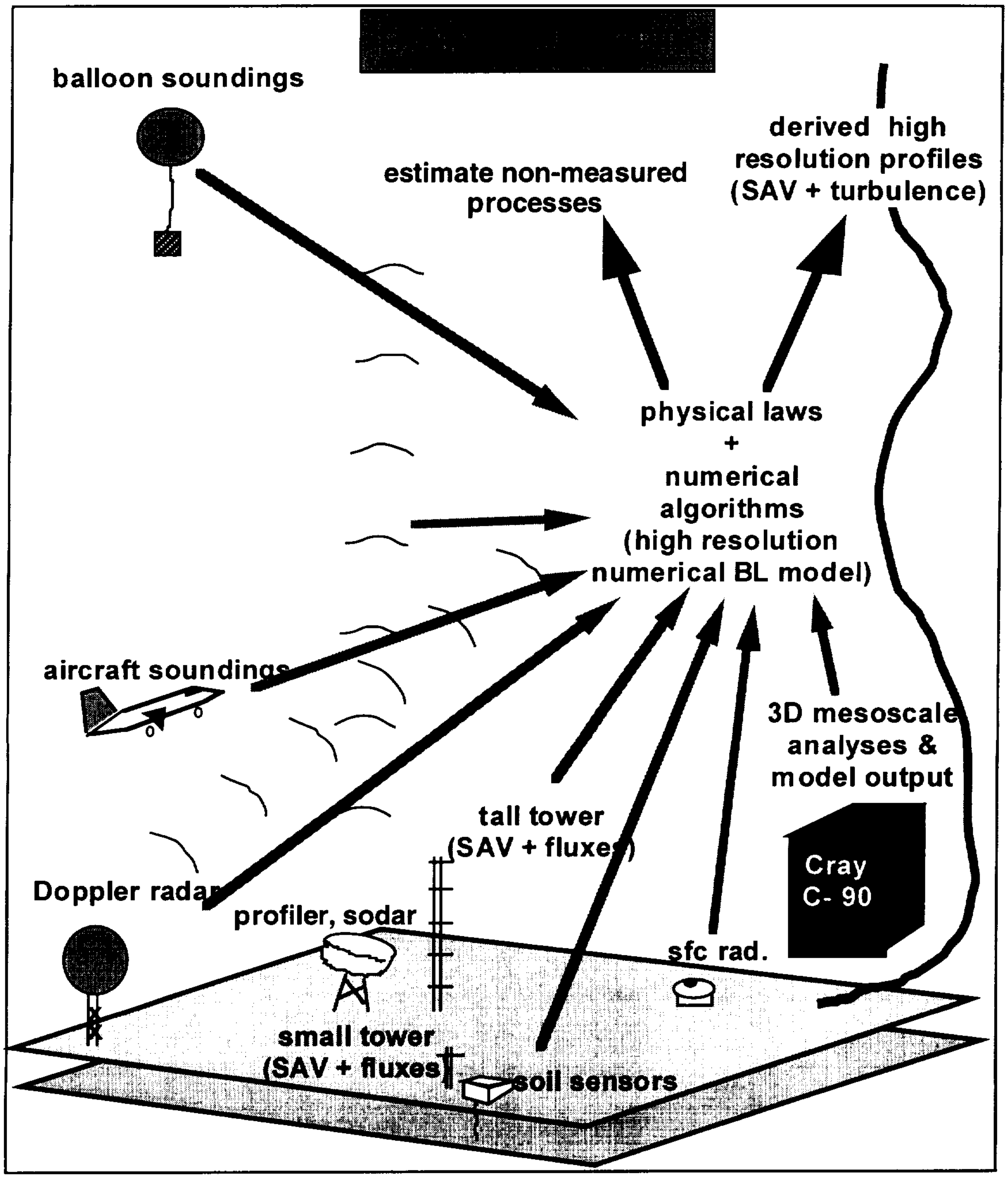
AVOSS support (diagnostic + forecast)



## Current atmospheric state :

## Concept :

- Use a numerical model as a "physical" interpretation tool and interpolator of boundary layer data



## Current design of COBEL : testing of 3 different assimilation configurations

---

- Level 1 : "basic" configuration

  assimilation of "standard" meteorological variables:

  - screen height (2m) temperature and humidity
  - 10m wind

- Level 2 : "enhanced" configuration

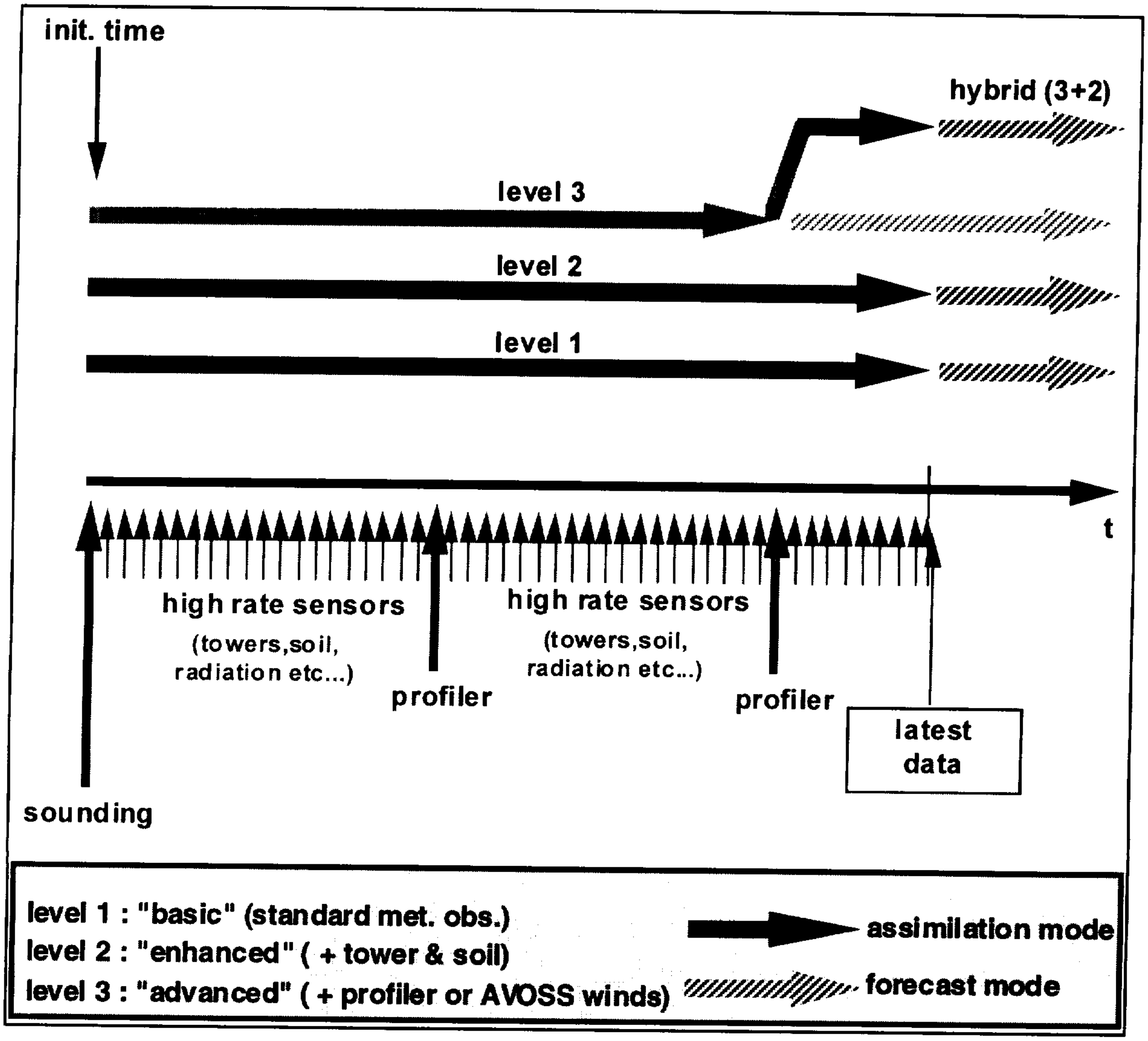
  - screen height (2m) temperature and humidity
  - 10m wind
  - <u>surface total (IR + solar) incoming radiation</u>
  - <u>soil temperature (1 level)</u>
  - <u>40 m tower (temperature, humidity, wind at 5 levels)</u>

- Level 3: "advanced" configuration

  - screen height (2m) temperature and humidity
  - 10m wind
  - surface total incoming radiation
  - soil temperature (1 level)
  - <u>40 m tower (temperature, humidity, wind at 5 levels)</u>
  - <u>profiler or AVOSS horizontal wind</u>
  - <u>profiler temperature (RASS)</u>

[illegible] at grid levels [illegible]

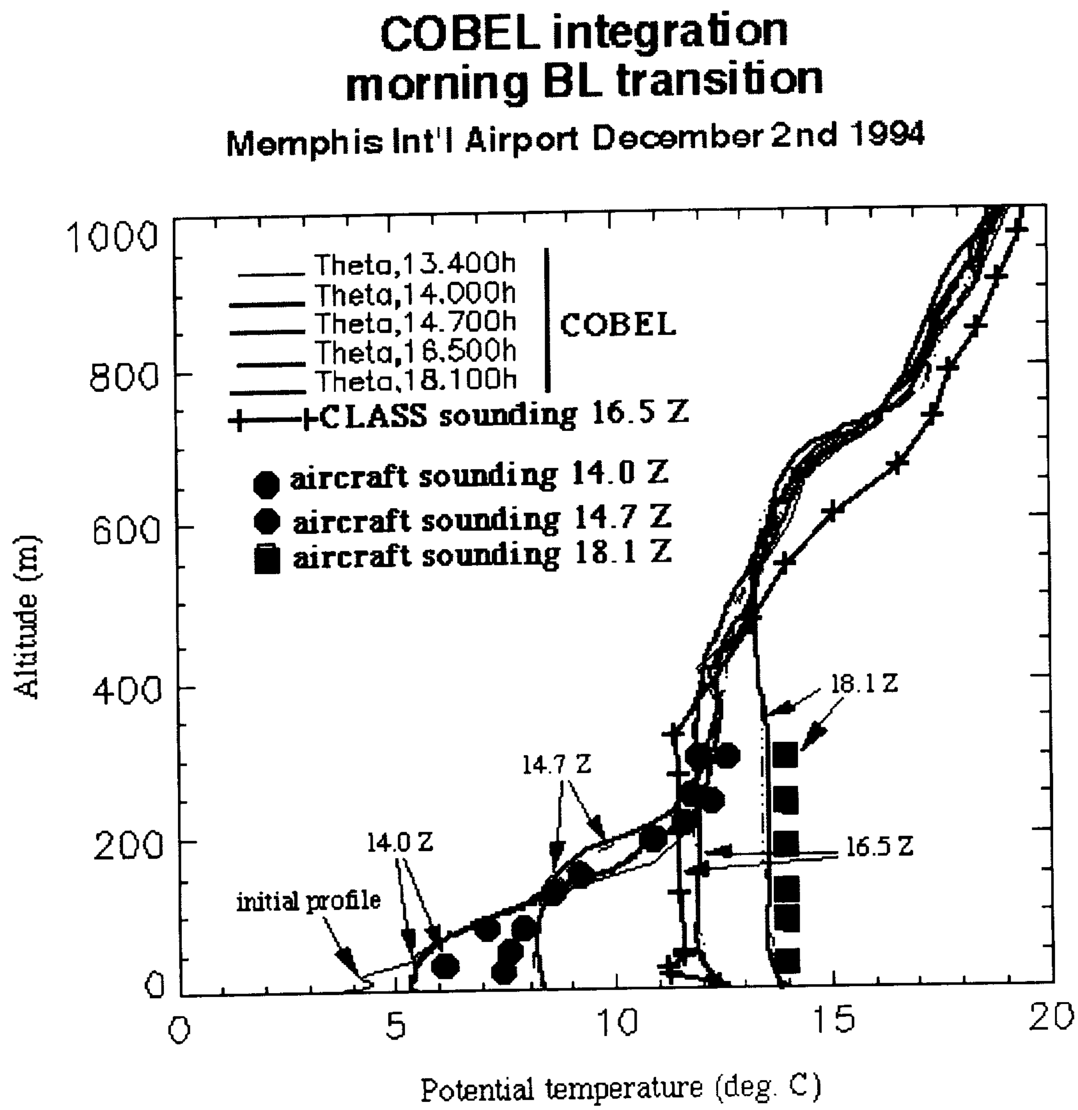
# COBEL/DFW assimilation cycle:



## • 5 VALIDATION EFFORTS

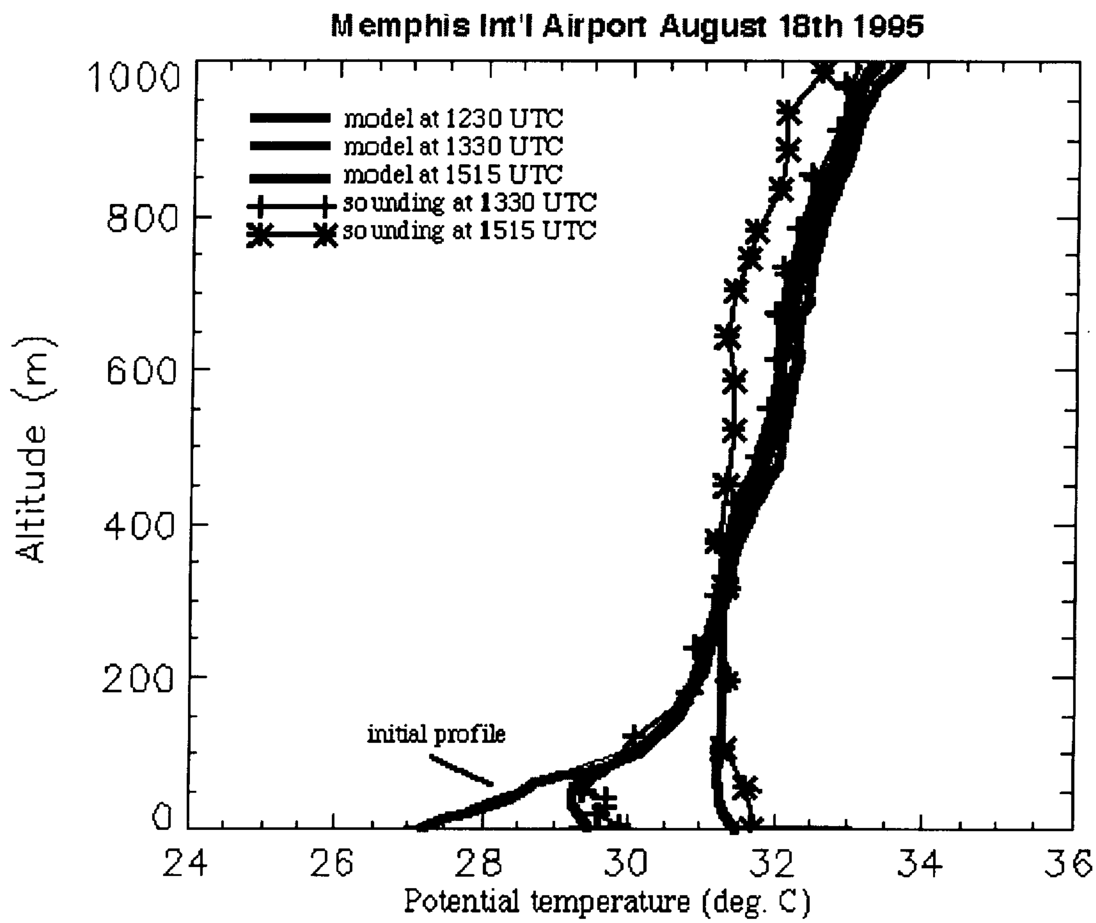
### Simulation of cases from Memphis Wake Vortex field measurement program

### (forecast mode)



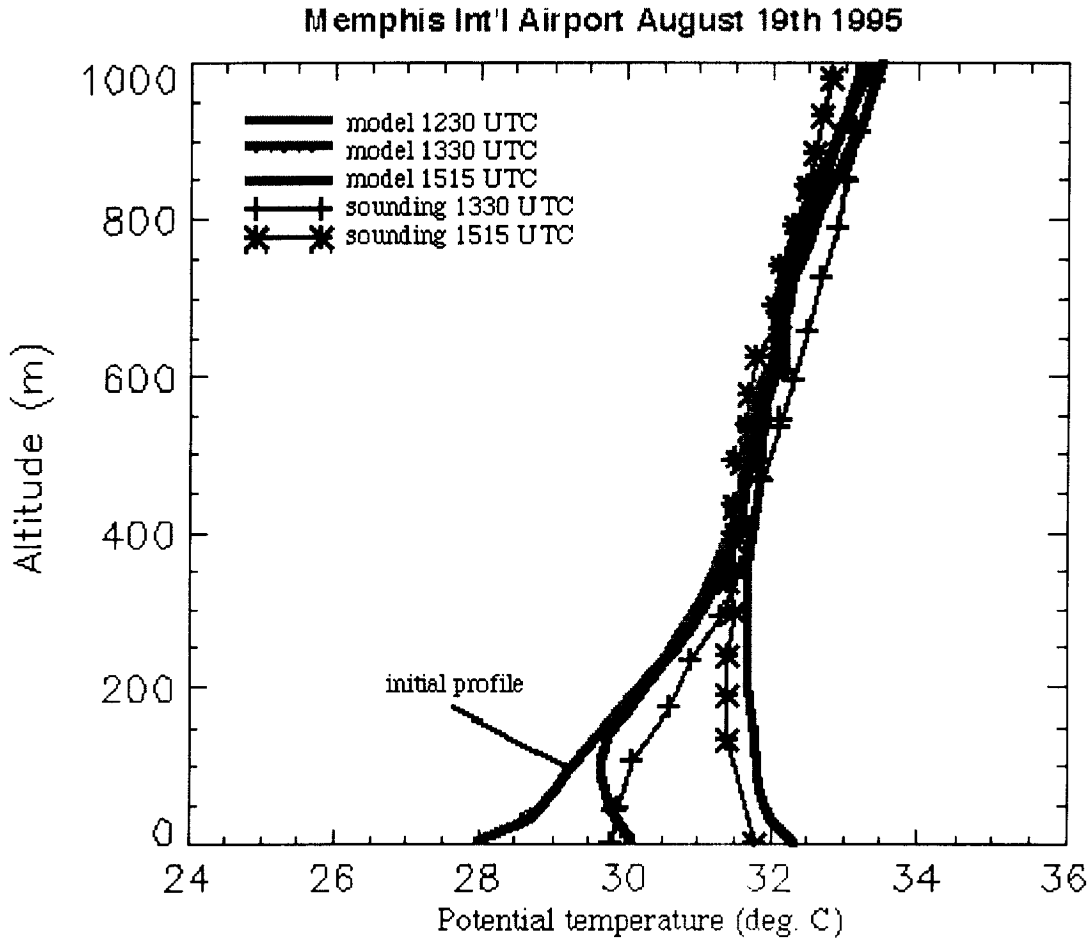
## forecast mode

## COBEL integration
## morning BL transition



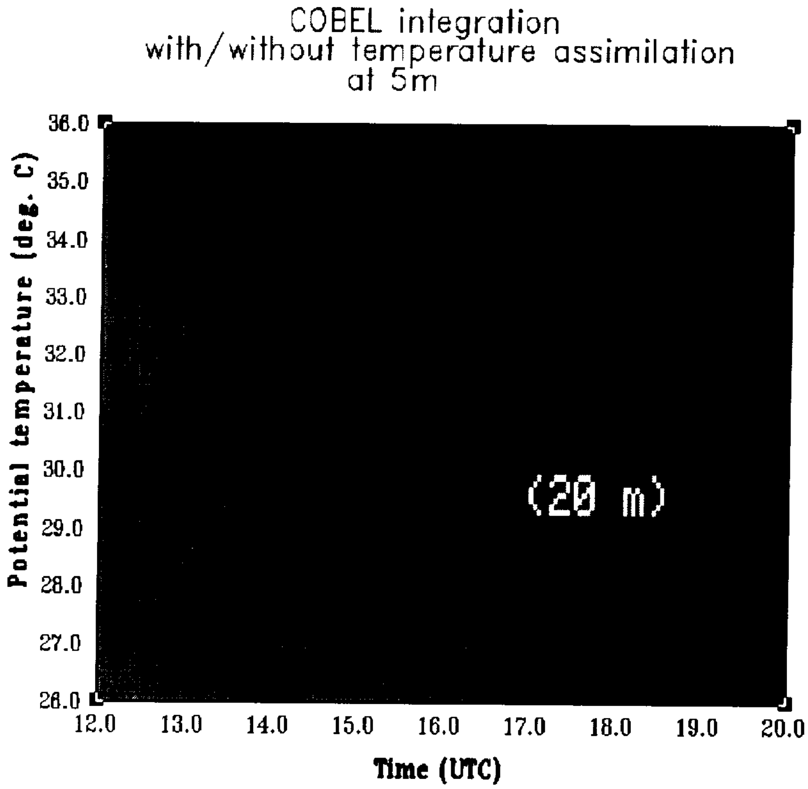
## forecast mode

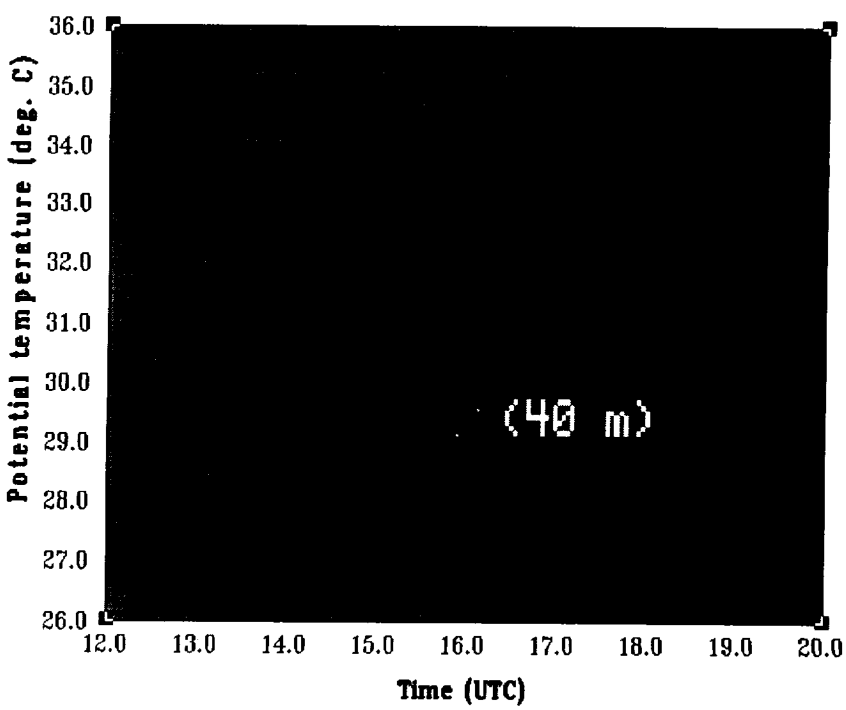
## COBEL integration morning BL transition



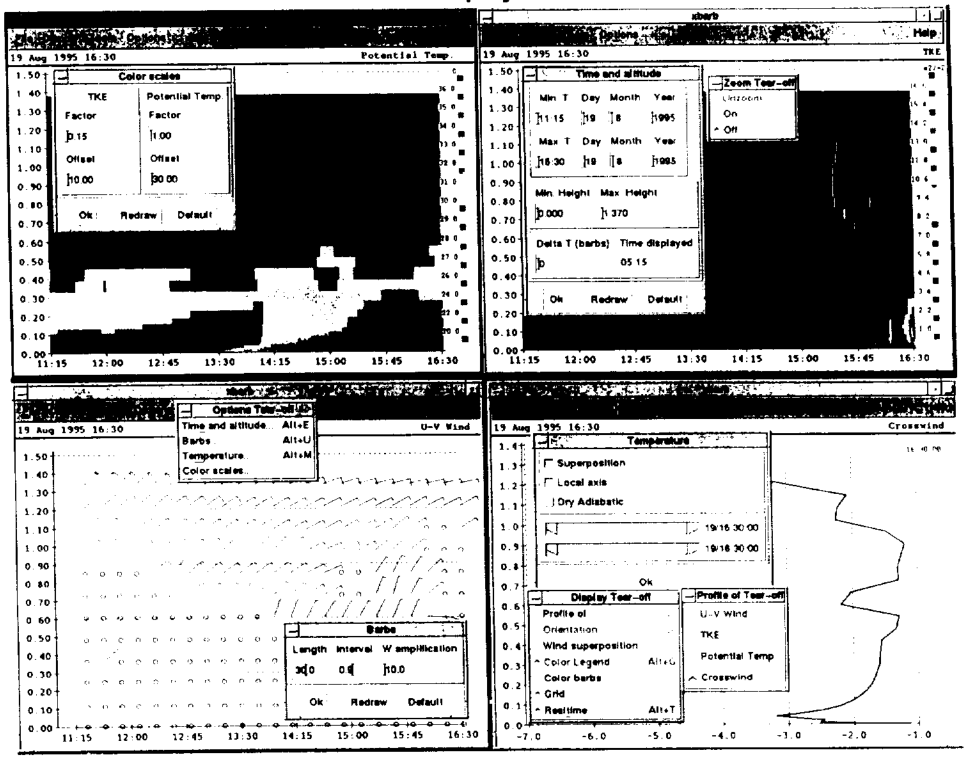
## Assimilation experiments

## Memphis Int'l airport, August 18th 1995



## COBEL display for DFW




First AVOSS Workshop, May 13-15,1997 15 P. Zwack, R. Tardif, U. of Quebec at Montreal

- **6 SHORT-TERM PERSPECTIVES**

- **Operational COBEL prototype at DFW (June 1997)**
- **Implementation of additional physical processes into COBEL (December 1997)**
- **Evaluation & problem detection of COBEL / DFW prototype (June - December 1997)**
- **Design and implement improvements (1998...)**

**Questions and Discussions Following Peter Zwack's Presentation (University of Quebec)**

Fred Proctor (Langley)
Have you done any validation studies of TKE profiles?

Zwack
No, not for the COBEL model. There was a comparison study model from Laboratoire D'Aerologie. They compared with LES TKE and they were quite similar.

Proctor
There is TKE data from Memphis and it might be interesting to work some comparisons.

Pal Arya (North Carolina State Univ.)
In terms of the standard PBL terminology, is it right that your COBEL model is a TKE closure model?

Zwack
Yes.

Arya
The model is primarily for horizontal homogeneous flat terrain is it not?

Zwack
Well, the idea is that you bring in inhomogenuity using mesoscale model, or data. In this case we have data also.

Arya
But you are bringing in height dependent variables, not the horizontal gradients.

Zwack
Yes, that is what I said, the horizontal gradients will come from either observations or mesoscale.

Arya
So model has evection terms in it?

Zwack
Yes, yes it does.

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# *The Application of Mesoscale Numerical Weather Prediction Models to the Terminal Area and Examples from Memphis 1995 Field Data*

*Michael L. Kaplan, Ronald P. Weglarz, Yuh-Lang Lin, Adam H. Langmaid, and David W. Hamilton*

Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina 27695-8208

NASA First Wake Vortex Dynamic Spacing Workshop
Langley Research Center (LaRC)
15 May 1997

North Carolina State University

ABSTRACT

This presentation will focus on the new weather forecast system which is designed to support AVOSS, i. e., the Terminal Area Planetary boundary layer Prediction System (TAPPS). The system will be described in terms of its two primary components which represent state-of-the-science mesoscale numerical weather prediction models. The first component is the Mesoscale Atmospheric Simulation System (MASS). This numerical model is designed to simulate phenomena which have spatial scales>100 km and temporal scales of 3 hours or greater. It is initialized from synoptic scale data including radiosonde, wind profiler, satellite, radar, and surface observations. MASS will then act to provide the initial and lateral boundary conditions for a cloud/LES scale numerical model known as the Terminal Area Simulation System (TASS). TASS then enables the forecast system to be applied to the county scale/aviation terminal area for time periods of <3 hours with a specific focus on predicting localized planetary boundary layer phenomena. TASS will be further updated and enhanced by the assimilation of local terminal area observations.

One of the most important aspects of short period local terminal weather is the problem of rapidly developing low-level jet streams. These wind maxima can have a dramatic effect upon the transport and dynamics of wake vortices just above the earth's surface. In this presentation we will focus on a TAPPS (Stage II) simulation from a case study exhibiting the strongest low-level nocturnal jet observed during the Memphis 95 field experiment and how said simulation verified against these special observational data sets. We will also compare the TAPPS (Stage II) product to one derived from the National Weather Service operational numerical model.

# Presentation Overview

- What is TAPPS? (Terminal Area Planetary Boundary Layer Prediction System)
- Observational Evidence of Nocturnal Low-Level Jets at Memphis
- National Weather Service (NWS) Model Simulations of Nocturnal Low-Level Jets
- TAPPS Mesoscale Model Simulations of Nocturnal Low-Level Jets

# What is TAPPS?

- County/Terminal Area Aviation Scale PBL Weather Prediction System
- Focuses on the Space-Time Evolution of the Planetary Boundary Layer (PBL) for 1-3 hour time periods
- Mesoscale Atmospheric Simulation System (MASS)
- Terminal Area Simulation System (TASS)
- PURPOSE IS TO PREDICT RAPID DEVELOPMENT OF PBL WINDS WHICH AFFECT WAKE VORTEX TRANSPORT WITHIN TERMINAL AREAS

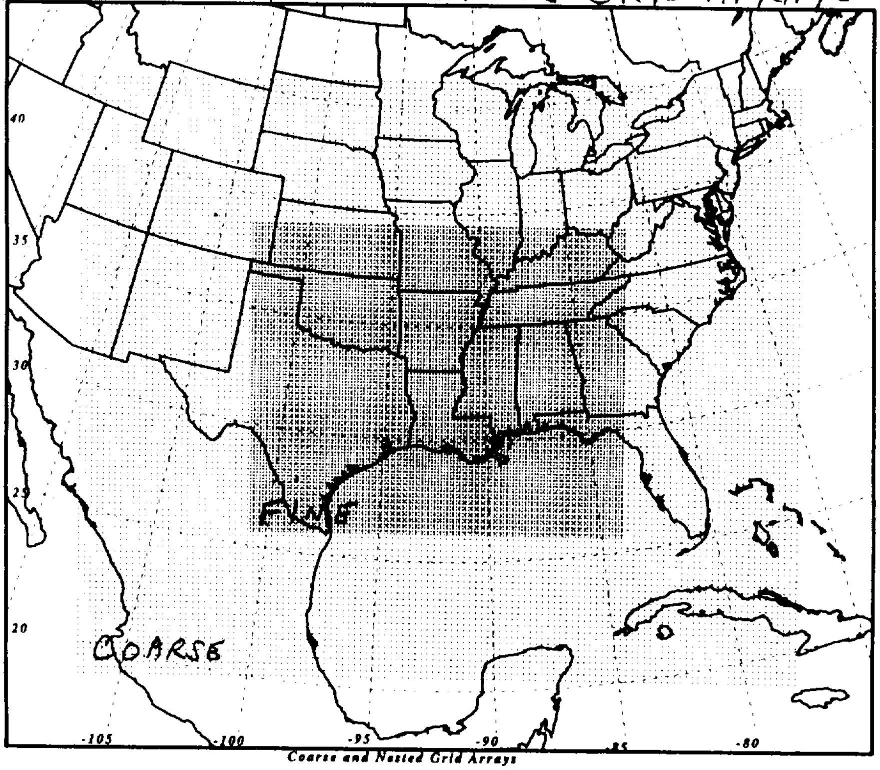
North Carolina State University

# Mesoscale Atmospheric Simulation System (MASS)

- MASS is a 3-dimensional, hydrostatic, terrain-following Meso-$\alpha/\beta$ Scale Numerical Weather Prediction Model
- MASS is initialized from comprehensive, 3-dimensional data sets including radiosonde data, surface data, satellite and radar-derived data sets (WIND PROFILERS)
- MASS employs a horizontal grid resolution of 10-30 km
- MASS employs comprehensive PBL and cumulus parameterization schemes
- MASS DEVELOPED UNDER NASA CONTRACT AND USED FOR RESEARCH AND OPERATIONS BY NASA SINCE 1979 AT GSFC, LARC, MSFC, KSC

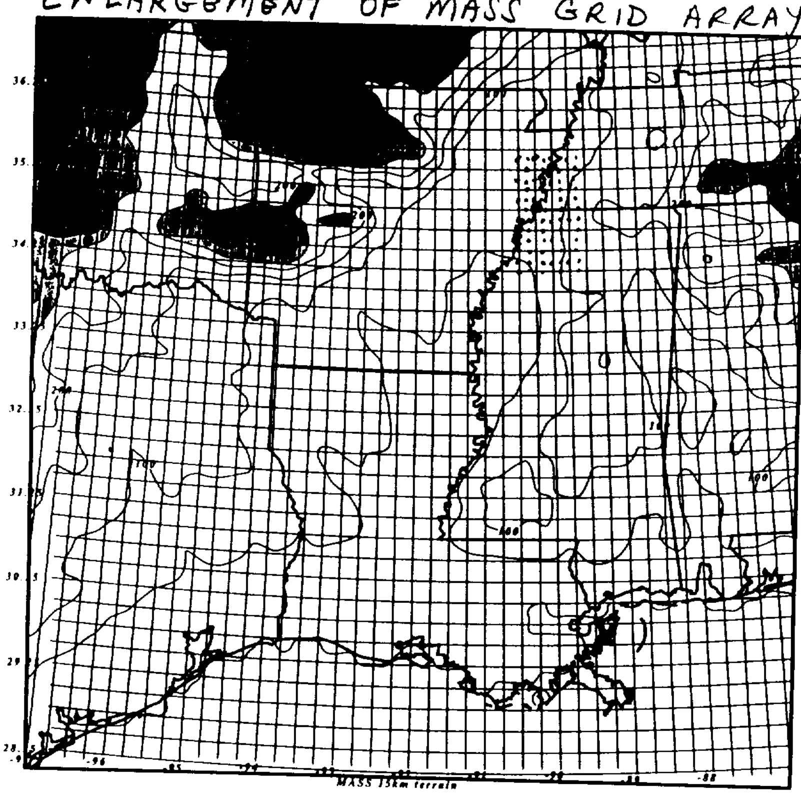
North Carolina State University

MASS MEMPHIS SIMULATIONS GRID ARRAYS




Coarse and Nested Grid Arrays

ENLARGEMENT OF MASS GRID ARRAYS



MASS 15km terrain

# Observational Evidence of Nocturnal Low-Level Jets at Memphis (August, 1995)

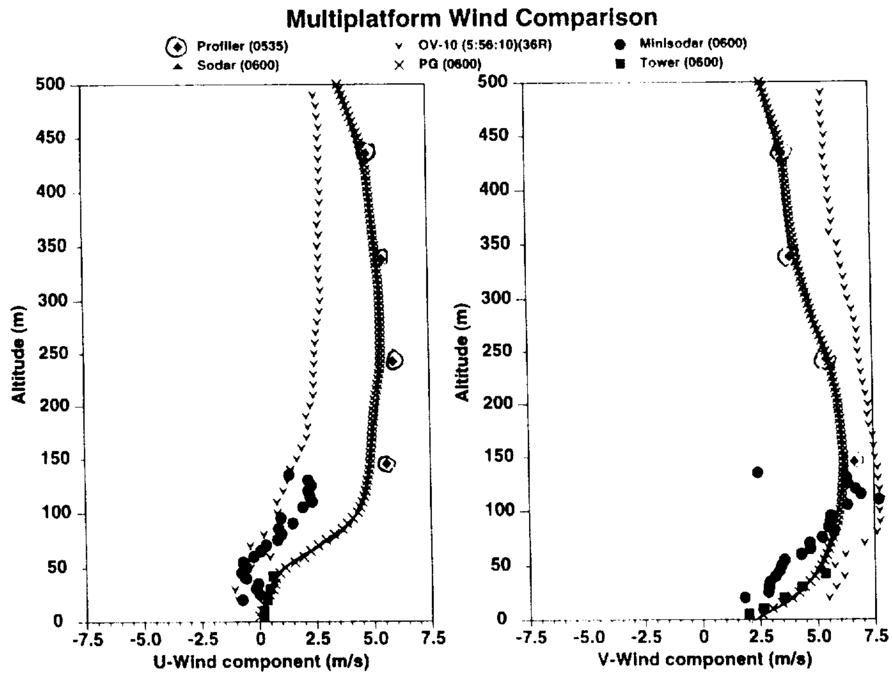
- Multi-Platform Wind Observations at Memphis
- MIT-Lincoln Labs 5-minute Wind Profile Time Sections
- Aviation Hourly Surface Wind Observations
- Rawinsonde 12-hourly Wind Observations
- Observed Mechanisms for Nocturnal Low-Level PBL Jet Formation

North Carolina State University

# Terminal Area Simulation System (TASS) 3-D LES Model

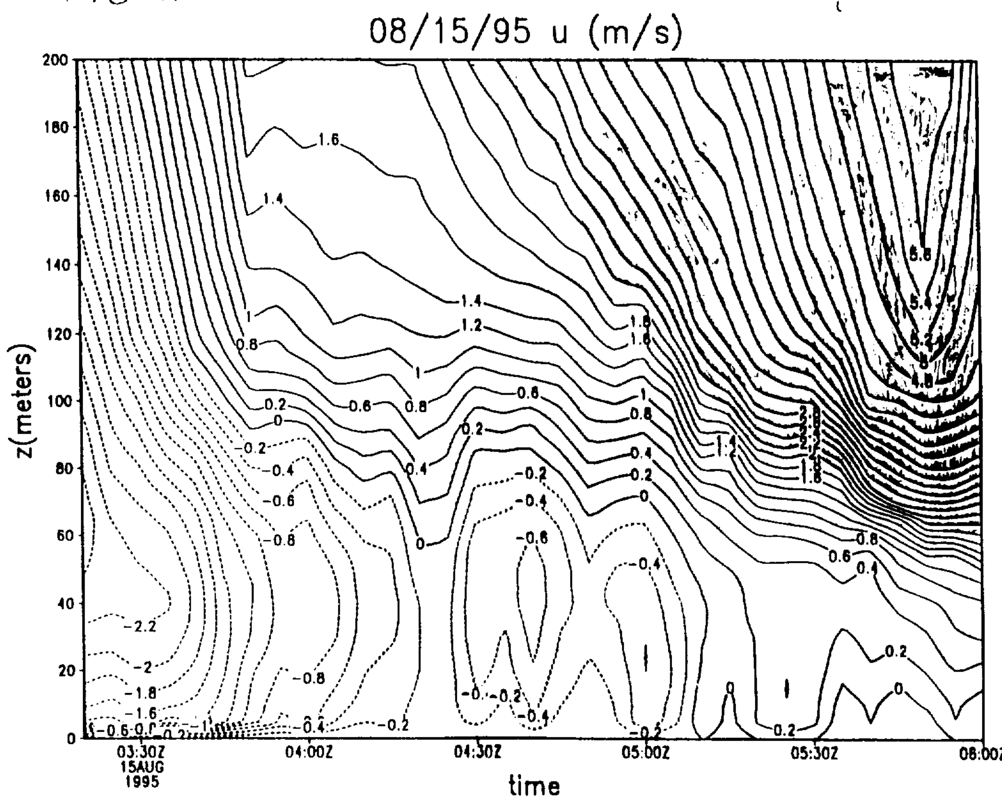
- TASS is a 3-dimensional, nonhydrostatic, Cloud/ Large-Eddy Scale (LES) Simulation Model
- TASS will be nested within MASS
- TASS will be initialized from MASS model simulated fields
- TASS will employ a horizontal grid resolution of 100 m - 10 km
- TASS employs state-of-the-science turbulence closure schemes and explicit cloud, liquid water, ice, snow etc. microphysics
- TASS capable of explicitly resolving large eddies and individual cloud elements within the PBL
- Local airport observations will be assimilated into TASS

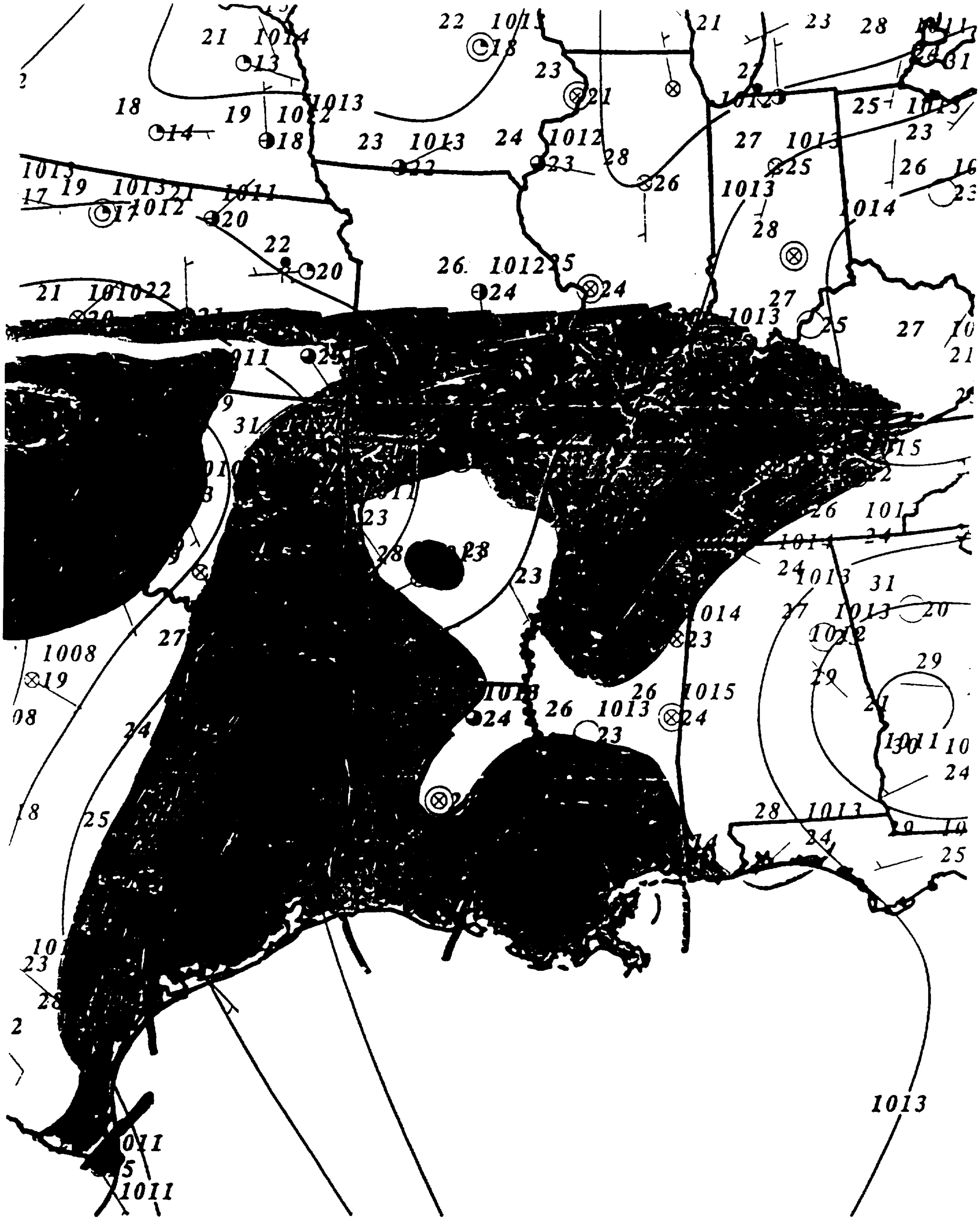
MEMPHIS (8/15/95)



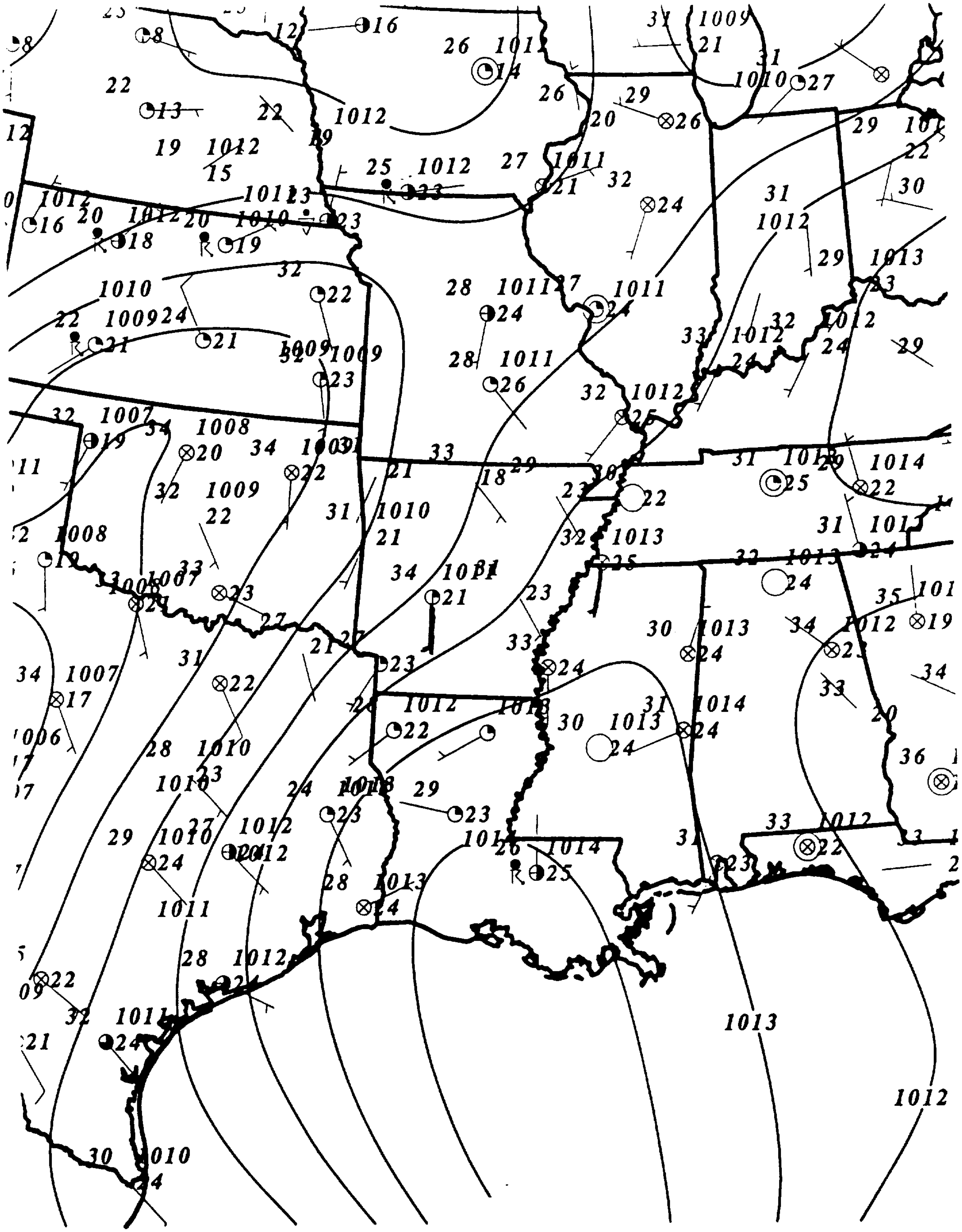

Date: 08/15/95

MEMPHIS OBSERVED





8 15 95 0300 00Z – 03Z ΔT SFC

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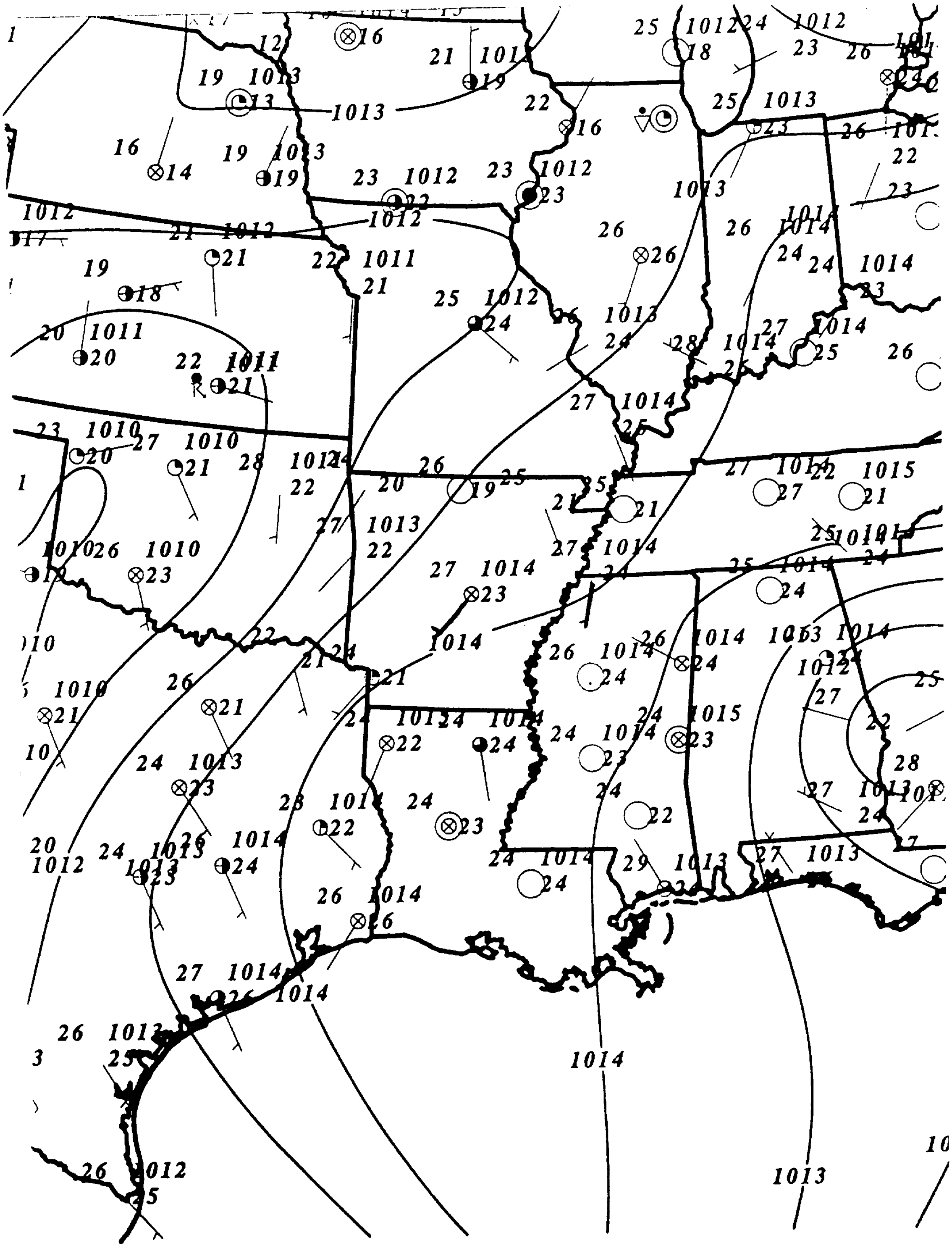
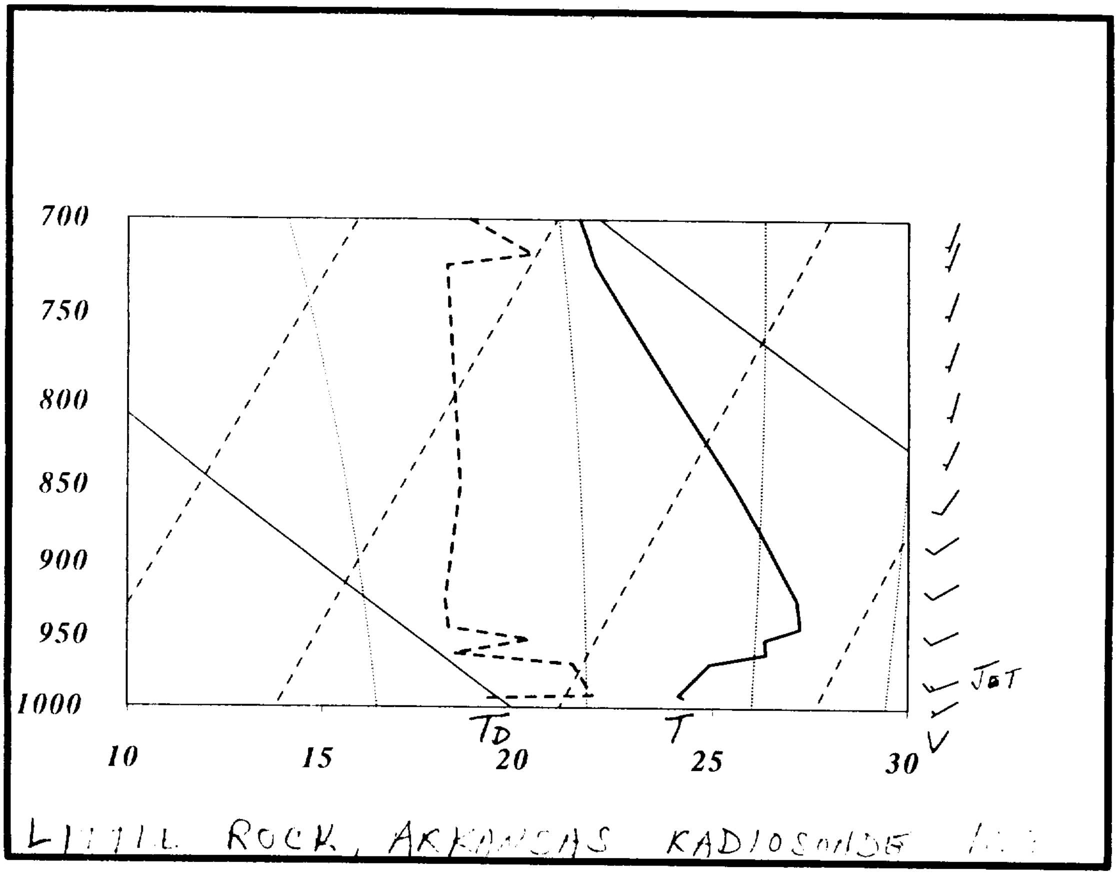
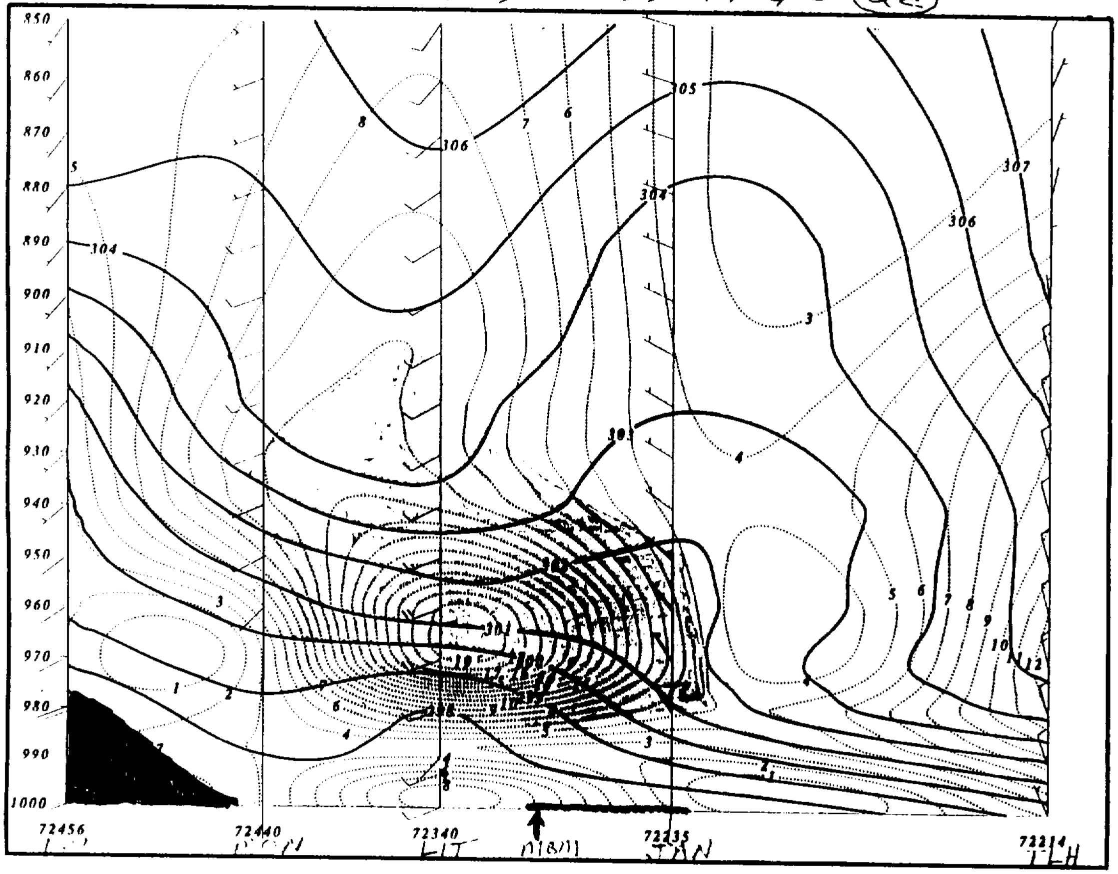





θ-(SOLID) + ISOTACHS (m/s; DOTTED) 95/08/15-(12Z)

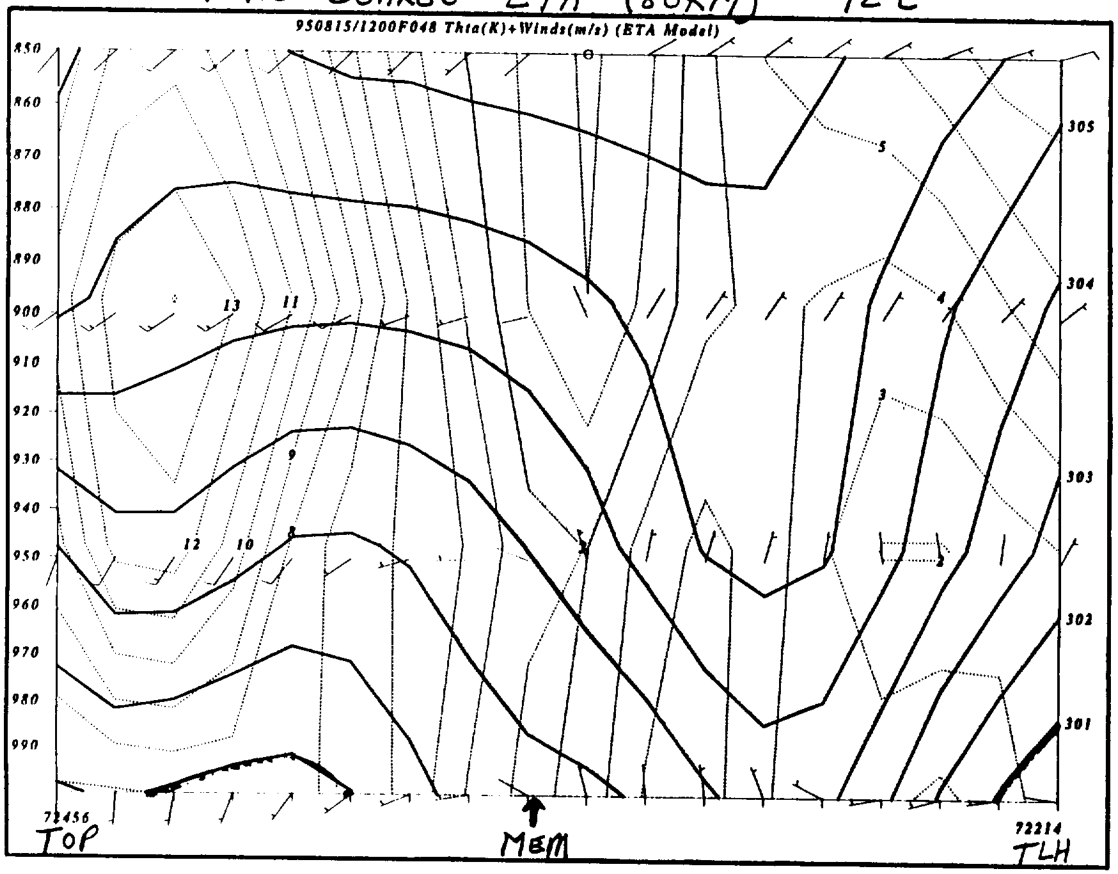


# National Weather Service (NWS) Model Simulations of Nocturnal Low-Level Jets

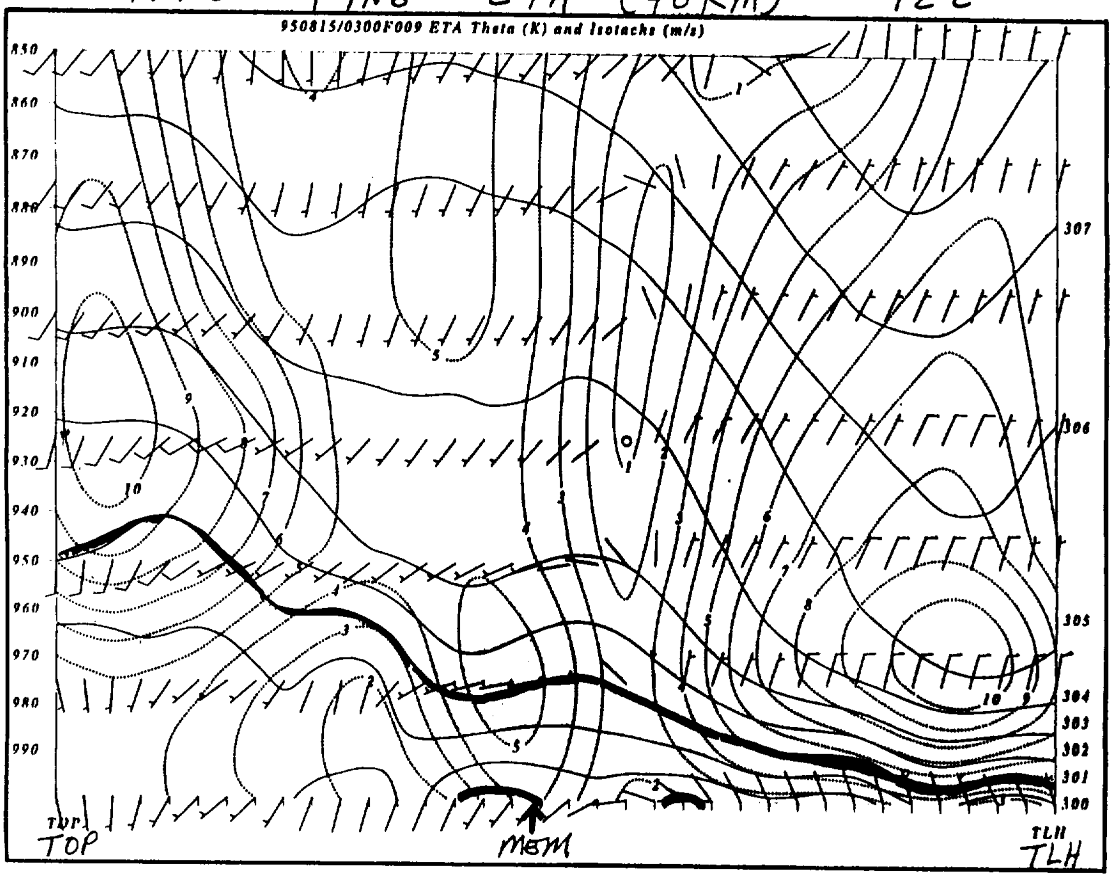
- Coarse Mesh ETA Numerical Weather Prediction Model Forecast
- Fine Mesh ETA Numerical Weather Prediction Model Forecast
- NWS Time-Interpolated Vertical Wind Shear and Turbulence Products

North Carolina State University

NWS COARSE ETA (80KM) 12Z



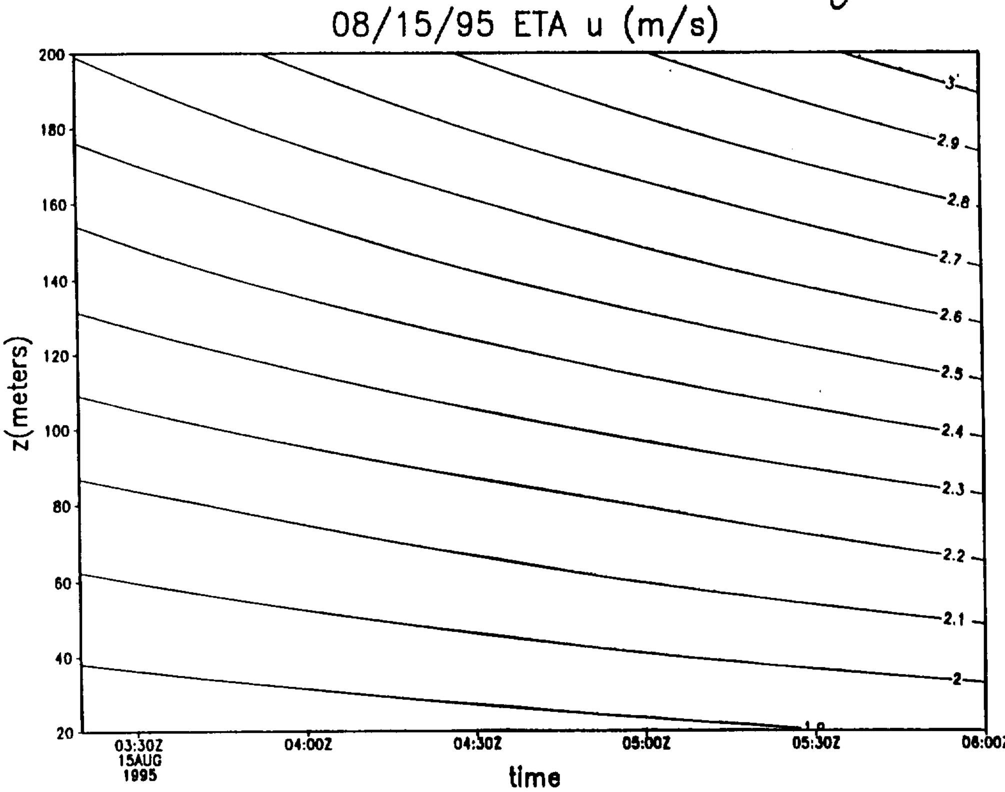

NWS FINE ETA (40KM) 12Z

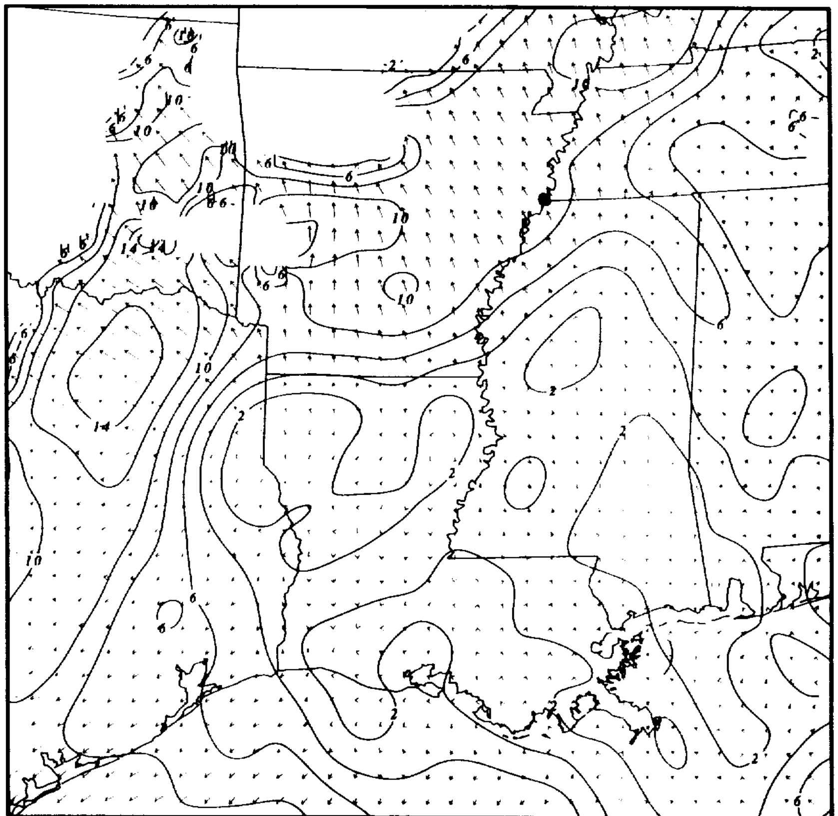


# TAPPS Simulations of Nocturnal Low-Level Jets

- MASS Fine Mesh Simulated Presssure Gradient Force (PGF) Vectors
- MASS Fine Mesh Simulated 3D PBL Jet Profiles
- TAPPS Time-Interpolated Vertical Wind Shear and Turbulence Products
- Comparison with NWS Products
- Comparison with NWS Products and Observations

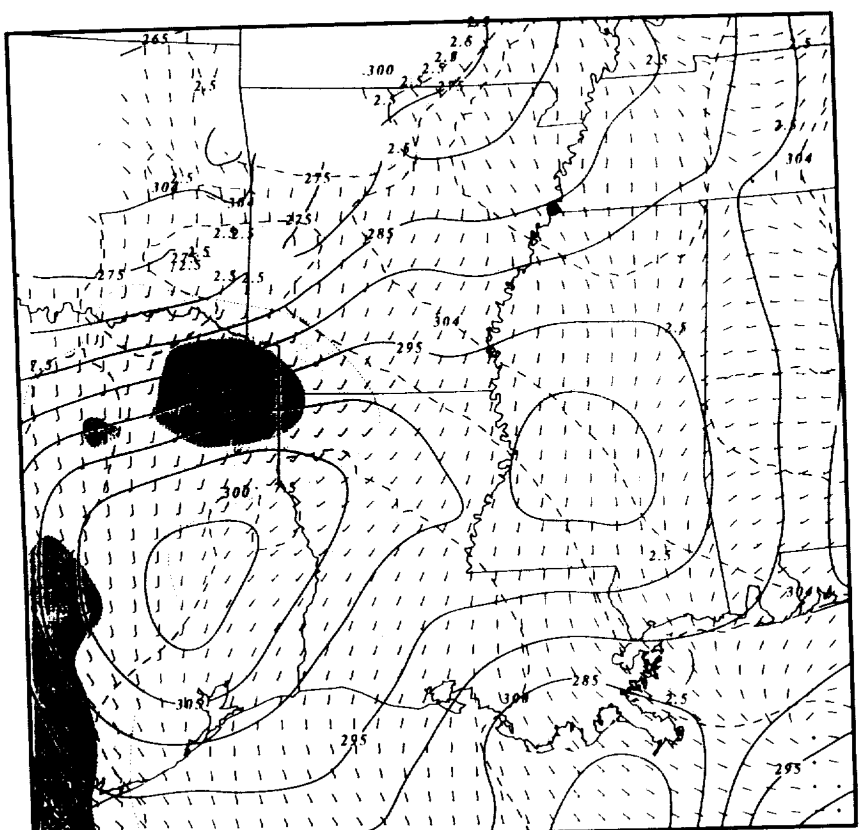
MEMPHIS NWS FINE ETA CROSS RUNWAY U





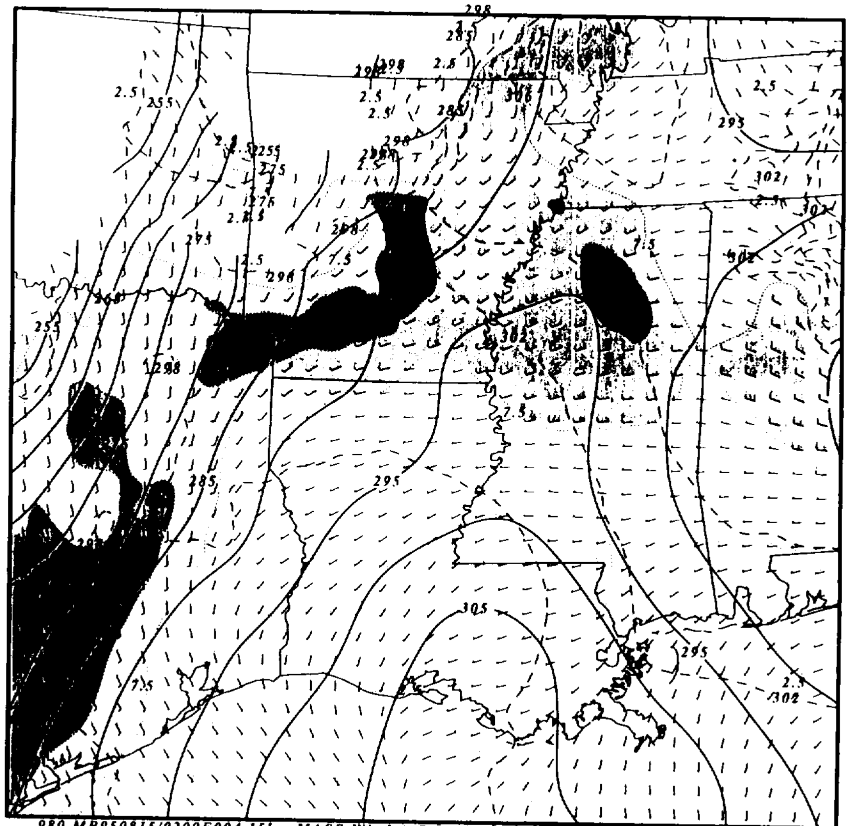
980 MB950815/0200F00145 15km NCAR MASS mag(PGF) and vectors 10*5

980 MB 15KM MASS 0345 t



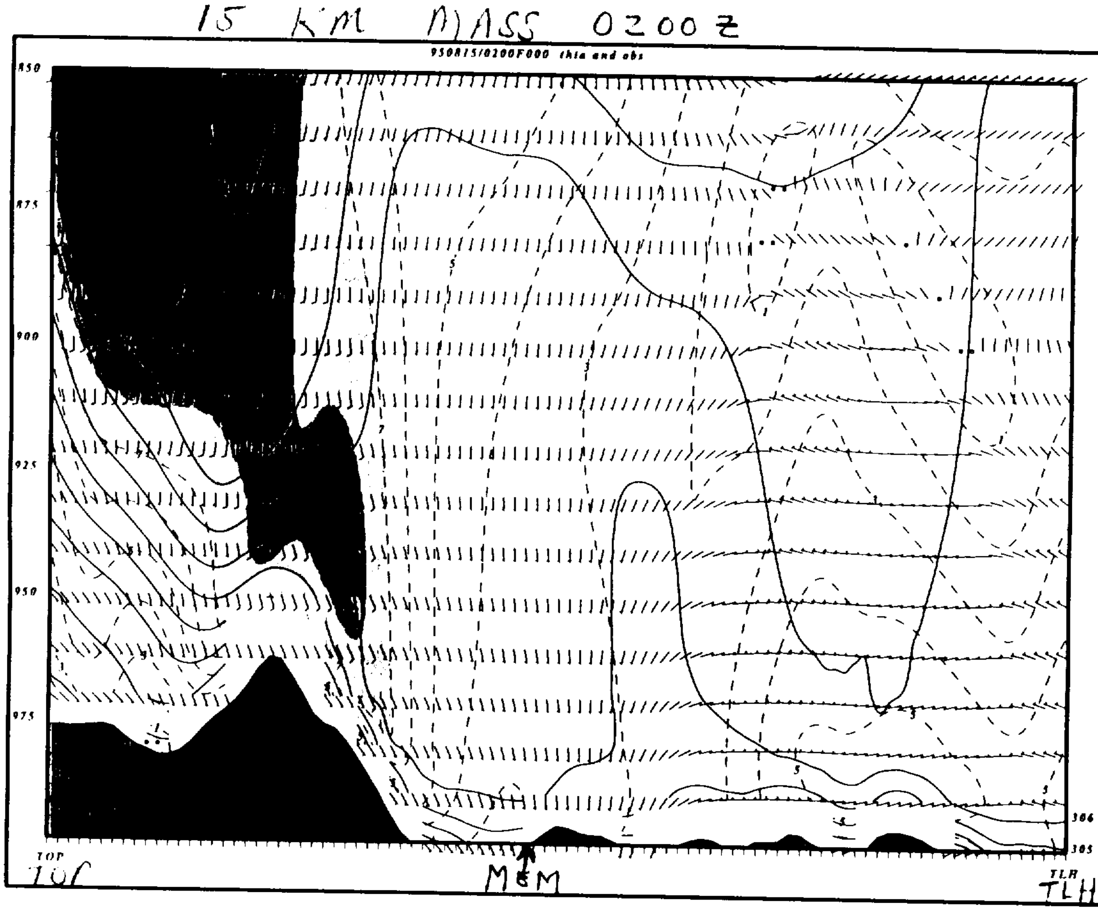
980 MB950815/0200F000 15km MASS Winds(>7.5 m/s shaded),Theta and Ht

980 MB 15KM MASS 0:00 t

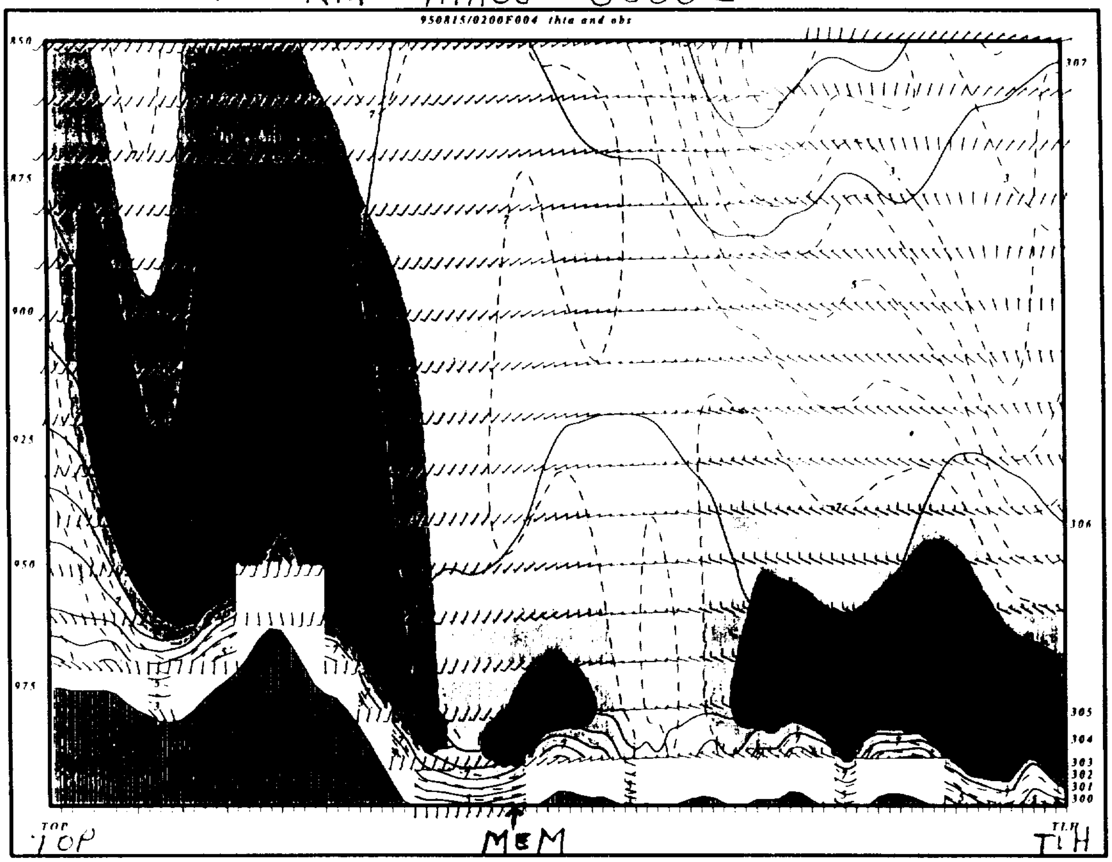

980 MB950815/0200F004 15km MASS Winds(>7.5 m/s shaded),Theta and Ht

980 mB 15 KM MASS 0600 Z

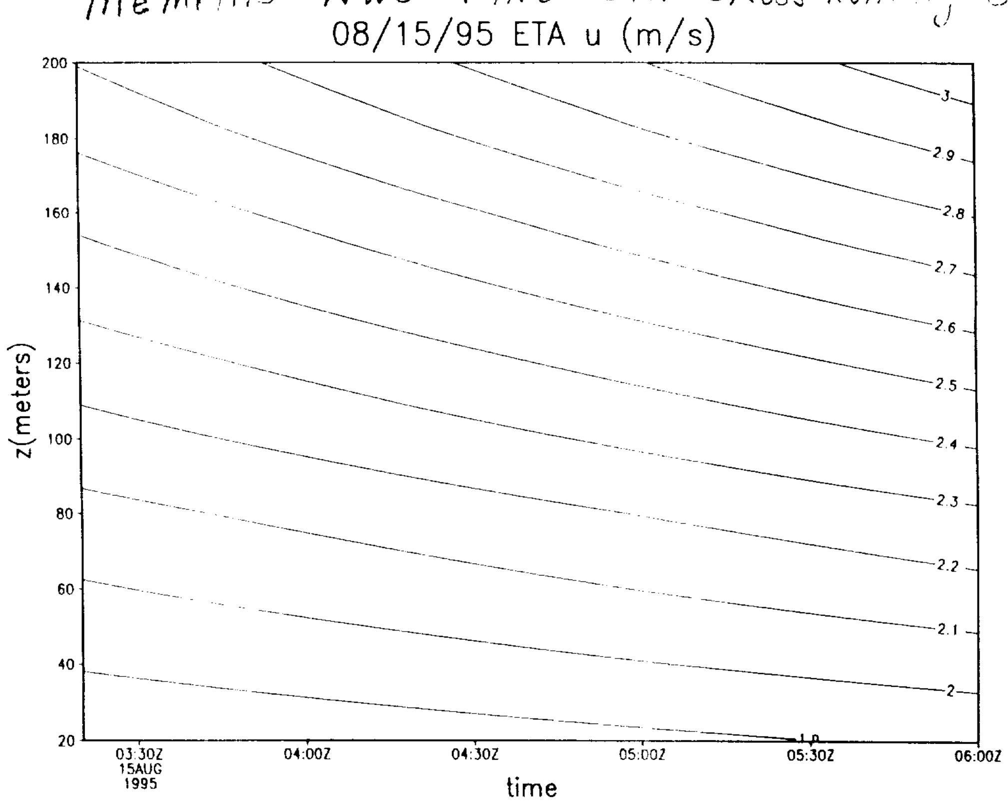
15 KM MASS 0200 Z

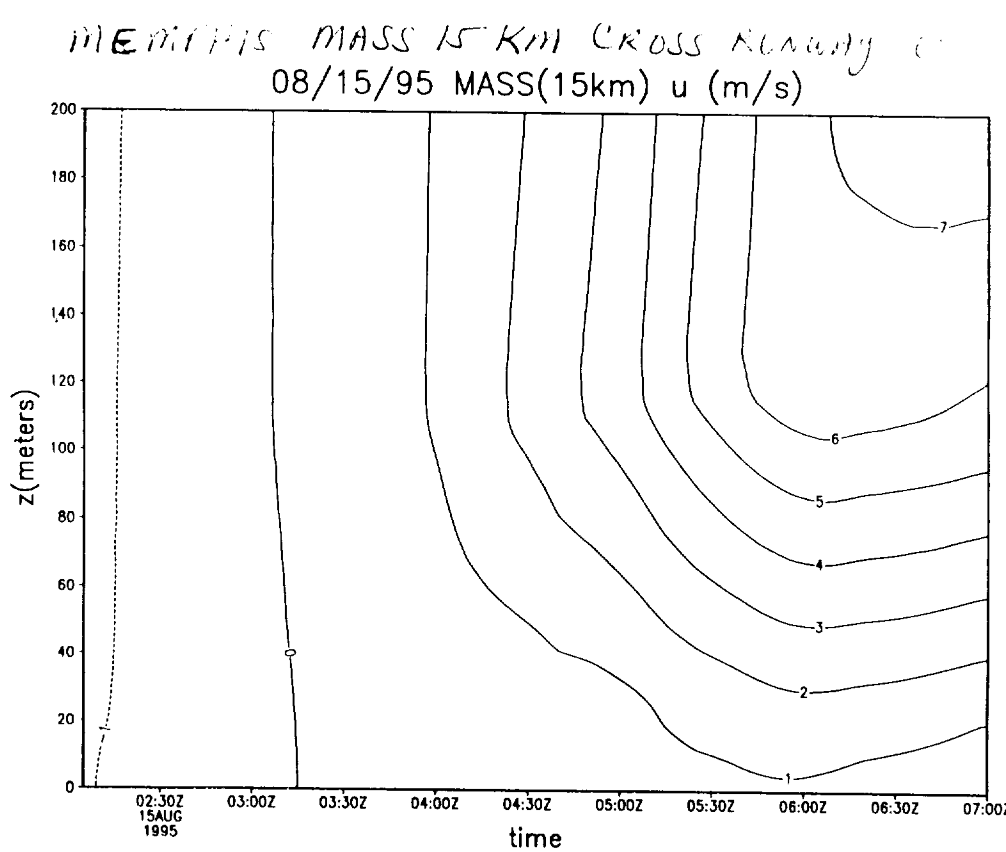


13 KM MASS 0600Z




MEMPHIS NWS FINE ETA CROSS RUNWAY U




MEMPHIS MASS 15 KM CROSS RUNWAY
08/15/95 MASS(15km) u (m/s)
z(meters)
time
02:30Z 15AUG 1995
03:00Z
03:30Z
04:00Z
04:30Z
05:00Z
05:30Z
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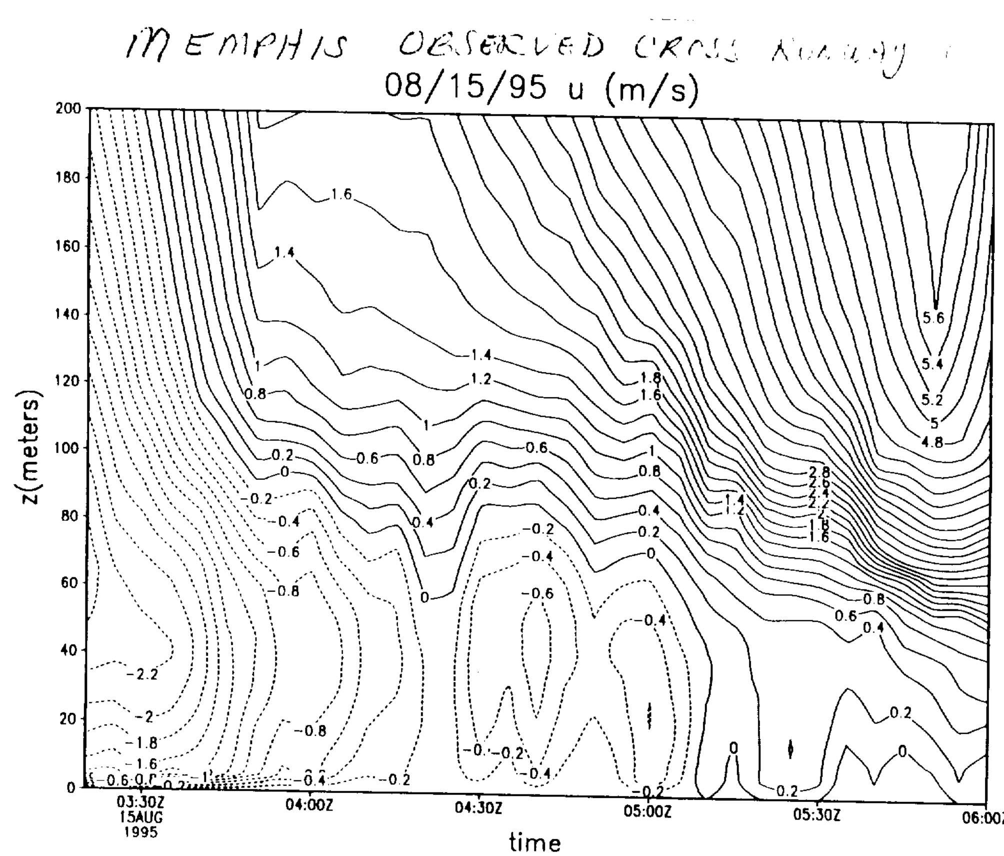
06:30Z
07:00Z


MEMPHIS OBSERVED CROSS RUNWAY
08/15/95 u (m/s)
z(meters)
time
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04:00Z
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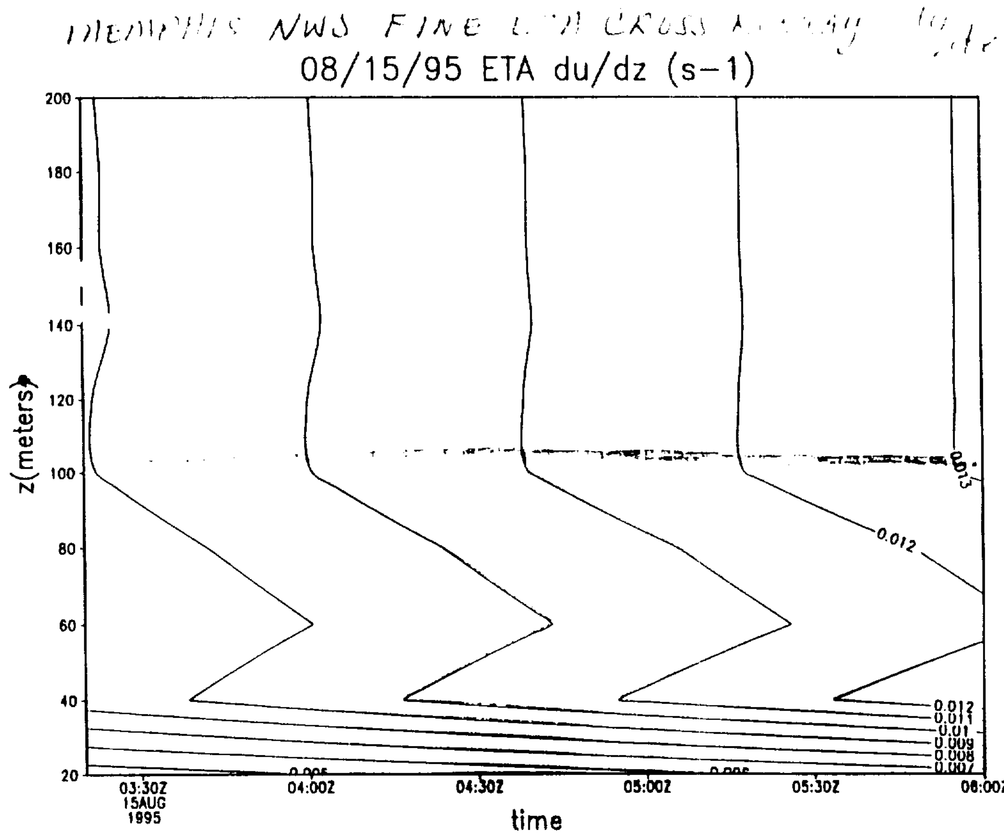
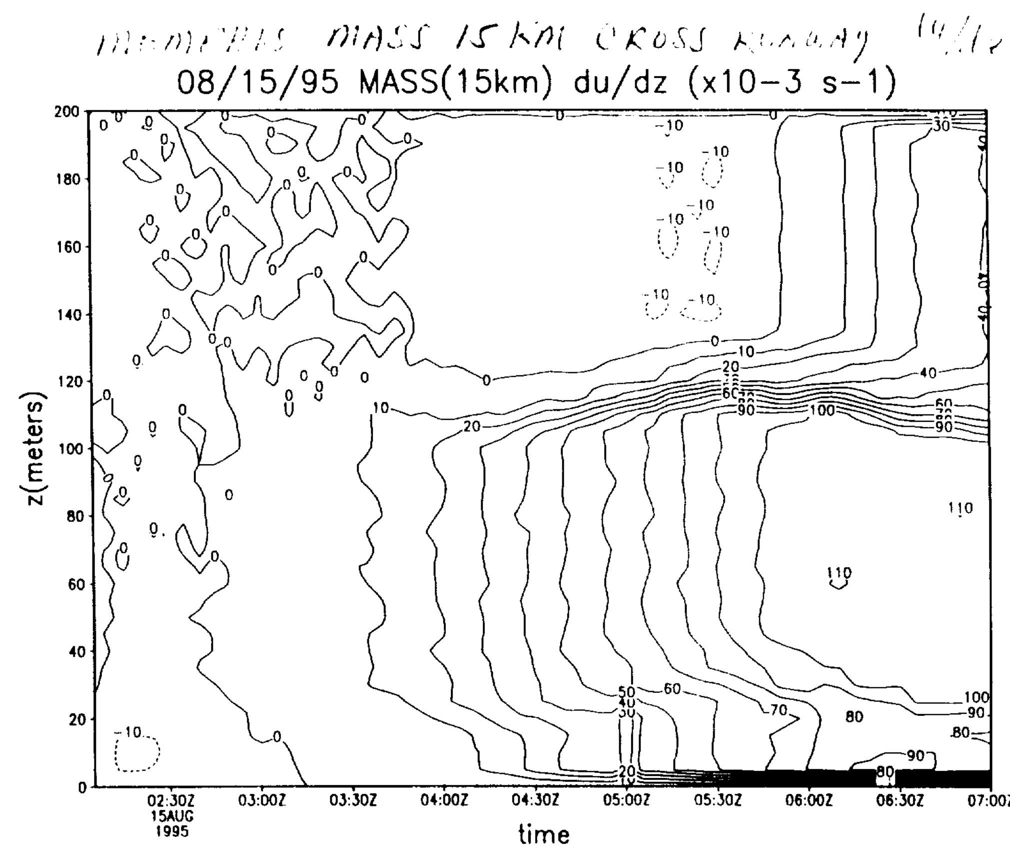
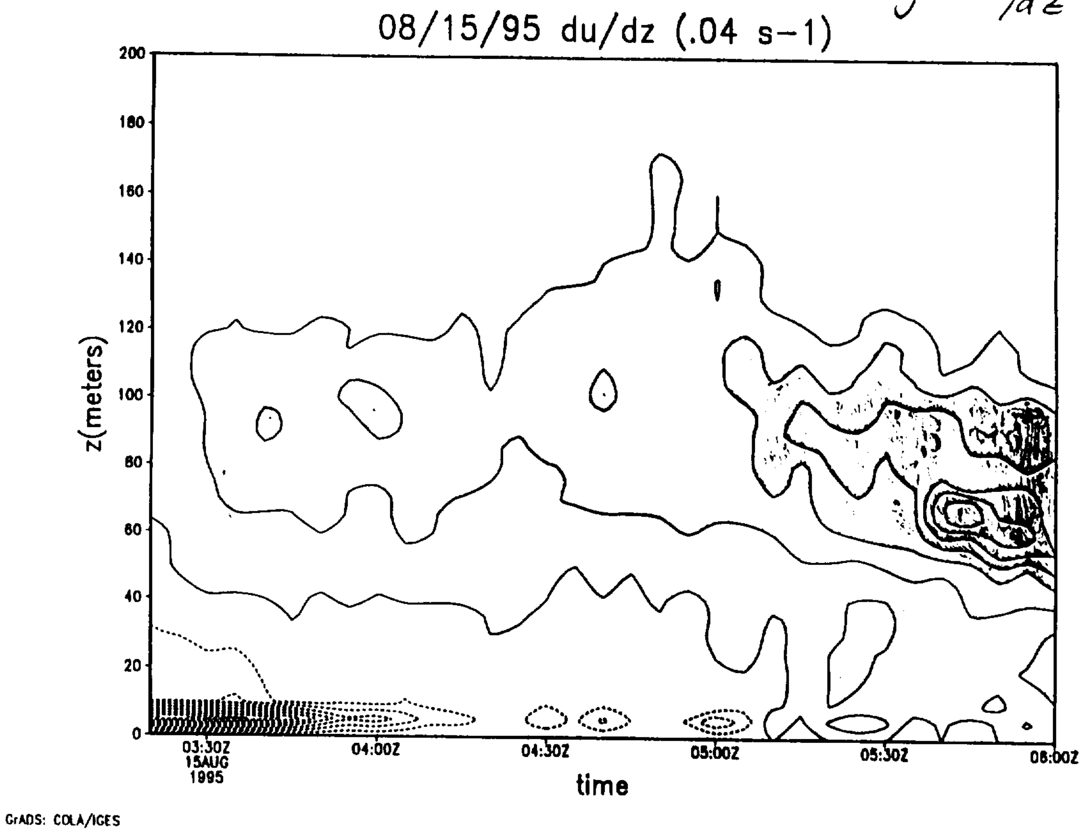



GrADS: COLA/IGES

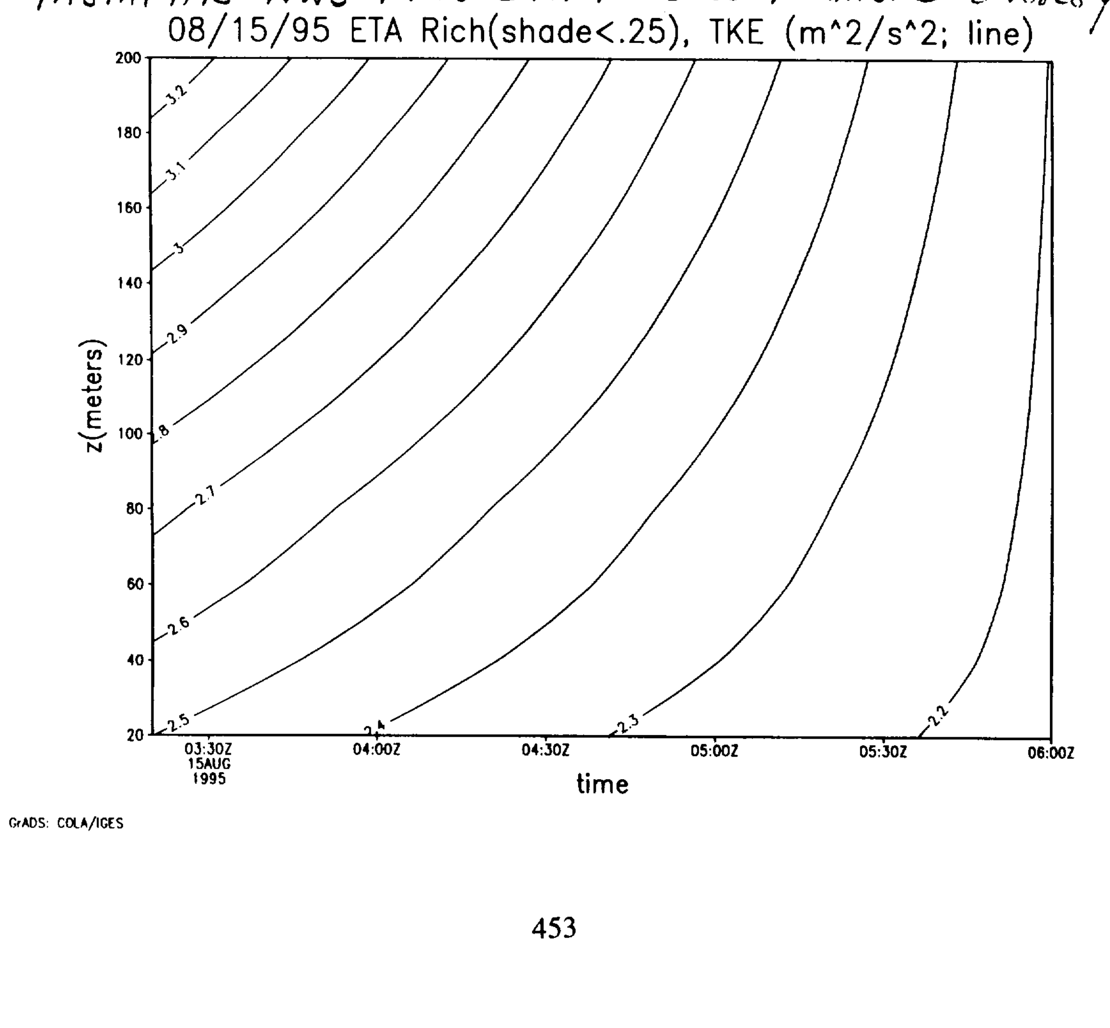



GrADS: COLA/IGES

MEMPHIS OBSERVED CROSS RUNWAY du/dz

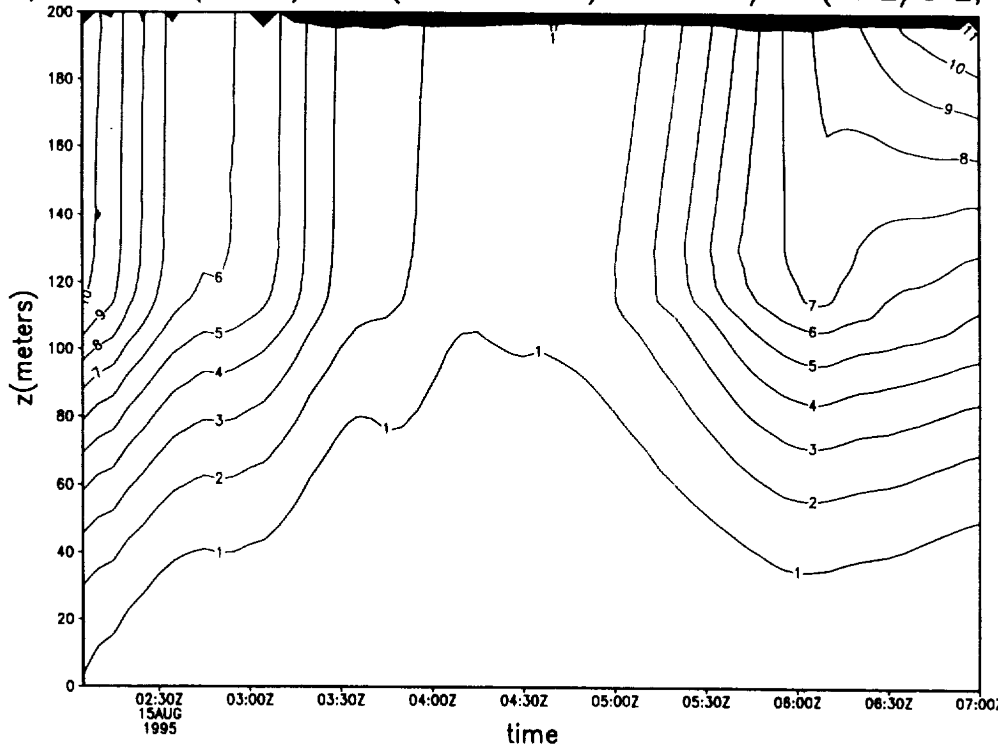



MEMPHIS NWS FINE ETA TURBULENT KINETIC ENERGY



MEMPHIS MASS 15 KM TURBULENT KINETIC ENERGY

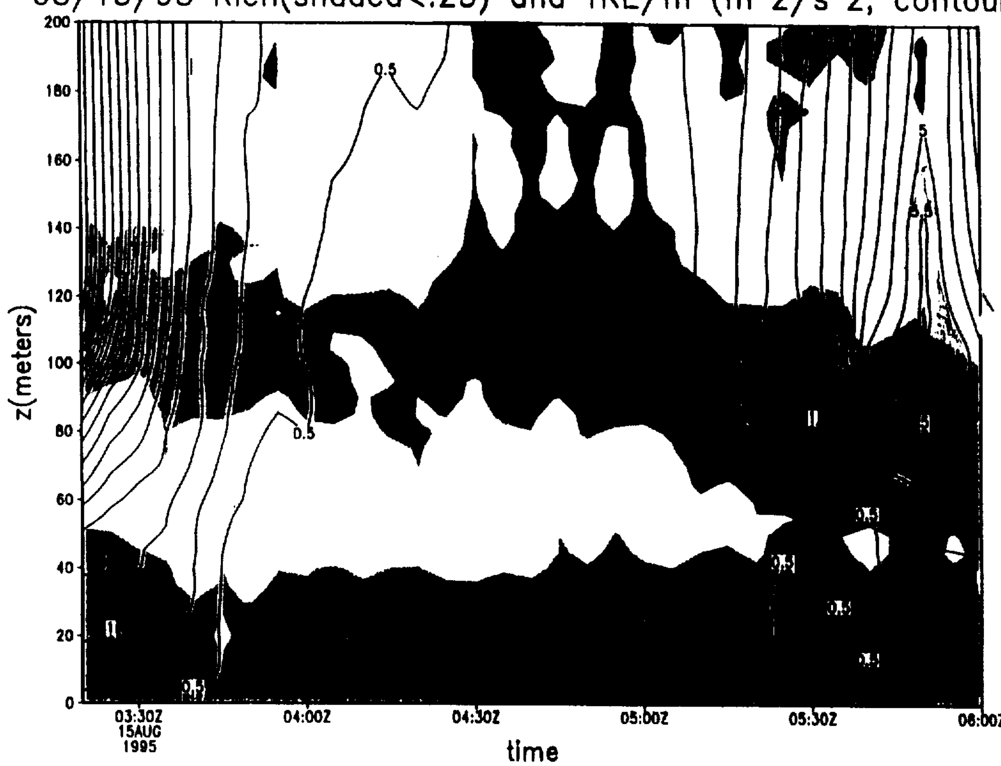
08/15/95 MASS(15km) Rich(shaded<.25) and TKE/m (m^2/s^2; cc




GrADS: COLA/IGES

MEMPHIS OBSERVED TURBULENT KINETIC ENERGY

08/15/95 Rich(shaded<.25) and TKE/m (m^2/s^2; contour)




GrADS: COLA/IGES

# TAPPS Progress Stages

- TAPPS Stage I (FY 97) -- MASS Coarse Mesh Simulations
- TAPPS Stage II (FY 98) -- MASS Fine Mesh Simulations
- TAPPS Stage III (FY 99) -- TASS Coarse Mesh Simulations Nested within MASS
- TAPPS Stage IV (FY 00) -- TASS LES Scale Simulations Nested within TASS Coarse Mesh (terrain-following and airport data assimilation phase)

**Questions and Discussions Following Mike Kaplan's Presentation (North Carolina State University)**

Tim Dasey (MIT Lincoln Labs)
This is an interesting analysis. Probably the more important aspect for wake vortex is the other side, when does the jet shut off. Because the development of the jet at midnight is at period of interest to Memphis, but is the exception because it has a ton of nighttime traffic. For most airports that is not a capacity limited time. I know for Dallas, the other side of the coin when it shuts off in the morning is probably of greater interest.

Kaplan
Well you are right, Memphis is so usual because of the Fed Ex traffic. Yes, this is an issue we have to study in depth.

Klaus Sievers (German Cockpit)
From what you say, I gather that this low level jet stream is supposed to be able to move vortices in an undesirable fashion. They are able to move vortices, let us leave it at that.

Kaplan
That is the assumption.

Sievers
Have you detected the moving vortices? Second question, would it be possible to detect these low level jet streams using ground-based anometers only?

Kaplan
The first question I would have to defer to the MIT Lincoln Labs people because they have looked at this data with lidar and other instrument systems and know more about the observation far more than I do. They have compiled a high amount of statistics on behavior of vortices which I am sure they would be glad to share with you if you speak to Tim Dasey or Mike Matthews. Second question, and I tried to point that out, but in limited time it is hard to do, no. You would not know from ground-based anometer that you have such very impressive local shear zones. We saw a slight turning of the surface wind at Memphis and Little Rock, but we didn't see any indication of the very strong local shears that both the model and the MIT Lincoln Labs data, and even the radiosonde showed. At the surface a person would not know this was going on.

Jim Evans (MIT Lincoln Labs)
No, you can't see them on the surface winds, you get a decoupling of the winds aloft and the surface. That is what is fundamentally going on.

Kaplan
A nocturnal decoupling, the development of that PBL field the friction layer from the

development of this feature. This has been known for a while due to the work of Blackadar and other people. But what has not been very well published is how shallow these features are and how quickly they develop, and how the influence of the local terrain can be very dramatic. Almost every major airport is near a mesoscale mountain range in U.S. with some exceptions.

Evans
Well, we see them at Dallas and I am not aware of any major mesoscale feature near Dallas. But that is not the key point. I think this is an important area. The problem is we have to decide where we are creating value. We have to focus on the meteorology associated with situations where we create value. Now this nocturnal jet occurs, generally speaking, in fair weather conditions and if I go around and say where is an AVOSS going to create value? It is not in under VFR conditions by and large. First order, at least now is under IFR conditions. I am simply going to say that whenever people talk about modeling they better figure out where they are going to deploy the system and its got to show a significant value, and you better deal with that meteorology. When you get into mesoscale modeling I can model a lot of things and you will do well on some and lousy on others. The modeling has to be tied to where you will produce value. You better decide what airports you are talking about and what meteorological circumstances. The overall idea that people better make of this is first focus on where the value is and not just on what is interesting meteorologically. Which I do agree that low level jet is interesting.

Kaplan
Well, we obviously see certain a level of value in this phenomena. The broader aspect of your comments is well taken.

Bob Robbins (Northwest Research)
I just want to answer a few of those questions. We will be showing some predictions tomorrow morning. There is no doubt that the nocturnal jet is blowing the vortices very severely, it is very clear. With the evection model we use in our prediction algorithm we can predict that very well. It is interesting to note that if you read the MIT Lincoln Labs commentary on the weather for that evening, it is light wind, with no idea of what is going on above from their surface level impressions. It was misleading because we saw what was going on and the wind data that was available for that night clearly shows very strong shear at about 100 meters.

Unrecorded comment.

Kaplan
Of course, but weakness doesn't necessarily mean that it is not important for this problem area we are studying.

Fred Proctor (NASA LaRC)
I would like to respond to Jim Evans' point. Since the AVOSS corridor is only to a depth of 500 meters, that is we need to protect a zone from surface to 500 meters, you will need a model that will be able to predict scale of motions that are very, very small scale as we are showing here, and even better. So features like this definitely need to be predicted.

Pal Ayra (N.C. State University)
I would like to comment on this low level jet. Some 7 or 8 years ago one of my students was involved in a project in Savanna River Labs with a scientist there. They had a project focusing on these low level jets at nighttime. A number of times they observed very strong jet at even 40 to 50 meters above the ground and there are no mountains nearby. It is a fairly flat region.

Kaplan
Where did you say this was?

Ayra
At Savanna River Labs in South Carolina.

Kaplan
It doesn't take much of a hill to do something like this.

Ayra
Yes, just small undulations can cause this.

David Smith (Seattle-Tacoma Airport)
I'm hearing a general theme there about the weather being predicted up to 1500 ft and calculating the AVOSS corridor basically from the outer marker on in. In some of the discussions with pilots over the last 24 hours, it's occurring to me as you begin to queue up the airplanes, and I'll speak for SETAC, we are starting to queue them 30 miles out and we lose our duel stream status at 5000 ft and 5 miles visibility. I would like to offer a general statement that before we lock ourselves into saying what we are going to do from the outer marker is that we need to understand on a broader scale, more how the queuing process works at various airports in the country. Because, for example, our outer marker is halfway from the airport to the city of Seattle. The city of Seattle is about the point where they have to make their final decision as to whether they will put them in single stream or not. So they will want to know at that point, whether they can avoid the wake turbulence or not.

Peter Zwack (University of Quebec)
Just to get back to the low level jet. In the COBEL studies in the middle 80's that was exactly the purpose of the COBEL work was to study low level jets. They actually were in northern France which is as flat as you can get yet there were low level jets. I just want to mention that it is not only time you get a low level jet when you have radiation cooling and you get a decoupling. There are other phenomena which can produce cooling at the surface like a little cold air evection like some region like the mountains like that, or from the sea, that can produce decoupling and produce the same kind of physics that produce low level jets, perhaps in the middle of the day. There are many phenomena that can produce this and it is important to be able to simulate it.

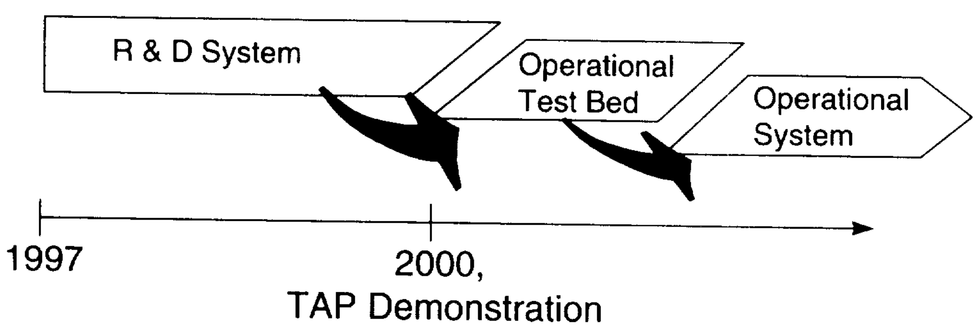
# AVOSS Development Approach

David A. Hinton
NASA - Langley Research Center

First Wake Vortex Dynamic Spacing Workshop
May 13-15, 1997

d.a.hinton@larc.nasa.gov
(757) 864-2040

## Three System Model




- TAP R&D system provides basis for industry involvement, design trades, performance data, deployment justification and decision.
- Test Bed system introduces actual separation reductions under carefully monitored and heavily instrumented conditions. Requires FAA support.

# AVOSS R&D Effort Scope

- Provide an end-to-end concept demonstration of a system architecture that can safely realize near-term capacity benefit and grow as experience and knowledge are gained.
- Utilize the best available products of each major discipline, and focus additional work where required.
- Provide design trade-off data and basis for test bed system deployment.
- Involve industry in design philosophy and safety considerations.
- Will not change operational aircraft spacing in 2000.

# Major Development Issues

- Stability requirements of the ATC systems.
- Ability of weather systems to support ATC stability requirements with meaningful system performance.
- System performance Vs. corridor size and other safety buffers.
- ATC interfaces for current and CTAS systems.
- Need for full-approach wake monitoring.
- Relative system benefits of wake motion and decay at each altitude, is a major driver for future research and sensor requirements.

# Concept System Development Process

- Aggressively integrate existing and developing subsystems and knowledge base.
  - Begin "system" thinking among disciplines.
  - Understand interface implications and discourage isolated development.
- Utilize resulting field experience and data to focus development and resolve issues.
- Establish test facility at Dallas-Fort Worth
  - Collocate with CTAS and ITWS.
  - Only bring subsystems ready for AVOSS integration and that fill specific needs.

# Initial AVOSS System Testing

- Version 1 AVOSS is under development for late summer testing at DFW.
- Objective:
  - Initial subsystem integration.
  - Provide run-time atmospheric profile consensus from multiple sensors.
  - Provide run-time wake prediction and validation.
  - Run-time separation matrices.
  - Provide field experience with integrated AVOSS and data to focus out-year development.

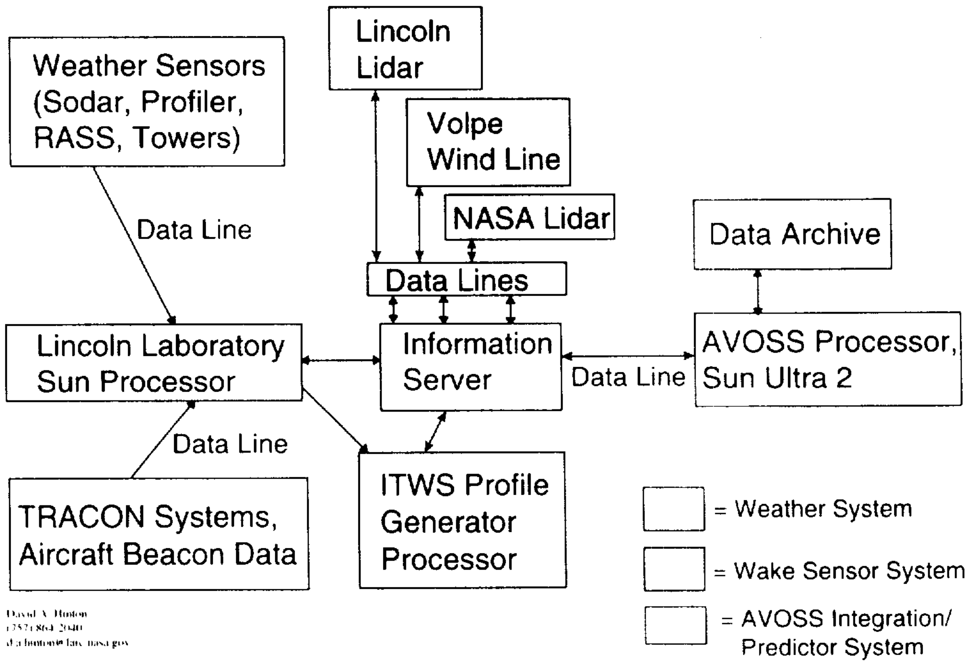
# Initial AVOSS Testing

- Approach:
  - Use recent wake prediction models, state-of-the-art atmospheric profiling, augmented ITWS products.
  - Predict wake behavior and aircraft separation requirements along approach path - validate at several close-in sites via Lidar and Ground Wind Line.
  - Evaluate atmospheric profile consensus, wake predictor, critical separation windows and factors.

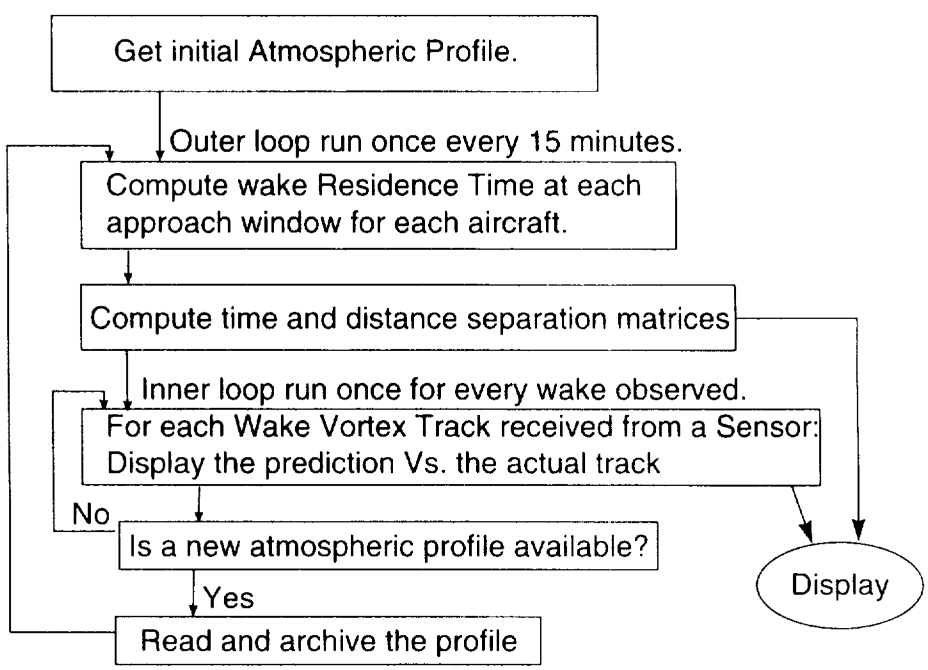
# Initial AVOSS Testing

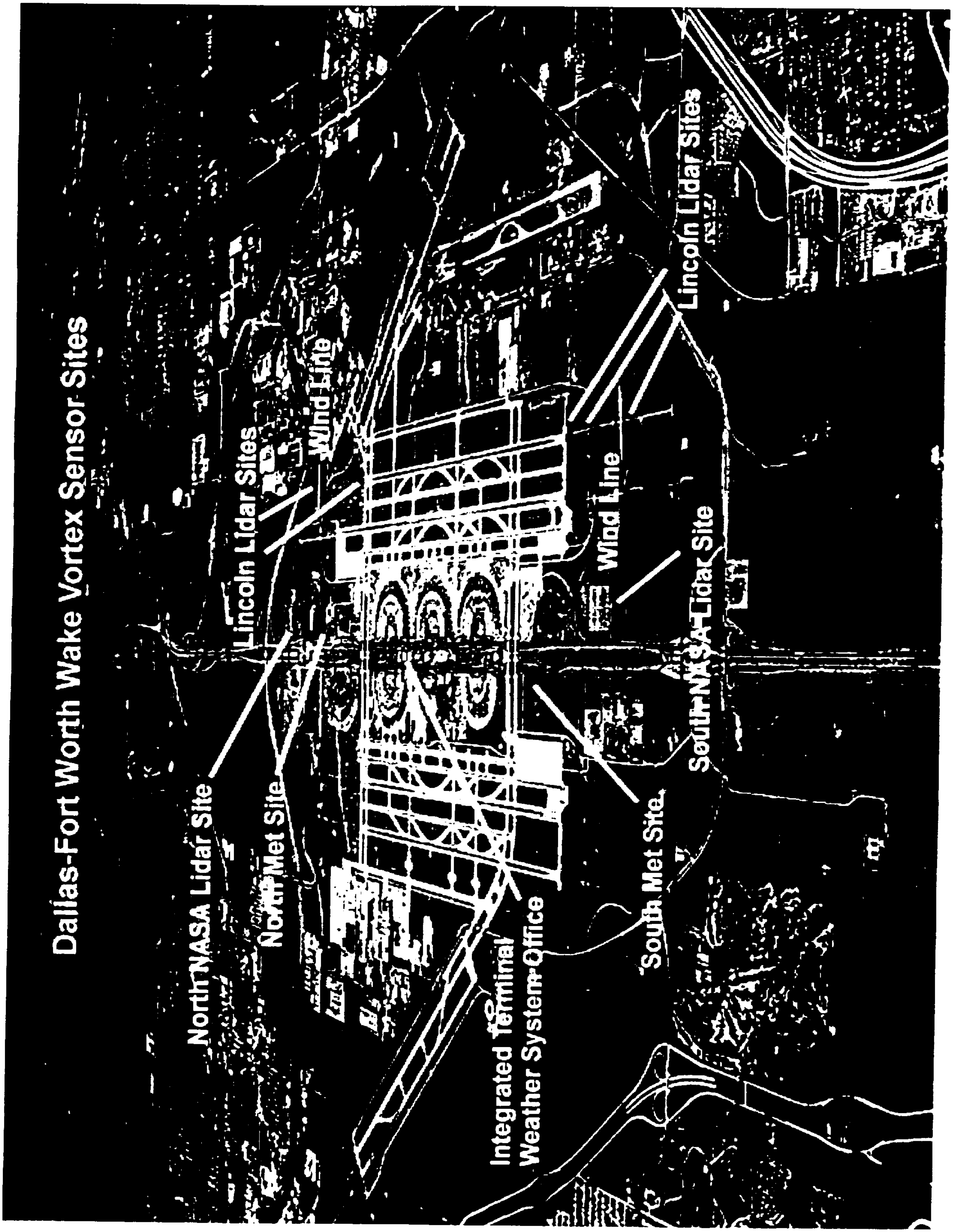
- Success Criteria:
  - Integration of subsystems.
  - Real-time data flow from all systems enabling run-time separation matrix calculation and wake monitoring.
  - Acquisition of performance data.
  - Systems in place for year-round development.
  - Reduced separation performance not a criteria in test 1.

# DFW System Architecture




# Basic Process Flowchart, 1997




Dallas-Fort Worth Wake Vortex Sensor Sites
North NASA Lidar Site
North Met Site
Lincoln Lidar Sites
Wind Line
Integrated Terminal Weather System Office
Wind Line
South Met Site
South NASA Lidar Site
Lincoln Lidar Sites

# Incremental Deployments

- Follow initial system integration with focused tests:
  - Improved wake prediction algorithm.
  - Initial acceptable wake strength thresholds.
  - Extend wake sensor envelop to outer marker.
  - Vary time of year (weather type).
  - Meteorological Status System and Nowcasting.
  - Safety / monitoring logic.
  - Interface to Ames ATC laboratory.
  - Collect performance statistics - operate at LaRC between wake sensor deployments.

# Concept Demonstration

- End-to-end system performance demonstration.
  - Field weather systems, wake predictions, and wake sensor validations.
  - ATC laboratory interface.
  - Controller in-the-loop performance.
- System design and cost / benefit data for informed industry decisions.

## Questions and Discussion Following David Hinton's Presentation

Rob Rivers (NASA Langley)
On the maps of Dallas airport, you showed all the different sites, lidar sites, windline. You are going to get real-time analysis. How are you getting data from all the sites back to Lincoln Business Office?

Hinton
It's data linked. They are using different technologies. Some will have buried lines, particular the met sites. Some RF links may be used between the lidar sites, but there will be data installed between each subsystem. The lidar site for example will have data lines running into the Dallas-Fort Worth Airport Business Office.

Steve Campbell (Lincoln-Lab)
It looks like initially you're going to be computing the separation matrix every time you get a lidar update. Is that right?

Hinton
No, we will be computing a new separation matrix every 15 minutes based on the profiles update.

Campbell
When do you think you will be actually doing longer term forecasting?

Hinton
It would be a mistake to do it in the first development for a couple of reasons. It adds too many variables to the performance assessment and nowcasting is not mature enough. Part of what I'll be doing this year is looking at utility or benefit of persistence, obviously for making predictions for the next 15 minutes period.

Kenny Kaulia (ALPA)
You are talking about in the first year just doing measurements on the airport, then eventually getting out to the outer marker for the demo in the year 2000. I was wondering, is the technology available to go out beyond the outer marker? The reason I ask is that a number of incidents we have heard about in the last couple of years are at 2000 to 4000 feet. Do you envision the possibility, beyond the year 2000, to go beyond the outer marker?

Hinton
That is an interesting question. When I say outer marker, I really should be saying glide slope intercept point because obviously that is some fairly high altitude at some airports with parallel runways particularly. We have to make a decision and you can be part of this decision as to how far out an AVOSS system will protect the aircraft. Obviously, we can't go out to 10,000 feet where there still may be some encounters. We have to understand and agree where we are going to operate the system, and where procedures may need to change further out. As far as the technology, I would

say the technology is available to scan somewhat further out, particular with lidars that can scan several kilometers. The bigger question, is the funding available?

Ed Spitzer (Volpe)
Do you have any plans to assess how effective the system is? With a 50 minute prediction, what will be the potential improvement in capacity?

Hinton
Yes, not the first year but that is part of the program by the time we get to the year 2000. It is to have a nowcasting system and making 30 to 60 minute predictions.

NorthWest Research
Associates, Inc.
P.O. Box 3027 • Bellevue, WA 98009 3027

S33-61
48116

# Development of Wake Vortex Prediction Algorithms

318768
20P.

Donald P. Delisi

Robert E. Robins

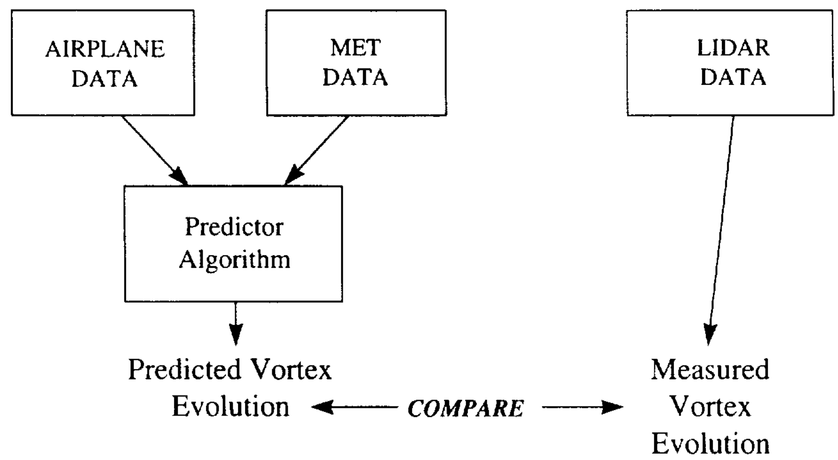
NASA Langley Research Center

15 May 1997

## Outline

- Algorithm Overview
- Recent Results
- Issues
- Future Enhancements

# Relationship of Algorithm to AVOSS




# Selected Review of Previous Algorithms

- Greene (1986): Constant N, includes turbulence effect, includes decay mechanism, no wind, no ground effect
- Liu (1991): Ground effect only, used constrained secondary vortex for ground effect, zero vertical velocity not satisfied at the ground
- Grant (1993): Modified Greene's approach for decay of vortices traveling along the ground, image vortices only (no secondary vortices)

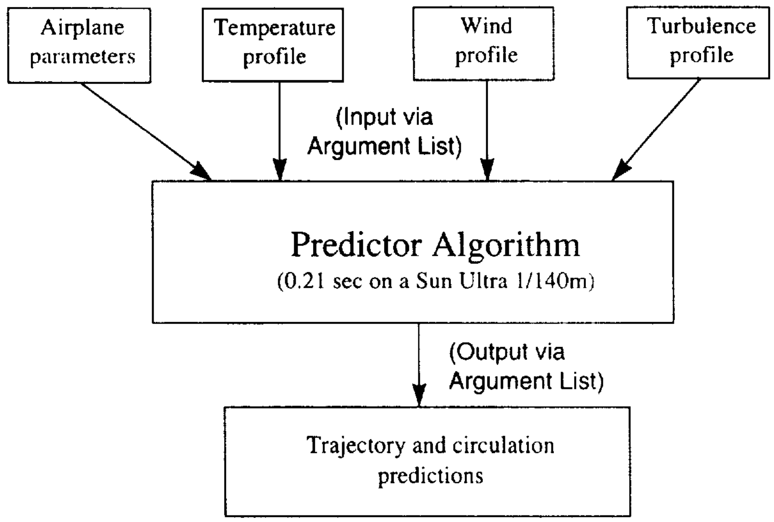
# Selected Review (cont'd)

- Corjon (1995): Used Greene's model and added ambient wind to Liu's model for ground effect, used constrained secondary vortex for ground effect, zero vertical velocity not satisfied at the ground

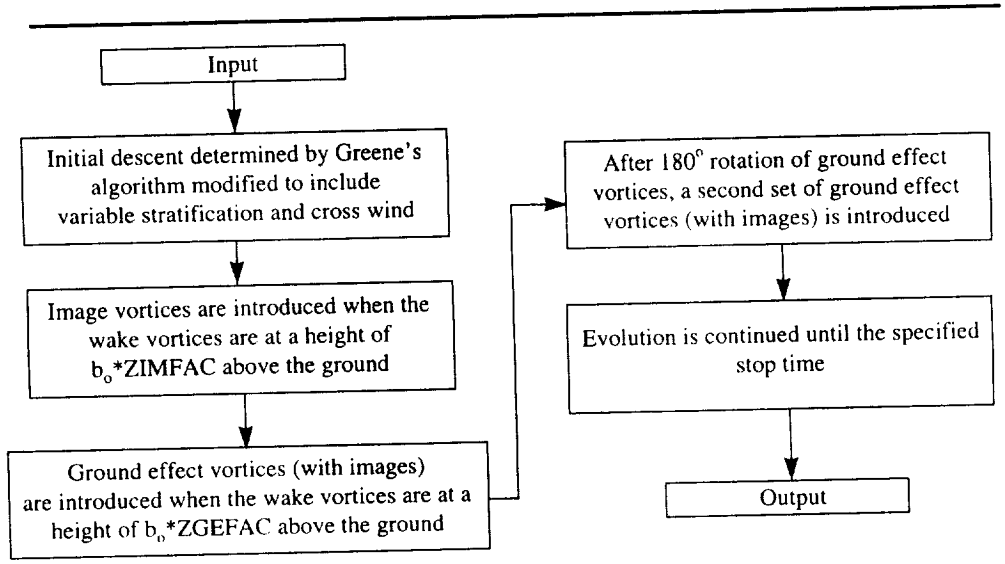
# Algorithm Requirements

- Needs to model the essential physics
- Needs to handle atmospheric parameters: profiles of variable stratification, wind and turbulence
- Needs to handle out-of-ground effect, near-ground effect, and in-ground effect
  - Transitions transparent to the user
- Needs to run quickly on a PC or workstation
  - Current plan is to run the algorithm numerous times between a pair of aircraft landings

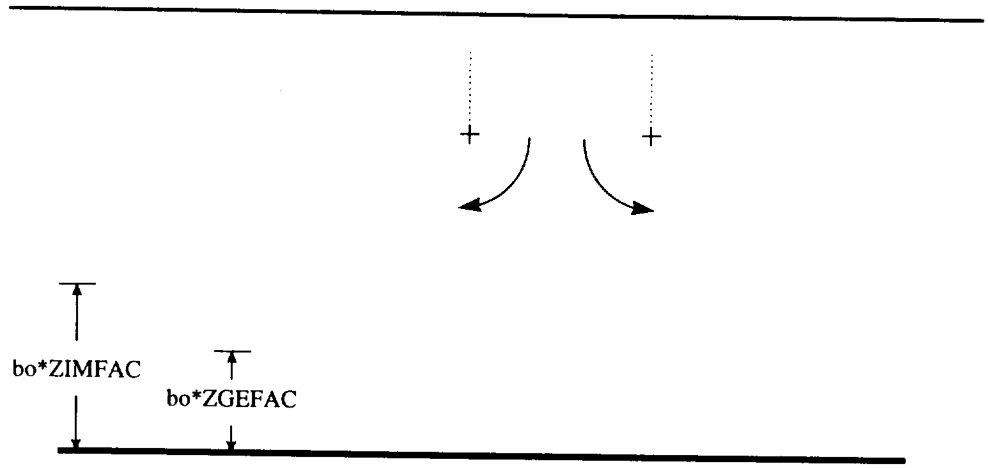
# Overview



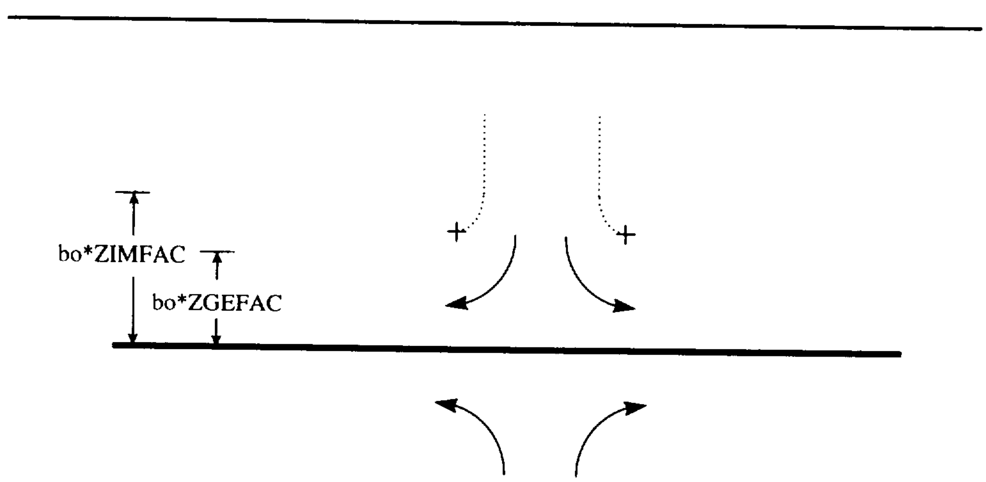

# Predictor Algorithm



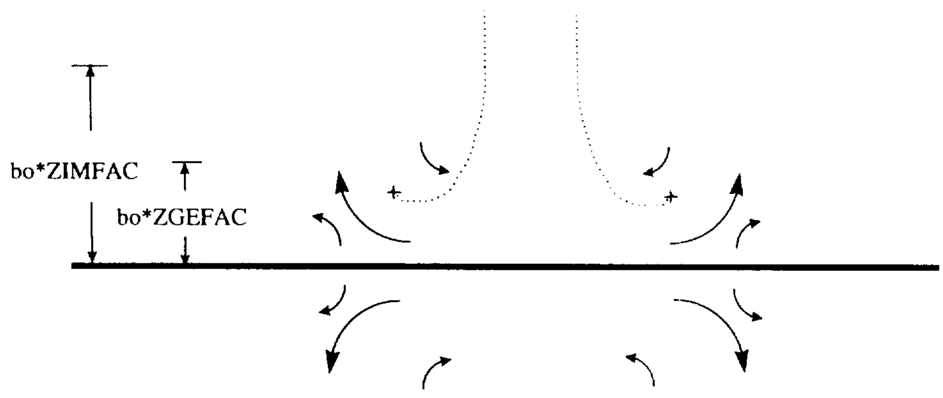
# Out of Ground Effect




# Near Ground Effect

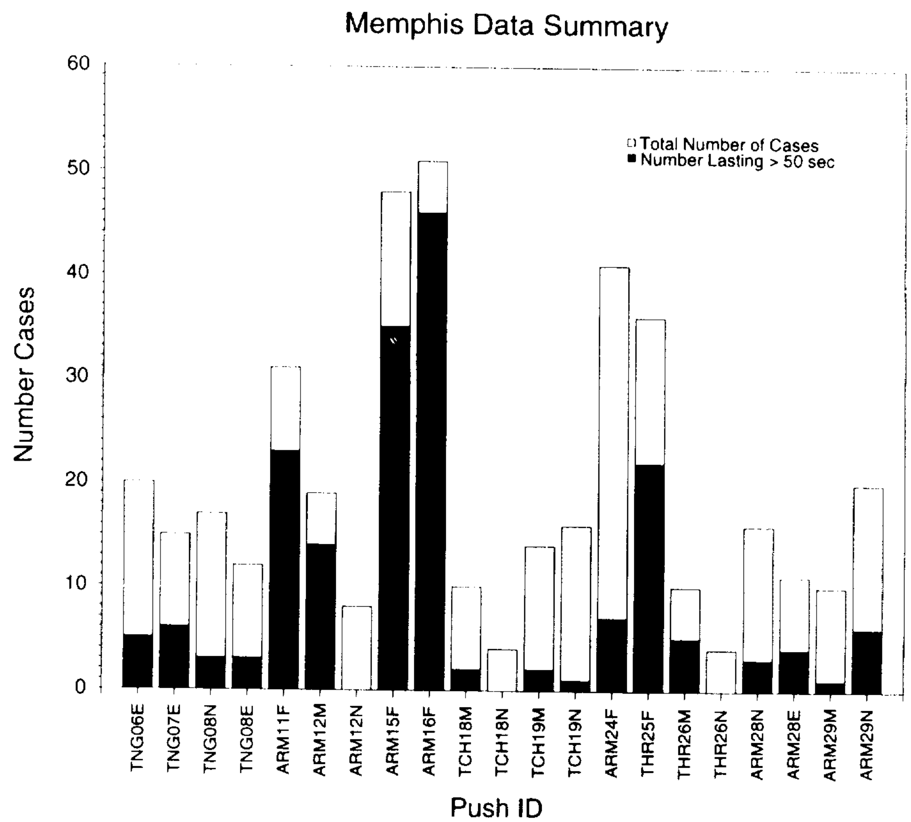


# In Ground Effect



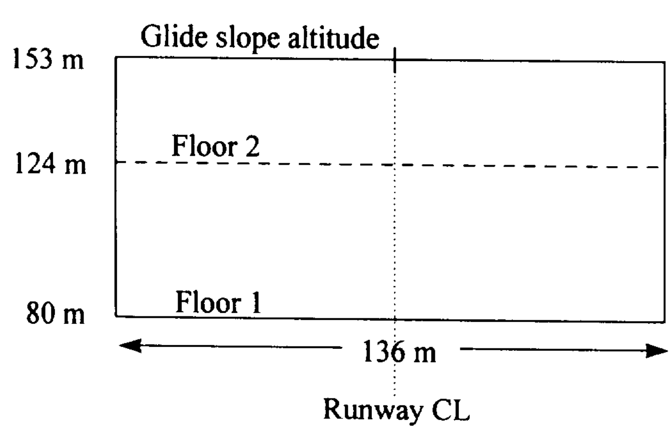

# Approach to Algorithm Calibration

- Compare algorithm output with data
- Adjust algorithm to agree with data
- Quantify agreement between algorithm and data
  - Time to exit corridor (out of ground effect)
  - Vortex height at a fixed time (in ground effect)
- Choose data sets with sufficient number of useful cases

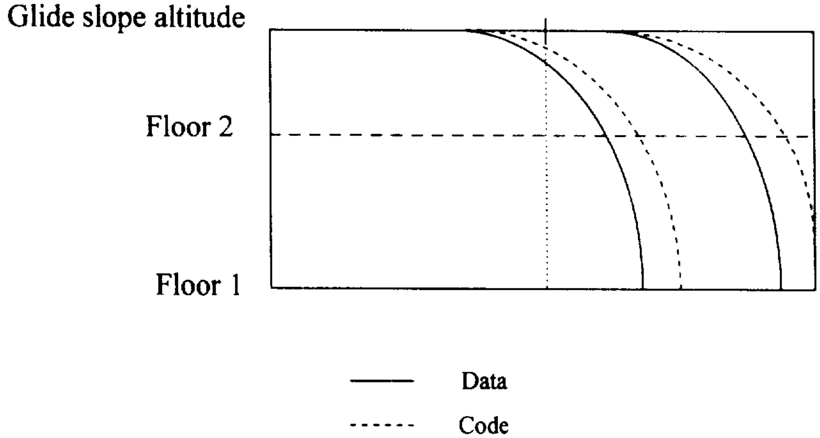



# AVOSS Corridor at the Armory

From Dave Hinton's AGARD paper:



# Predicted vs Observed Exit(s) of the AVOSS Corridor



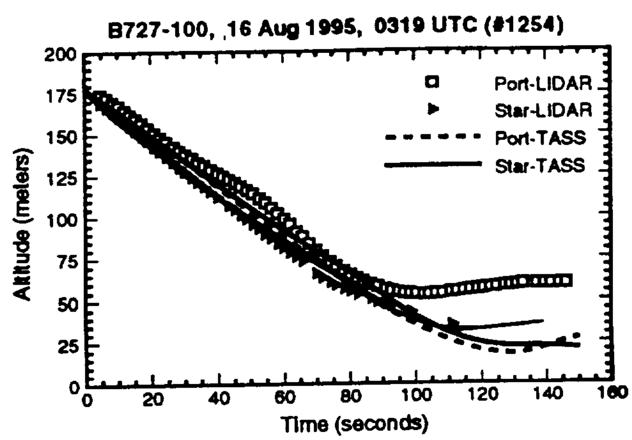




**Figure 8.** Comparison of TASS results with field data

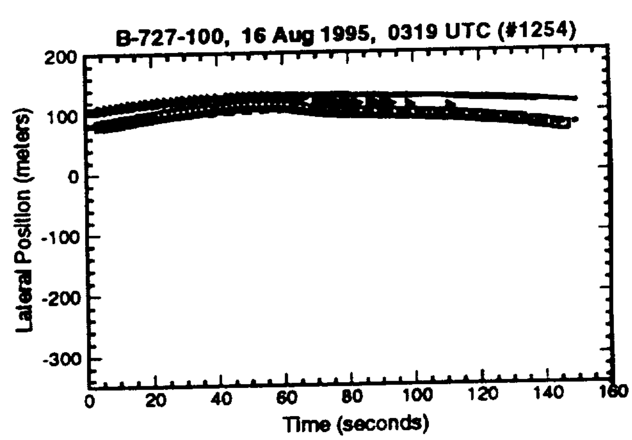
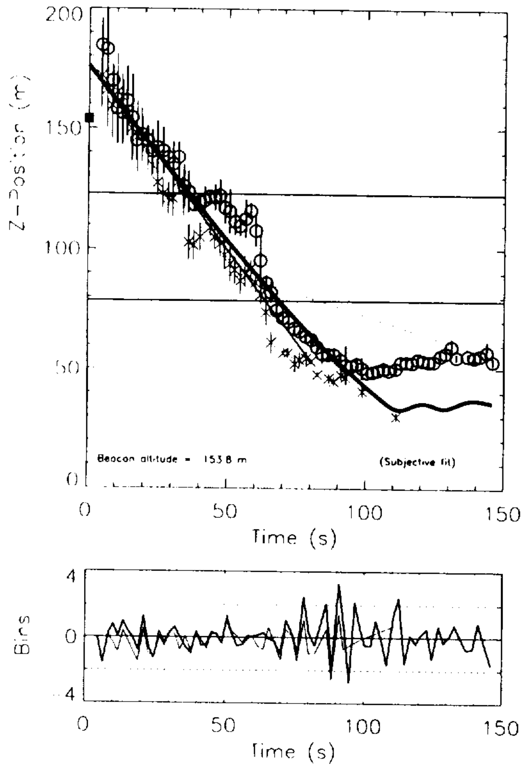
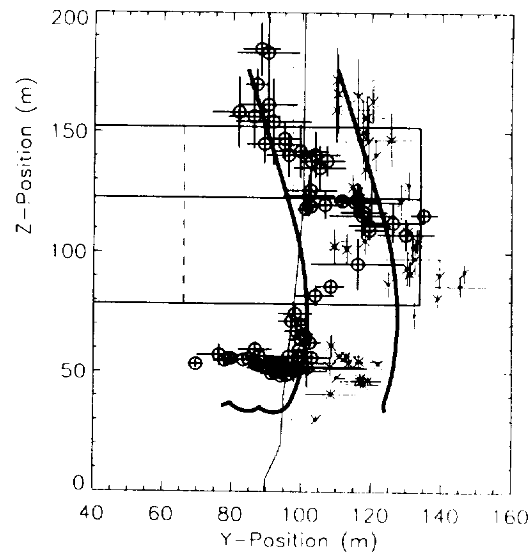



**Figure 9.** Same as Fig. 8, but for lateral position of t

MEM1254, 36R_Armory, 8/16/95 3:19:7, B727, 100 unsmoothed **circle = port** X = starboard




Notes:

Error lines are dely and delz from data file
Bins = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude

Solid line starting at initial altitude indicates descent at Vo theoretical
Dotted line in Z vs T plot is Gamma/Gamma zero

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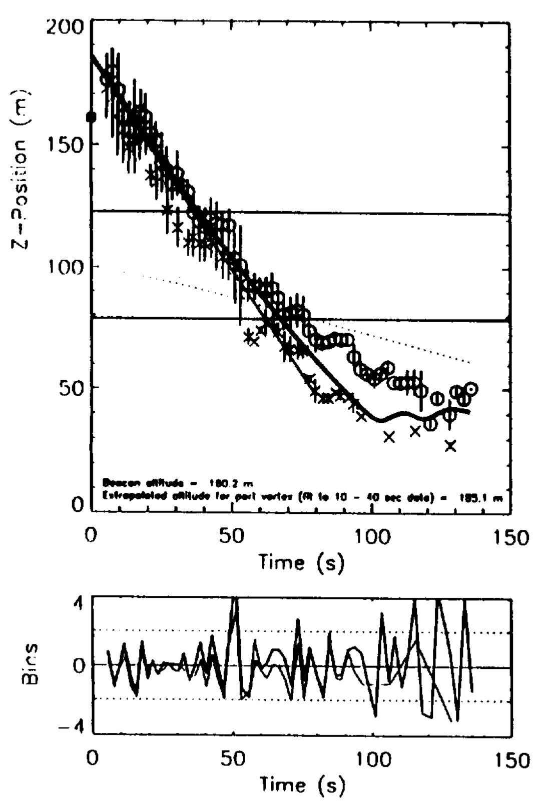
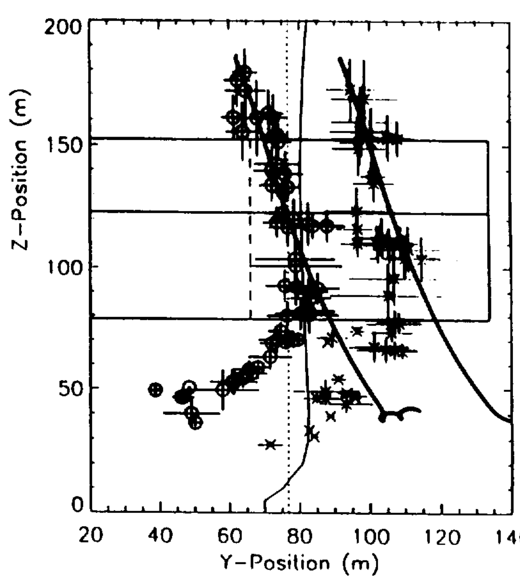
Mar 22 1997

**MEM1252, 36R_Armory, 8/16/95 2:57:24, B757, N/A unsmoothed** **circle = port** X = starboard



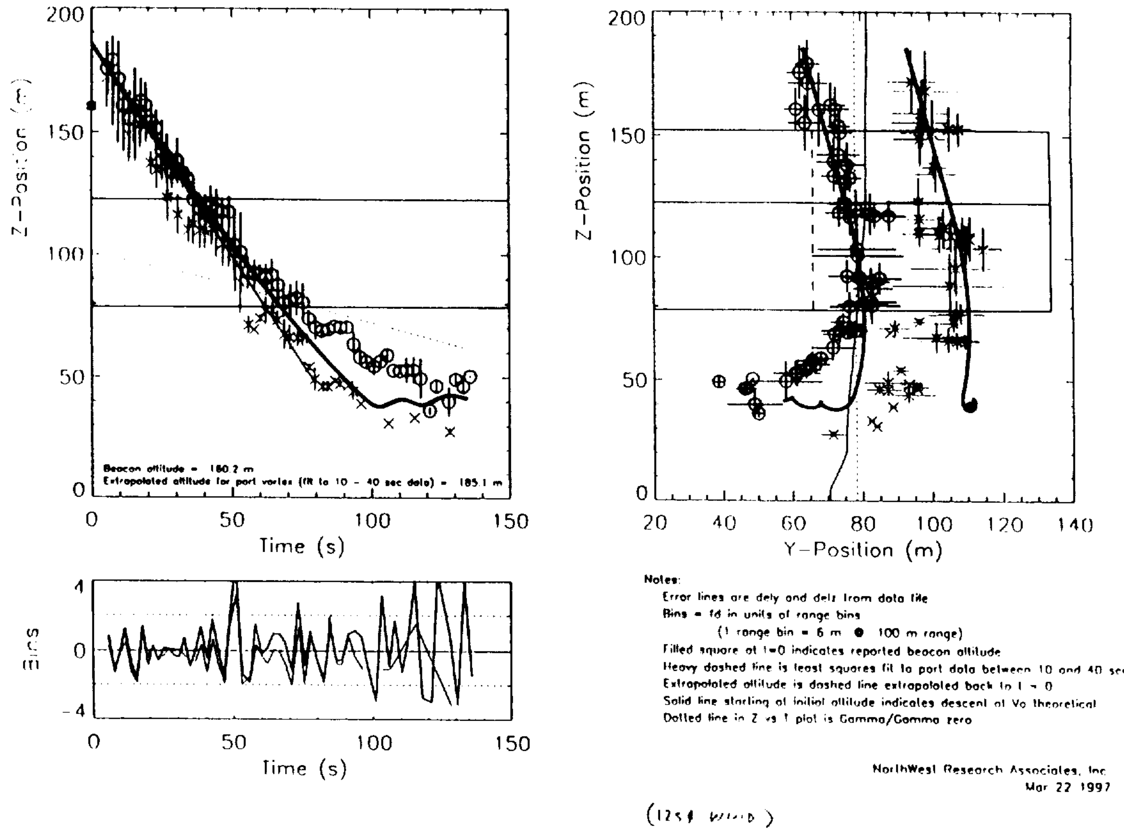




**Notes:**

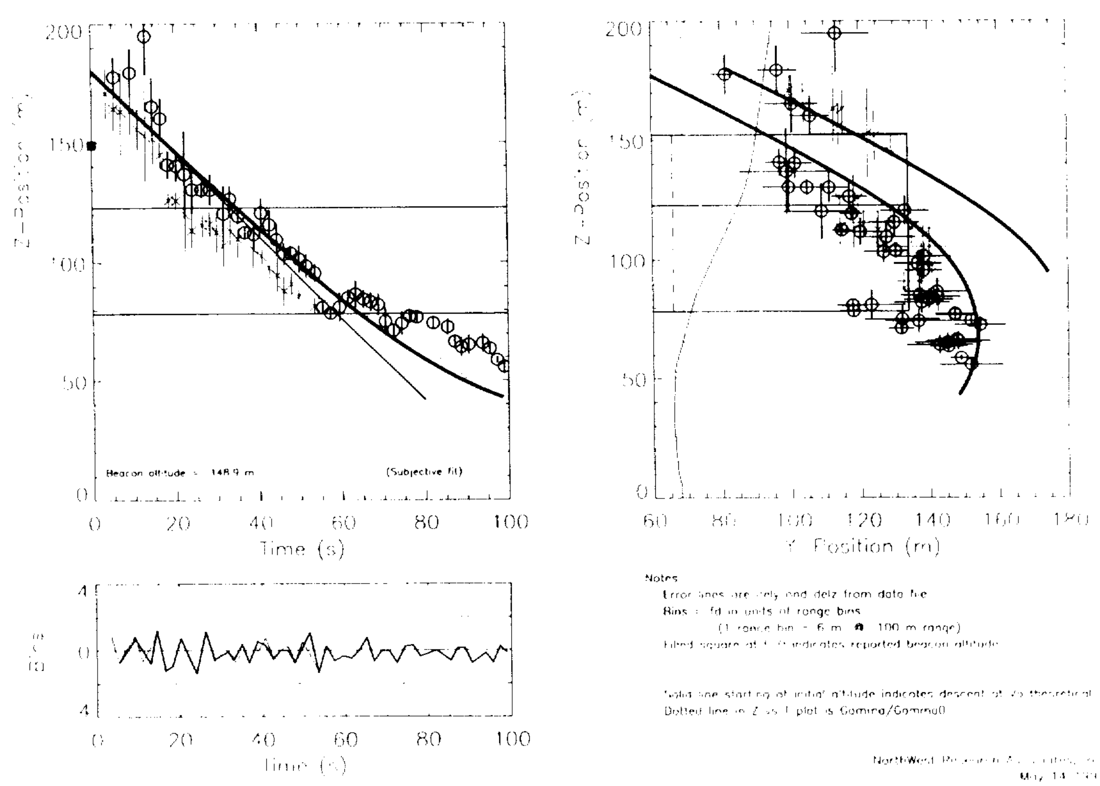
Error lines are dely and delz from data file
Bins = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Heavy dashed line is least squares fit to port data between 10 and 40 sec
Extrapolated altitude is dashed line extrapolated back to t = 0
Solid line starting at initial altitude indicates descent at Vo theoretical
Dotted line in Z vs T plot is Gamma/Gamma zero

NorthWest Research Associates, Inc.
Mar 22 1997

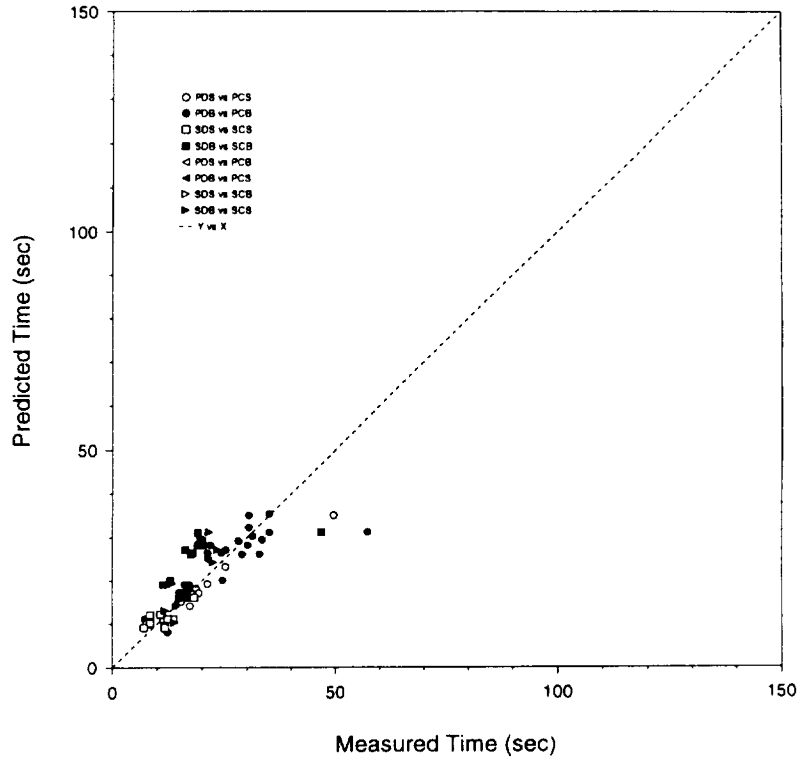
MEM1252, 36R_Armory, 8/16/95 2:57:24, B757, N/A unsmoothed circle = port X = starboard



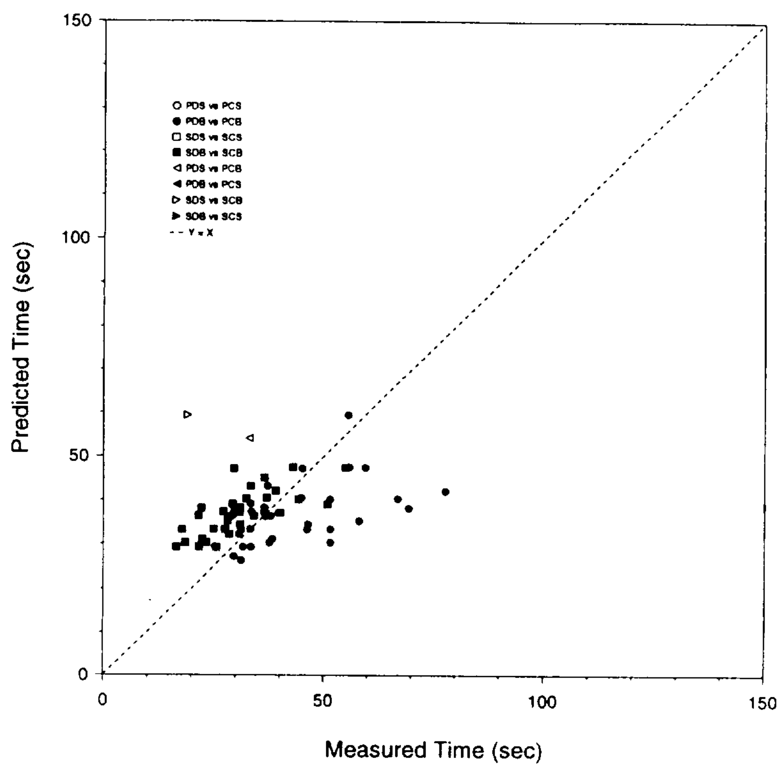

MEM1214, 36R_Armory, 8/15/95 4:30:31, B727, 200 unsmoothed circle = port



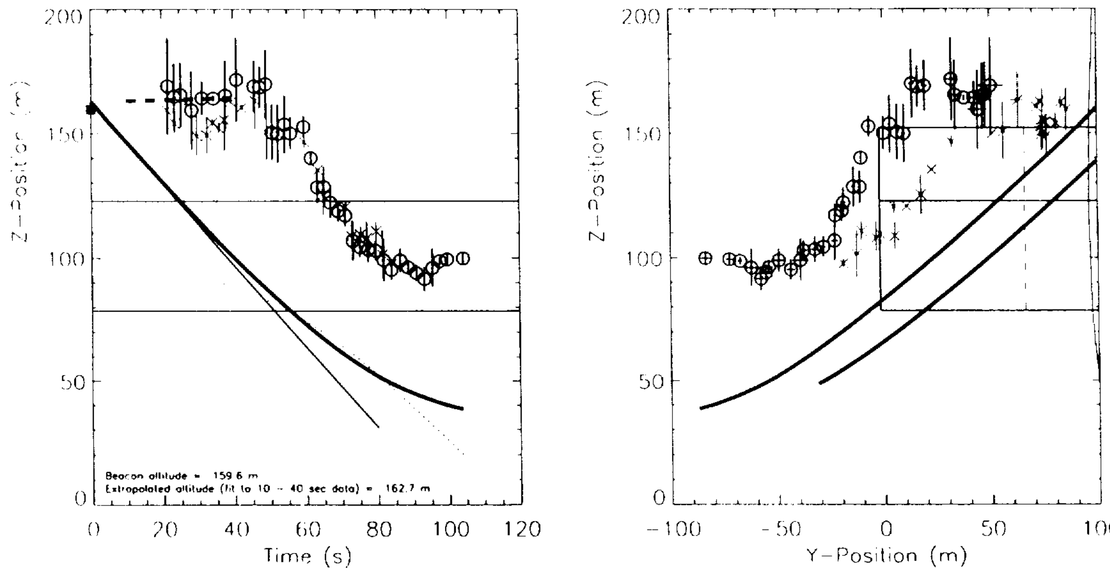
Memphis (8/15/95) Corridor (Floor 2) Exit Times

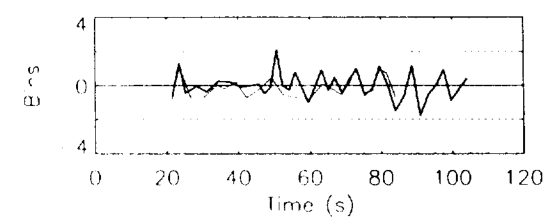



Memphis (8/16/95) Corridor (Floor 2) Exit Times



MEM1307, 36R_Armory, 8/16/95 5:49:42, B727, 200 unsmoothed **circle = port** x = starboard




Notes:
Error lines are dely and delz from data file
Bins = fd in units of range bins
(1 range bin ~ 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Heavy dashed line is least squares fit to data between 10 and 40 sec
Extrapolated altitude is dashed line extrapolated back to t = 0
Solid line starting at initial altitude indicates descent at Vo theoretical
Dotted line in Z vs T plot is Gamma/Gamma0

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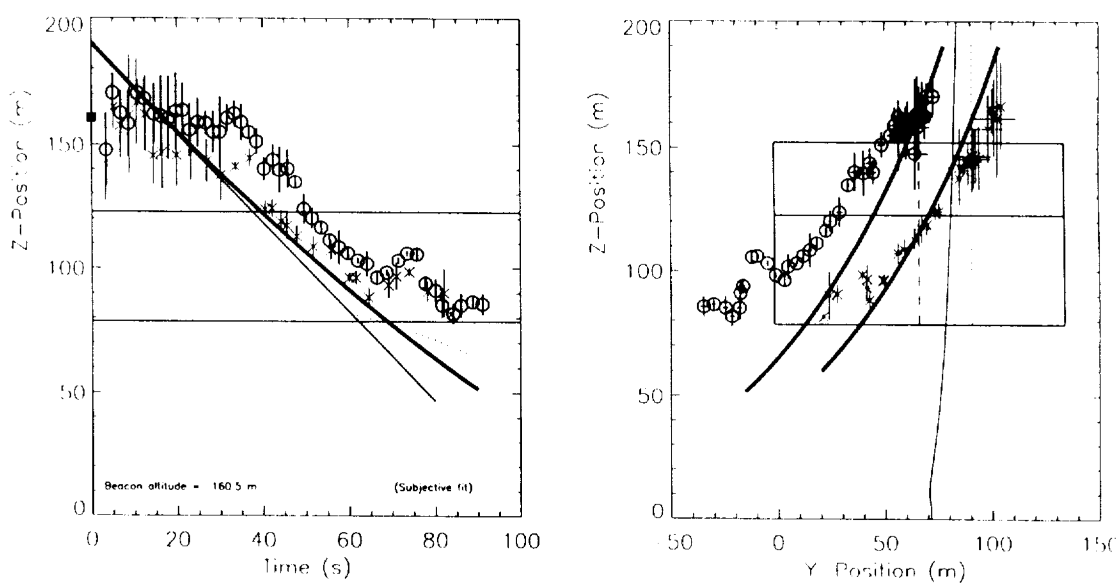
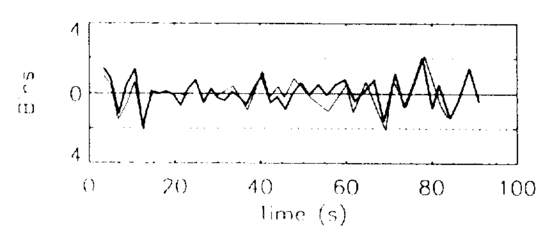
MEM1288, 36R_Armory, 8/16/95 4:51:15, B727, 200 unsmoothed **circle = port** x = starboard




Notes:
Error lines are dely and delz from data file
Bins ~ fd in units of range bins
(1 range bin ~ 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude

Solid line starting at initial altitude indicates descent at Vo theoretical
Dotted line in Z vs T plot is Gamma/Gamma0

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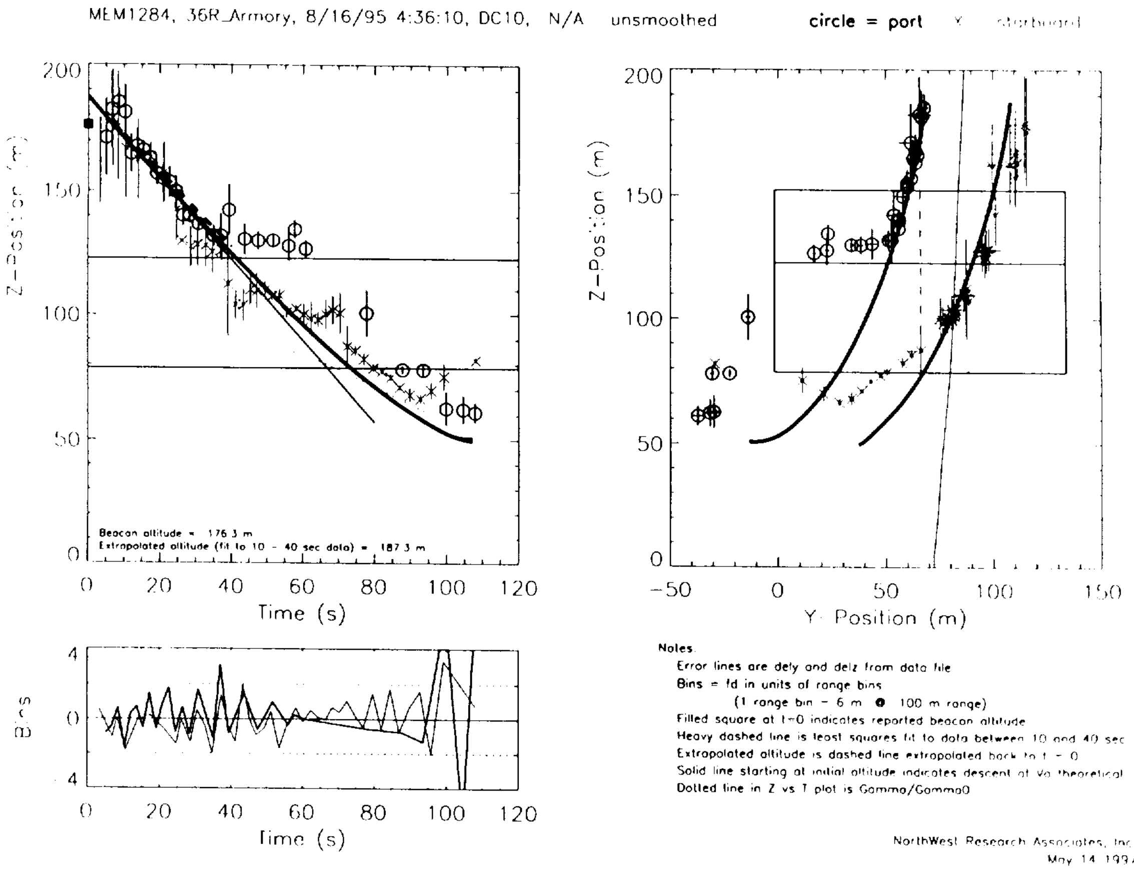
MEM1284, 36R_Armory, 8/16/95 4:36:10, DC10, N/A unsmoothed
circle = port
Z-Position (m)
Time (s)
Beacon altitude = 176.3 m
Extrapolated altitude (fit to 10 - 40 sec data) = 187.3 m
Bins
Y-Position (m)
Notes.
Error lines are dely and delz from data file
Bins = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Heavy dashed line is least squares fit to data between 10 and 40 sec
Extrapolated altitude is dashed line extrapolated back to t = 0
Solid line starting at initial altitude indicates descent at Vo theoretical
Dotted line in Z vs T plot is Gamma/Gamma0
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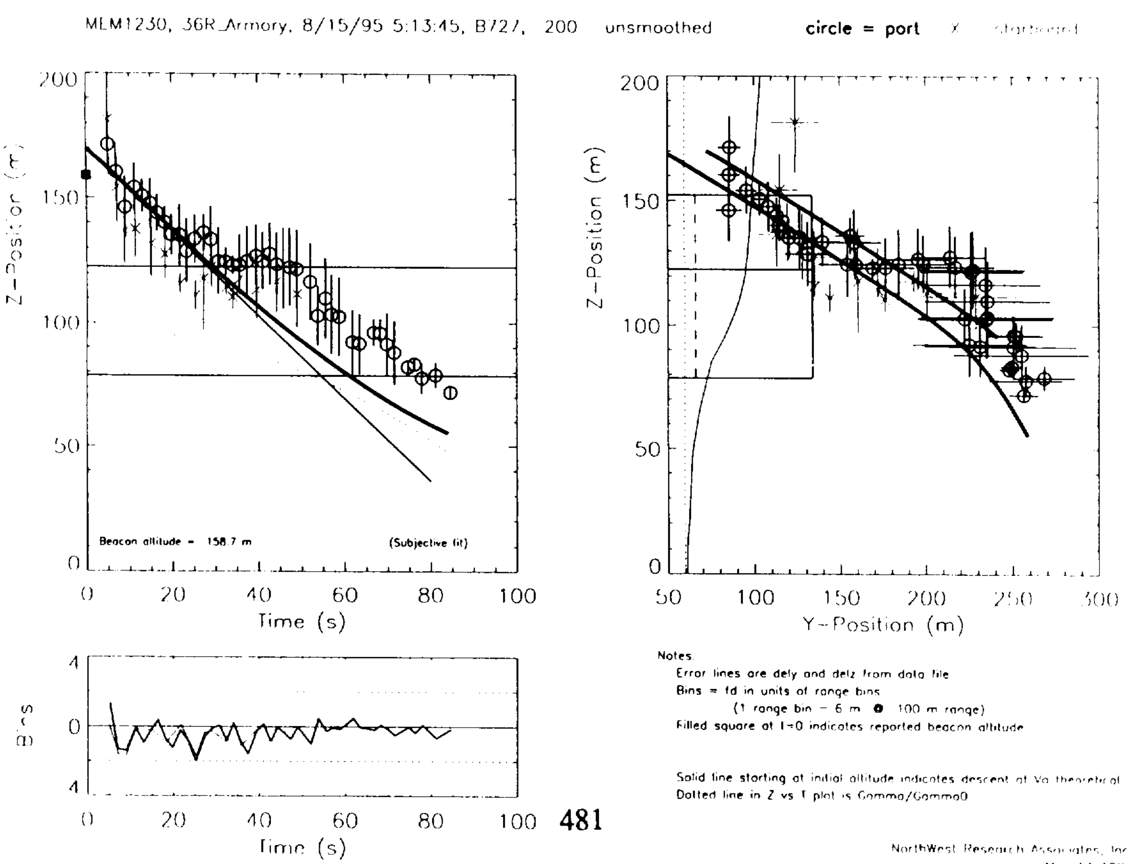
MEM1230, 36R_Armory, 8/15/95 5:13:45, B727, 200 unsmoothed
circle = port
Z-Position (m)
Time (s)
Beacon altitude = 158.7 m
(Subjective fit)
Bins
Y-Position (m)
Notes.
Error lines are dely and delz from data file
Bins = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Solid line starting at initial altitude indicates descent at Vo theoretical
Dotted line in Z vs T plot is Gamma/Gamma0
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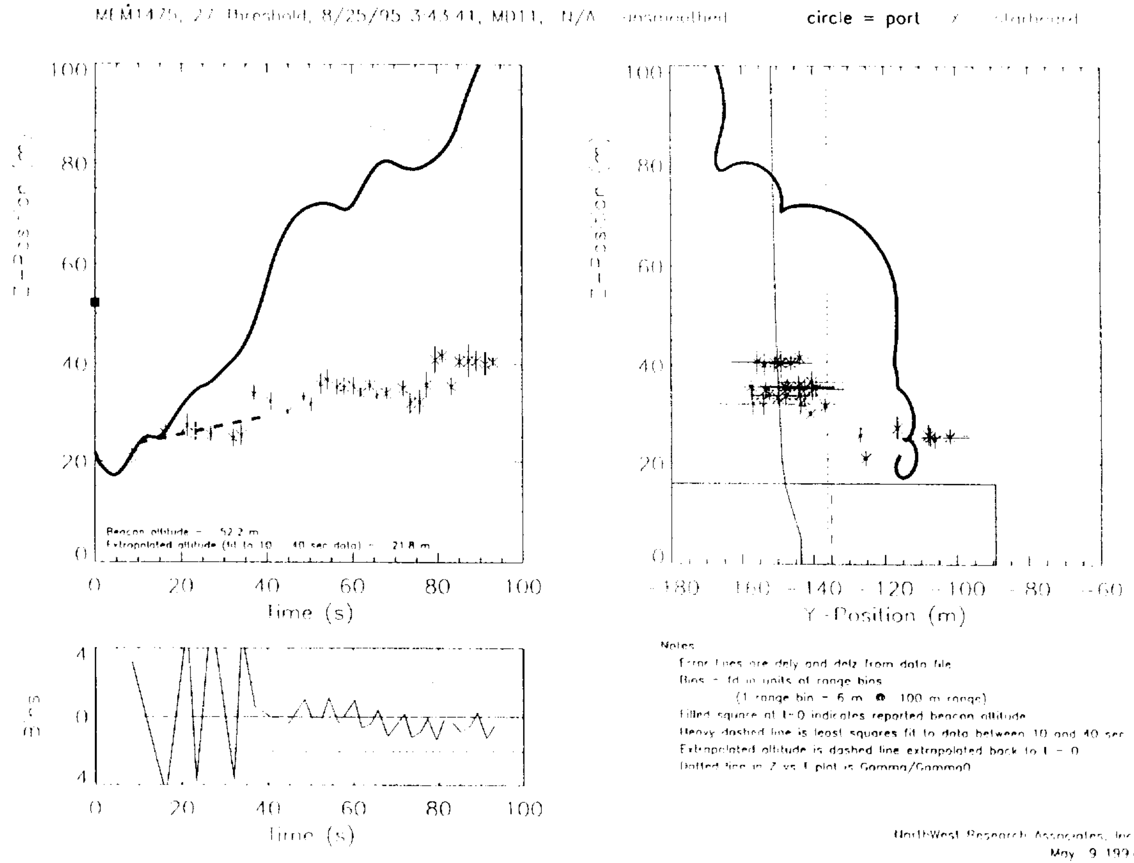
MEM1425, 27 threshold, 8/25/95 3:43:41, MD11, N/A unsmoothed
circle = port
Beacon altitude = 52.2 m
Extrapolated altitude (fit to 10 - 40 sec data) = 21.8 m
Time (s)
Y-Position (m)
Notes
Error lines are dely and delz from data file
Bias = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Heavy dashed line is least squares fit to data between 10 and 40 sec
Extrapolated altitude is dashed line extrapolated back to t = 0
Dotted line in Z vs T plot is Gamma/Gamma0
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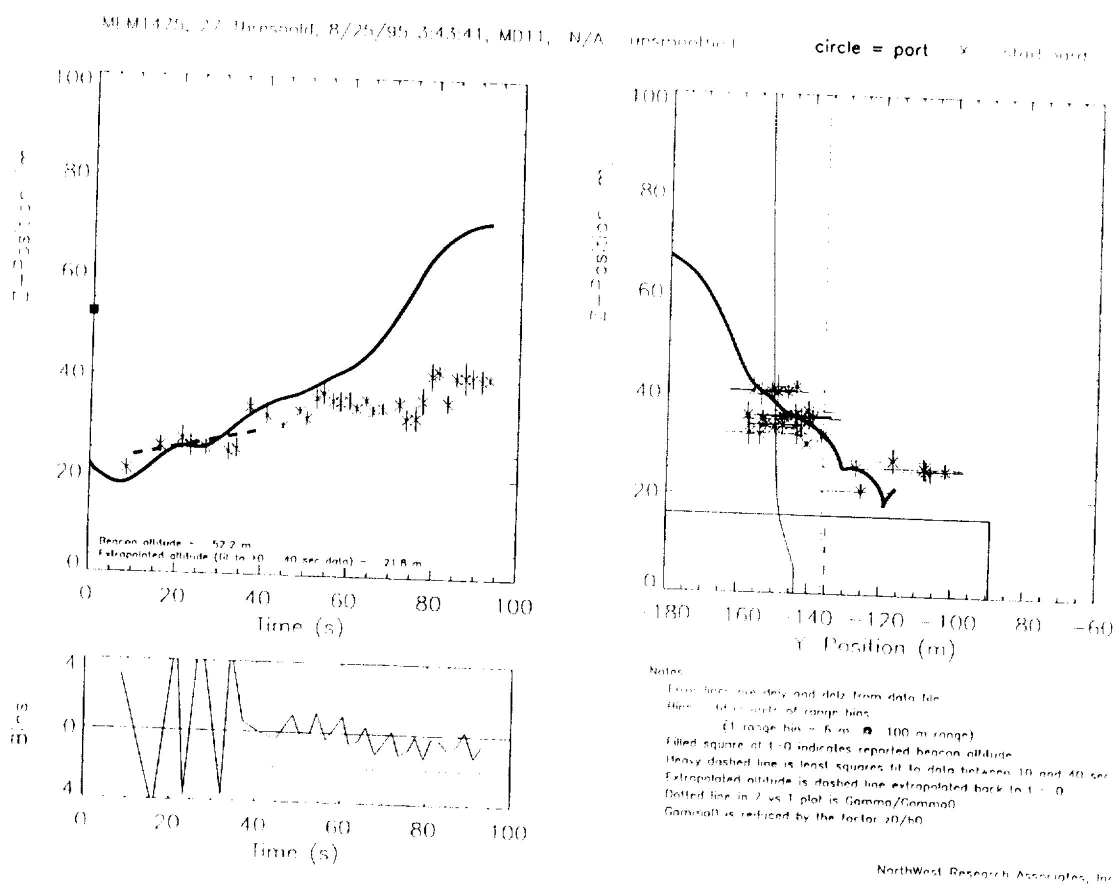
MEM1425, 27 threshold, 8/25/95 3:43:41, MD11, N/A unsmoothed
circle = port
Beacon altitude = 52.2 m
Extrapolated altitude (fit to 10 - 40 sec data) = 21.8 m
Time (s)
Y-Position (m)
Notes
Error lines are dely and delz from data file
Bias = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Heavy dashed line is least squares fit to data between 10 and 40 sec
Extrapolated altitude is dashed line extrapolated back to t = 0
Dotted line in Z vs T plot is Gamma/Gamma0
Gamma0 is reduced by the factor z0/b0
NorthWest Research Associates, Inc
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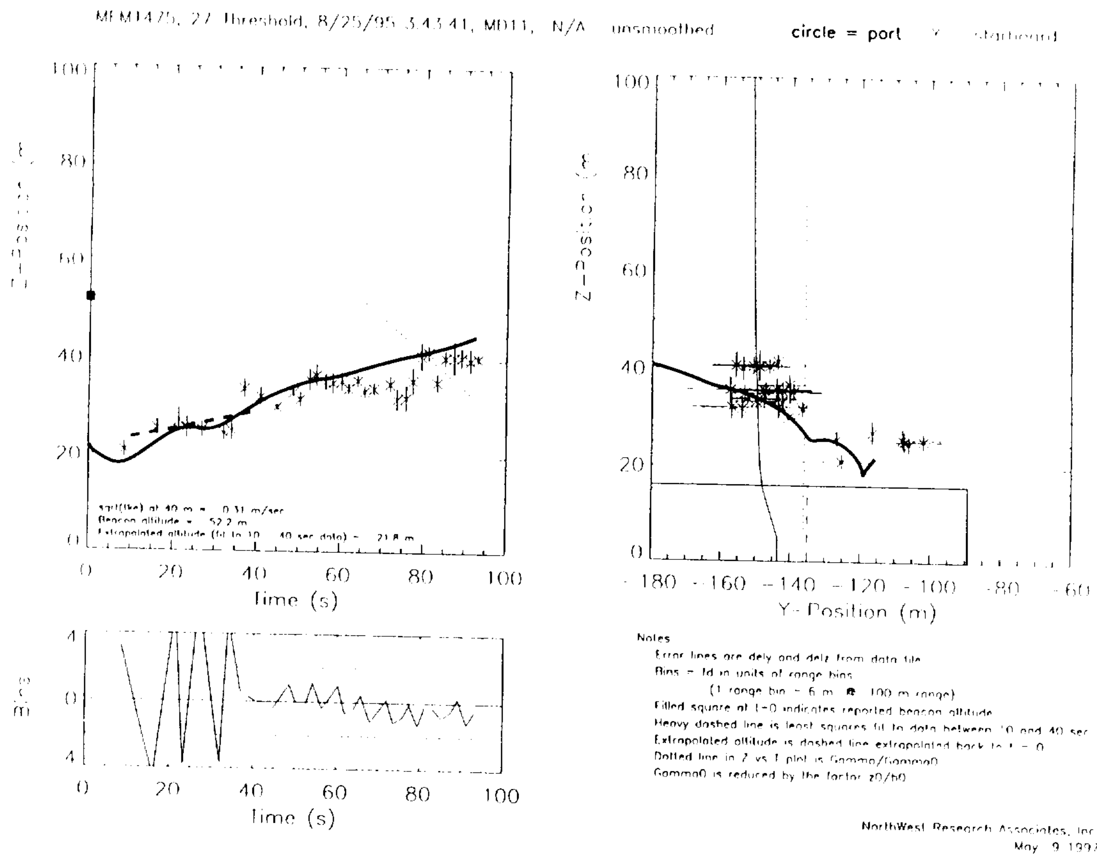
MFM1475, 27 Threshold, 8/25/95 3:43:41, MD11, N/A unsmoothed
circle = port
sqrt(tke) at 40 m = 0.31 m/sec
Beacon altitude = 52.2 m
Extrapolated altitude (fit to 10 40 sec data) = 21.8 m
Time (s)
Z-Position (m)
Y-Position (m)
Notes
Error lines are dely and delz from data file
Bins = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Heavy dashed line is least squares fit to data between 10 and 40 sec
Extrapolated altitude is dashed line extrapolated back to t = 0
Dotted line in Z vs T plot is Gamma/Gamma0
Gamma0 is reduced by the factor z0/b0
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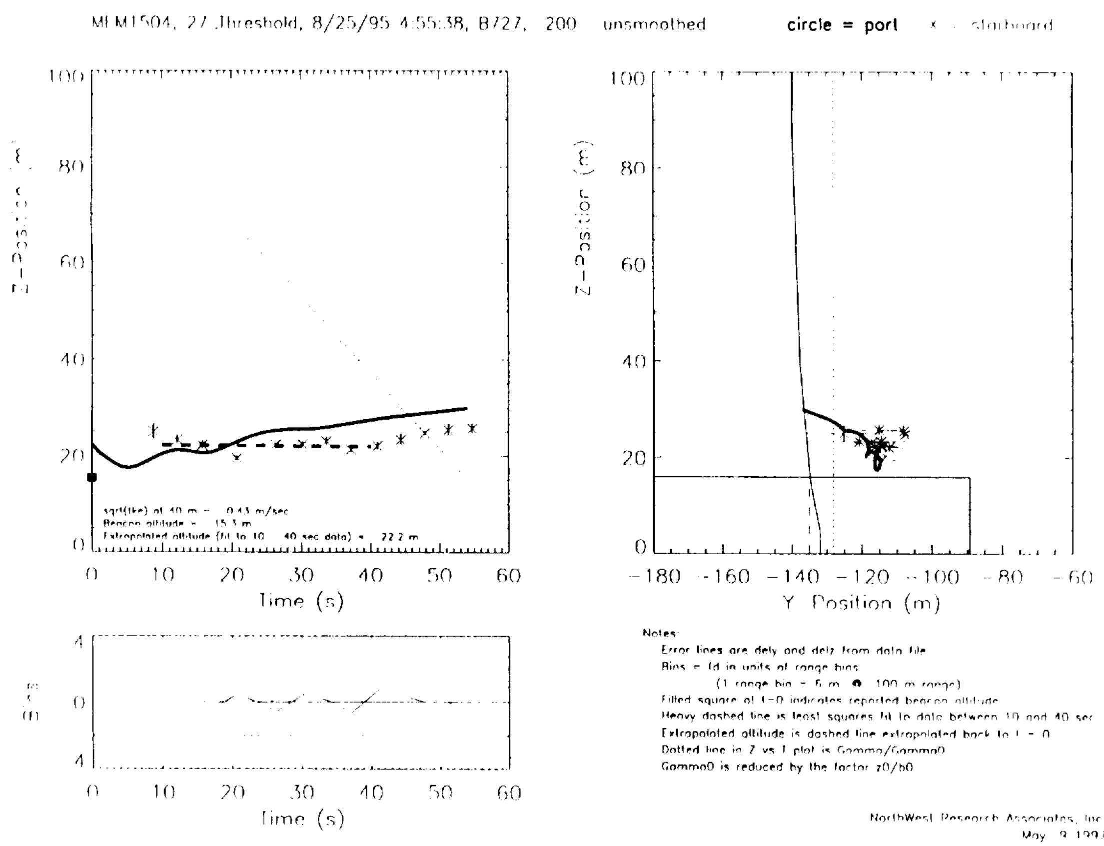
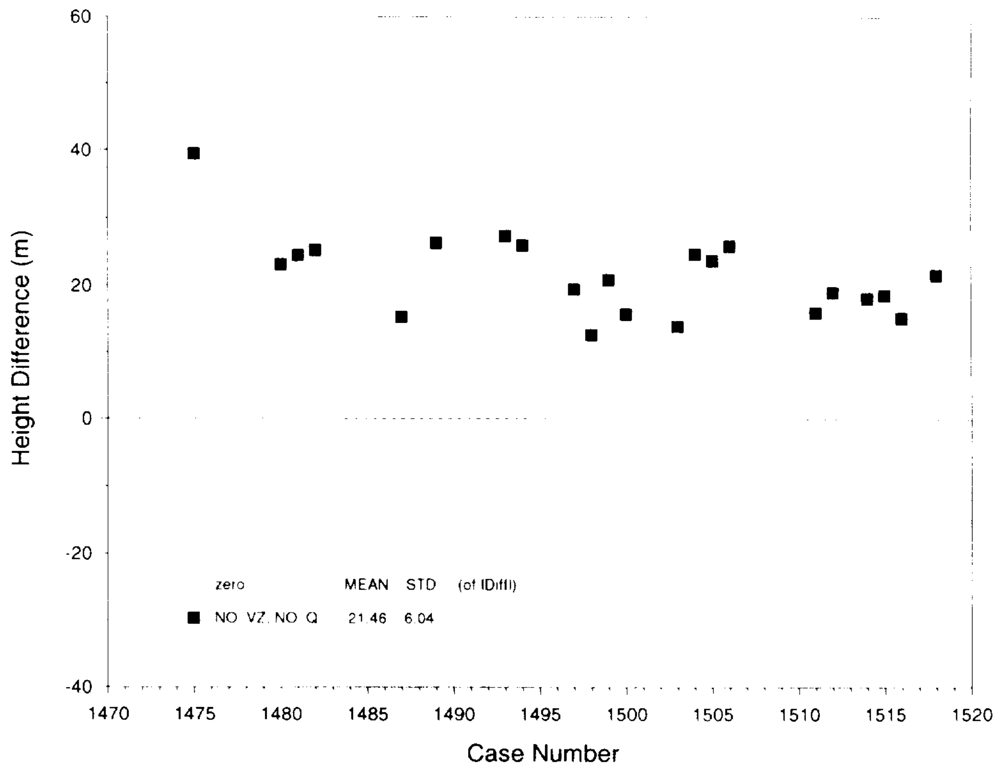
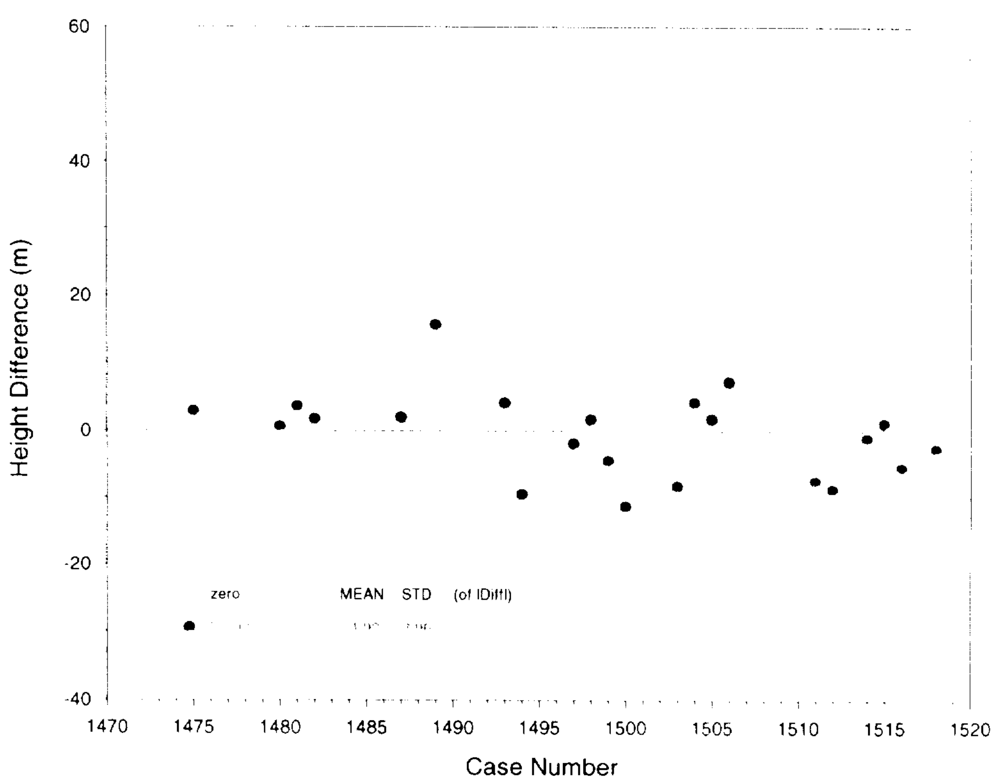

MFM1504, 27 Threshold, 8/25/95 4:55:38, B727, 200 unsmoothed
circle = port
sqrt(tke) at 40 m = 0.43 m/sec
Beacon altitude = 15.3 m
Extrapolated altitude (fit to 10 40 sec data) = 22.2 m
Time (s)
Z-Position (m)
Y Position (m)
Notes
Error lines are dely and delz from data file
Bins = fd in units of range bins
(1 range bin = 6 m @ 100 m range)
Filled square at t=0 indicates reported beacon altitude
Heavy dashed line is least squares fit to data between 10 and 40 sec
Extrapolated altitude is dashed line extrapolated back to t = 0
Dotted line in Z vs T plot is Gamma/Gamma0
Gamma0 is reduced by the factor z0/b0
NorthWest Research Associates, Inc
May 9 1997

Difference Between Predicted and Measured Heights at 50 Seconds




## Threshold Site, 25 August 1995

Difference Between Predicted and Measured Heights at 50 Seconds



# Algorithm / Data Issues

- Initial position of aircraft
- Wind profile - proximity and resolution
- Shear effects
- Ground effect
  - What is the best way to model the incomplete roll-up and reduction of initial circulation due to ground effect?
  - What is the best way to handle vortex rebound?
  - ➪ We need field observations of secondary vortices!
- What is the best way to model atmospheric turbulence?

# Future Enhancements

- Refine treatment of ground effect
  - Ground vorticity
  - Dissipation
- Incorporate shear effects
- Headwind

# Summary

- Predictor algorithm results have been compared with data for vortices in and out of ground effect
- Algorithm works reasonably well but needs refinement
- Current predictor algorithm will be used at DFW

**Questions and Discussions Following Don Delisi's Presentation (Northwest Research Associate)**

Tim Dasey (Lincoln Lab)
The MD-11 case seems to be heavily simulated, so I thought I would put out a warning, which I had done to a smaller group earlier but now to this group as a whole. The MD-11 didn't land; it came within a few meters of touchdown, then did a go around. The characteristics may be different than for planes that did land.

Klaus Sievers (German Cockpit Assoc.)
I have two questions. What type of airplane data is fed into your system? Is it just the aircraft type or is the gross weight at the moment of landing? What are you using? The second thing is, you mentioned as a difficult issue, the initial aircraft position. I don't quite understand. If you take a position along the approach path, you have the glide slope, the localizer, and as close as you are making observations to the runway, aircraft should have very little dispersion.

Delisi
Let me take your second question first because I forgot what the first was. On the aircraft, we are going to get significantly better estimates of position. What we found at the middle marker was that the aircraft were not exactly where we thought they were. That is fine if you are going to validate the code. It is different if you are going to use it as a prediction algorithm for how long the vortices are going to stay within a certain box. If the vortices start outside the location where you thought they were, then your prediction times may be significantly different. So we are going to be checking that at Dallas. I am sorry, what was the first question?

Sievers
What type of airplane data do you feed into the model? Also, what kind of dispersion were you observing at the middle marker position. How many meters left or right were the aircraft?

Delisi
Why don't we talk about that later and let me show you some of those things. We used, in validation, the actual aircraft, the recorded weight, and recorded speed. In the validation we used what the aircraft was. At Dallas, we will be doing a complete matrix because we won't know at any given time which airplane is coming in and the weight and speed. So we will be taking nominal values and taking variances around that.

Alex Praskovsky (NCAR)
Am I right, if I say that I understand from your presentation that your concept and algorithm is to parameterize what is wake dynamics as a function of atmospheric conditions? Is that correct? You take some data, assume you know the wind conditions, atmospheric conditions, and then you define some formulas what is wake dynamics and put it into output of system. Is that correct?

Delisi
Yes, the profile will be coming from the ITWS profile generator. So they will be coming every 15 minutes. Then they will be running.

Praskovsky
Excuse my interruption, you know this data, profiles everything. So you take for example decay, some formula, linear, experimental, some coefficients which you parameterize. Is that correct or are your coefficients adaptive in real time?

Delisi - I don't follow that question, Bob do you know?

Bob Robbins (Northwest Assoc.)
What we do is that we are solving for the evolution of the point vortices. We use a forth order Runge Kutta adaptive ODE algorithm to actually complete the motion of the vortices. It isn't a statistical parameter, it isn't a one equation kind of thing. It is a dynamic solution. I don't know if that answers the question.

Praskovsky - Yes, thank you.

Susan Ying (McDonnell Douglas)
One quick comment regarding the incomplete roll-up or those cases you classify as incomplete rollups. There was another comment there about going around. I think it is very possible that when your aircraft go around you probably have faster speeds and also the flap edge vortex might not be as strong and rolled up with wing tip vortex. So you may be getting less vortex strength.

Delisi
Yes, that was motivation for changing the strength as a function of height inside of $AB_o$ from the ground.

# The Final Approach Spacing Tool (FAST)

**Rhonda Slattery**
**Air Traffic Management Branch**
**NASA Ames Research Center**

# FAST: What is it?

- The ***Final Approach Spacing Tool (FAST)*** is a decision support tool for terminal area (TRACON) air traffic controllers
- FAST utilizes 4D trajectory synthesis, human performance modeling, and a graphical user interface to plan and advise efficient, conflict-free aircraft trajectories for arrival traffic
- FAST increases airport capacity, reduces arrival delays, and reduces controller workload by issuing:
  - sequence and runway advisories (***"Passive" FAST***)
  - speed and heading advisories (***"Active" FAST***)

Terminal Area Productivity Program

# Dynamic Spacing Human Factors



**Barbara G. Kanki**
**NASA Ames Research Center**
**Moffett Field, CA 94035**
**415 604 5785**
**bkanki@mail.arc.nasa.gov**

Wake Vortex Dynamic Spacing Workshop
NASA Langley Research Center / May 13-15, 1997

# AGENDA

- **Dynamic Spacing Human Factors Overview**
- **Preliminary Test**
  - ▼ Specific Objectives
  - ▼ Measures & Variables
  - ▼ The Set Up
  - ▼ Results of Training Runs
  - ▼ Results of Test Runs
  - ▼ Summary
- **Current Research Status & Plans**

# The Final Approach Spacing Tool (FAST)


**Rhonda Slattery**
**Air Traffic Management Branch**
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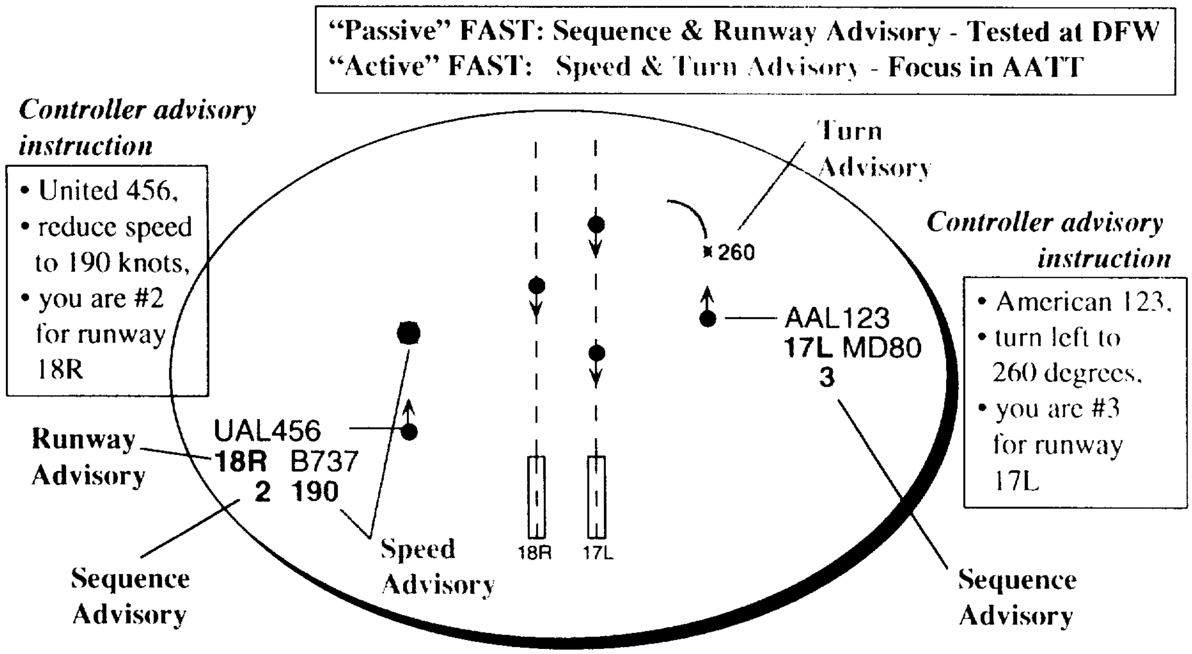
  - sequence and runway advisories (***"Passive"*** ***FAST***)
  - speed and heading advisories (***"Active"*** ***FAST***)

# FAST - Integrated Controller Display



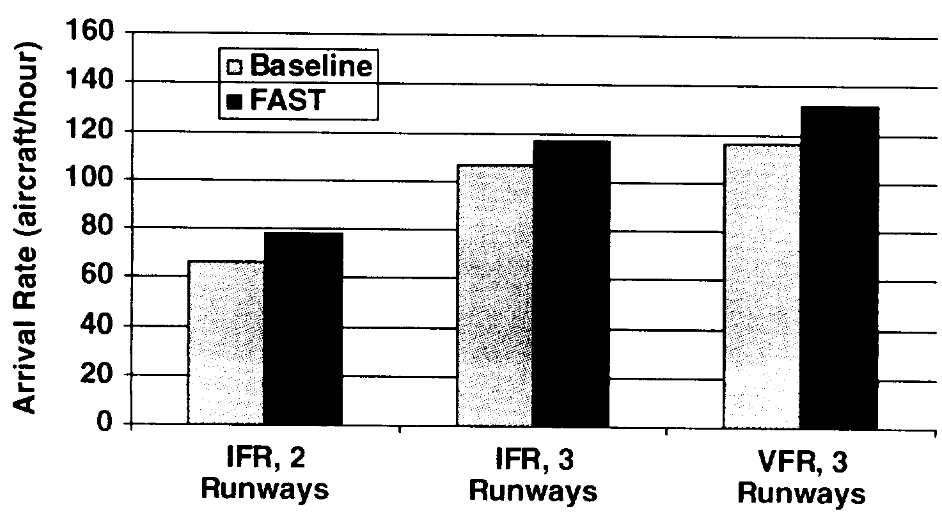

# FAST Operational Testing (to date)

- Test Site: Dallas/Fort Worth (D/FW) TRACON
- Test Period: February-July, 1996
- *Passive FAST* functionalities tested (**runway and sequence advisories**)
- System evaluated by D/FW-appointed "Assessment Team"
  - Specifically trained for evaluation (FAST functionality + Human Factors Assessment)
  - Active participation from ATA and NATCA
- Operational Test-Airport Configurations
  - South Flow, VFR, 3 runways
  - North Flow, VFR & IFR, 3 runways
  - North Flow, IFR, 2 runways

# Passive FAST Test Highlights

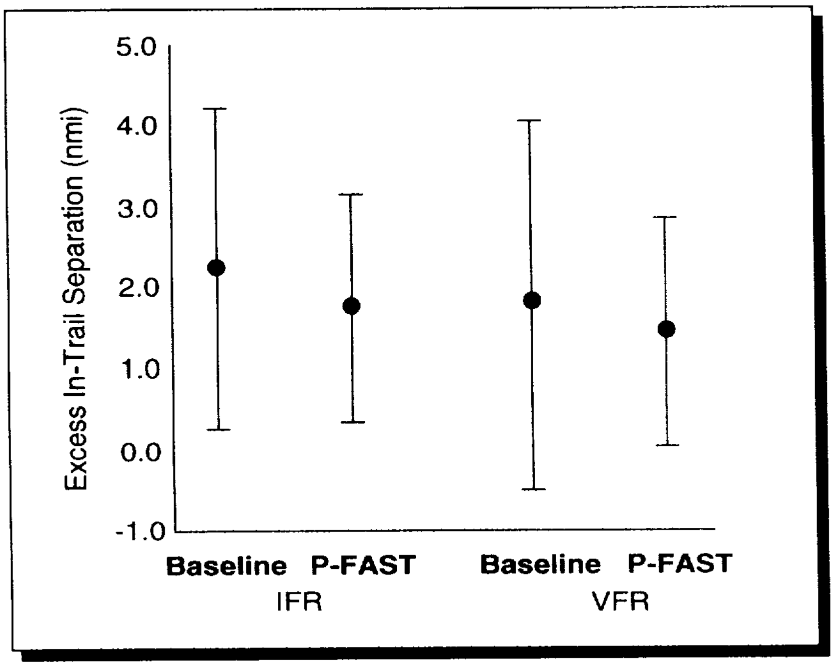
- Many rushes were "free-flowed" (cancelled metering) 10-15 minutes after they began
  - Arrival rate increases 10-15% depending on conditions
  - Small, but acceptable, workload increase during increased traffic levels
  - Sharp workload reduction during current traffic levels
- Positive feedback from tower/ground control
  - "Near-perfect runway balancing"
  - No measured increase in taxi-in or taxi-out time

# Passive FAST vs. Current Operation (Aircraft Arrival Rates)



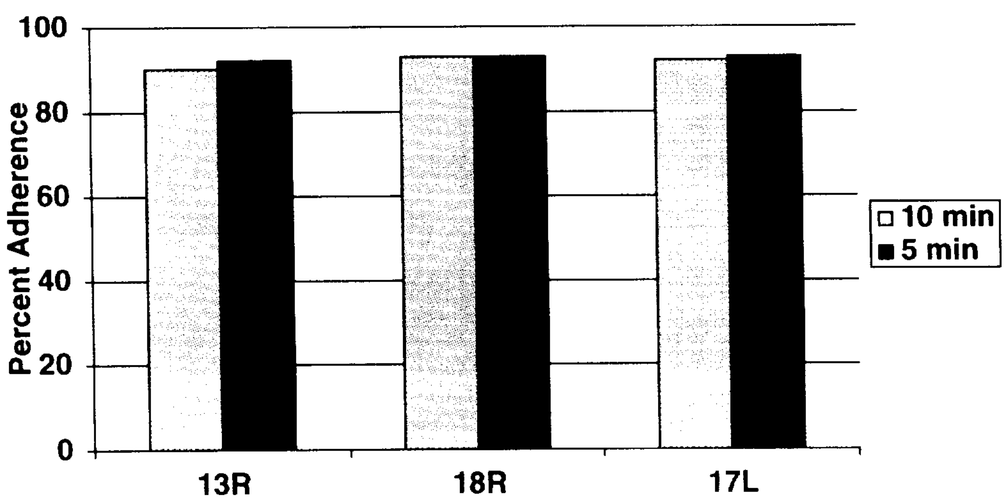

*11:30 am rush,*
*VFR corrected for inboard landings*

# Passive FAST vs. Current Operation (Excess in-trail Separations)



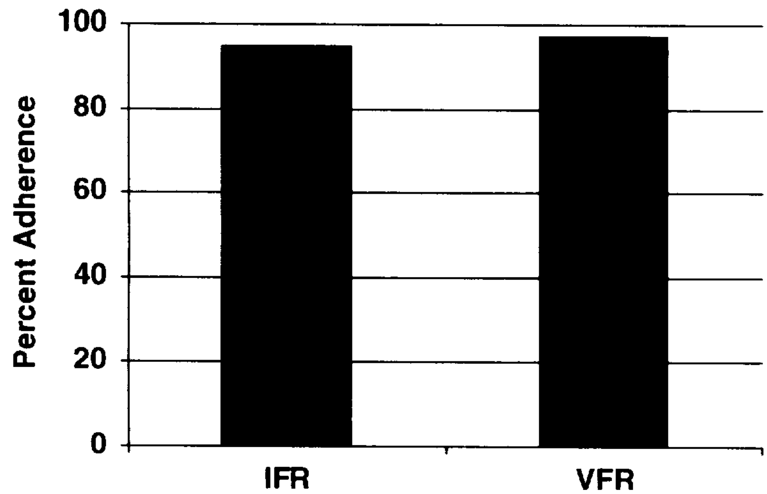

*11:30 am rush, measured at Outer Marker*

# Passive FAST Sequence Advisory Adherence

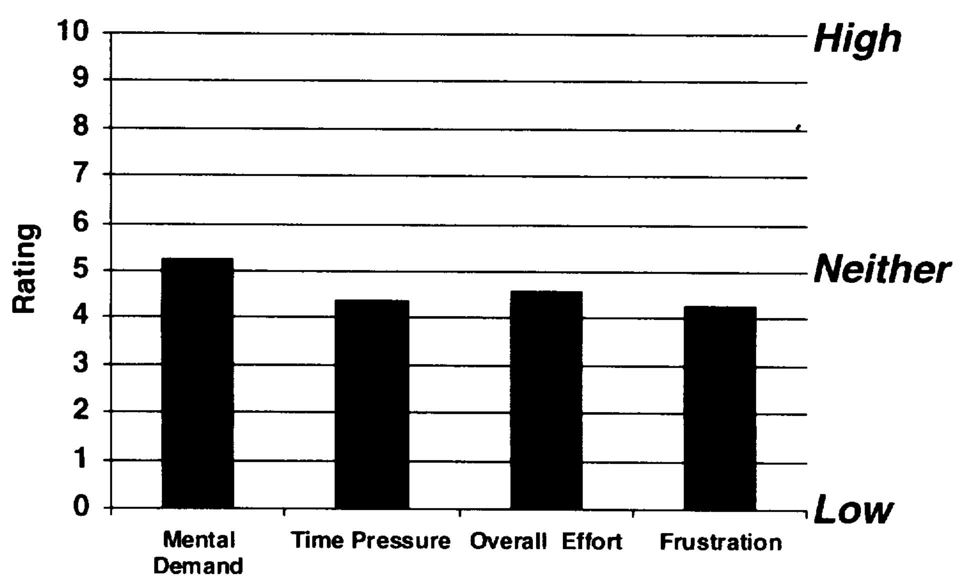



*Note: These results are updated from previously published results*

# Passive FAST
# Runway Advisory Adherence




# Passive FAST Workload Ratings



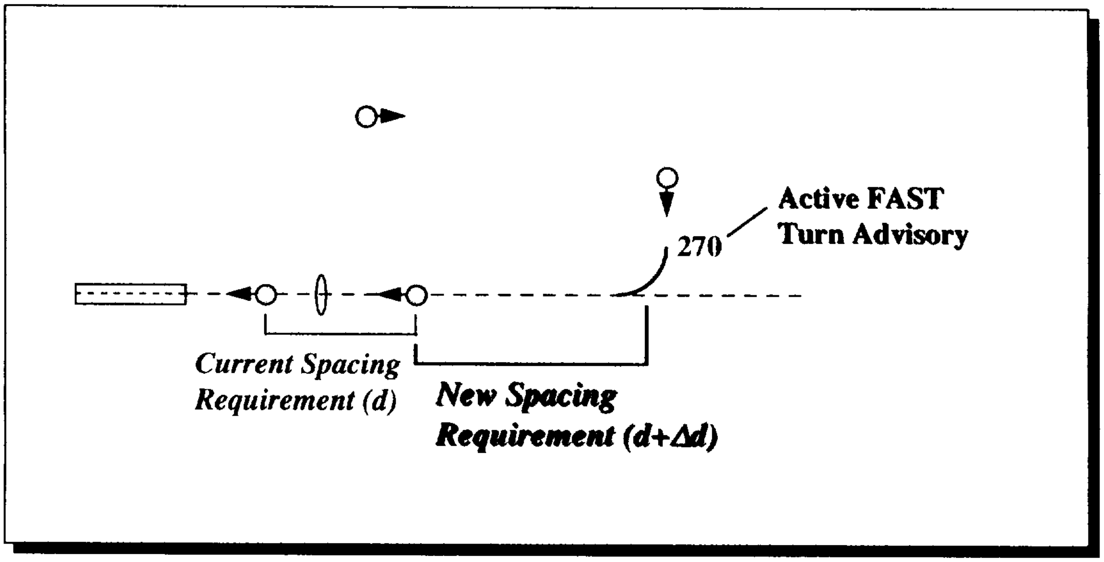
## Passive FAST: What's next?

- FAA plans permanent installation of ***Passive FAST*** at D/FW by 5/97
  - contractor on-board for "code-hardening"
  - re-adaptation for D/FW Metroplex airspace
  - new interface for upgraded FAA computers
- FAA plans future deployments of ***Passive FAST*** to LAX, Denver, Chicago, and New York
- NASA documenting system design and field test results

## Active FAST: Concept Basis

- Analysis of D/FW Baseline data shows (ref. Ballin & Erzberger, NASA TM 110397, July 96):
  - controllers have difficulty spacing traffic at half-mile increments
  - controllers have difficulty in achieving different spacings for the different weight classes and speeds
  - wide varations in spacing performance for similar conditions
  - large potential to reduce the controller separation buffer through increased spacing precision
- *Active FAST* provides the advisories and mechanism to achieve a higher precision inter-arrival spacing given varying separation requirements on final approach

# Active FAST: Dynamic Spacing




# FAST Development Schedule

- Passive FAST
  - Permanent Installation at DFW: June, 1997
  - Final Documentation (Algorithms, Test Results): August, 1997
- Active FAST
  - Operational Concept of Integrated Departure/Arrival Tool (Active FAST/EDP): September, 1997
  - Initial Real-Time Simulation: December, 1997
  - Operational Field Test: December, 1999

**Questions and Discussions Following Rhonda Slattery's Presentation (NASA Ames)**

Jan Demuth (FAA Flight Standards)
I am intrigued by your separation analysis chart and have a question. Do I understand that 0 is ...

Slattery
0 would be 2.5 miles exactly, 3, 4, whatever the required separation is.

Demuth
This says to me in IFR that they are running about 2 miles in excess of standard.

Slattery
Yes, that analysis of current traffic showed that we could increase throughput widely if you could just reduce those excess separations.

Demuth
Would you have data like that at the threshold?

Slattery
I don't have it. The problem is that they can land on two runways if they compress too much. So there is varying issues on that.

Demuth
You understand the question about threshold spacing?

Slattery
I do understand, but this is the separation that should be met at the outer marker to meet the minimum separation at threshold or wherever it should be for faster aircraft behind slower aircraft or whatever.

Joerg Rankenburg (German Air Traffic Services)
I have a question concerning those marks on your radar scope. You said these marks are printed automatically. I just want to know what happens if the controller misses the ideal turning point? What happens to the other aircraft? Is there an automatic update?

Slattery
What both passive and active FAST does is update every time it gets a radar hit. So if a controller misses a turn, all the following aircraft would be recalculated.

Rankenburg
That is future music. That is not done in the present.

Slattery

Yes, at present controllers do their own planning, no automation.

Rankenburg
You won't issue any speed or headings up to now. So how does the computer know where to put his turning point unless he knows what the speed is on the preceding and succeeding.

Slattery
He knows what the current speed is, I am not sure what...

Rankenburg
He takes it out of...

Slattery
Yes we get data which include position, speed, and have a wind estimate to get airspeed.

Phil Hogg (United Airlines)
I saw where the installation was to occur in June and the documentation to be available in August. When do you anticipate the operational availability to the controllers on a permanent basis?

Slattery
The plan is for June. The documentation is more at a code level, there is training documentation which has already been done.

Hogg
So the installation in June would also be operational and permanent.

Slattery
Yes, operational and unless it dies, the plan is to be permanent.

David Smith (Seattle-Tacoma International Airport)
I am trying to understand as a follow-on to the in-trail separation and the variance in that. Was that data operational across the entire flight schedule? What I am trying to get at is the demand, that is if you only had one aircraft show up.

Slattery
Right, no that is actually only data for that particular rush. But it aggregated across all the aircraft types and things. I agree if there are only two aircraft in the sky and they are miles and miles apart, we don't measure that.

Jerry Robinson (Boeing Company)
I have a couple of questions. What position receives advisories from FAST? What role is NACA playing in making active FAST become operational?

Slattery
All TRACON positions, both feeder and final. Is anyone here from NACA? I couldn't answer that question.

Tom Doyle (Adsystech)
Formerly an area manager at DFW, I am not representing NACA, but I can say that NACA did take part in all activities of FAST. They are on the FAST team, still on the active FAST team. I think you have a cadre of at least half a dozen controllers from NACA. Also there are five positions, and a satellite position who is handling diagonal runway operation.

Jim Evans (Lincoln Lab)
I would also comment that looking at these separations, you probably have to look at the threshold. A lot of times we were running at Dallas you see much stronger winds aloft, 2000 ft, than you see at the surface.

Slattery
I have seen threshold plots, but I didn't put this together.

Leonard Credeur (NASA Langley)
On the VFR separation, the excess separation, do you know how the base separations were determined? In other words there is no standard in VFR, so when you have excess separation, excess to what is my question?

Slattery
I believe in this case it is also the required IFR separation. I am not completely sure for this plot, but that is generally what people are using for analysis because there is no VFR standard.

Steve Campbell (Lincoln Lab)
I think what happens is that you apply the wake vortex standard to the outer marker then let them go inside to threshold.

Klaus Sievers (German Cockpit Association)
Just a final doubting question. Are you really sure of your graph and your measurement? What this says to me is that they are running at double the required separation at Dallas and that can't be true.

Slattery
All I say is that I have seen numerous plots. Some controllers do pretty good at about half a mile. 2.5 miles is a minimum and they don't really aim for that. They have to put in a buffer so they don't violate the minimum.

Credeur
If you saw the excess plots for the threshold, you would probably see those excess separations are not as big as the plot. So in a capacity sense it is not as bad as this

plot would indicate.

[Editor's note inserted]
[If one takes the 18 seconds often used as the standard deviation of manual controller precision of separation and multiply that by 1.65 to keep separation violations less than 5%, then you get about 30 seconds of buffer which at typical approach speeds means a mile or so of extra or buffer separation.]

Slattery
I would agree with that. It is definitely not a 50% increase in capacity; it is more in the order of 20% if you reduced excess separation.

Robinson
I would imagine that is probably a box-whisker type plot. Aren't those letting you know the lower 25 and 75 percentile range of separation and the dots are the medium values? So you don't know what the distribution is around it.

Slattery
Right, there could have been a couple of real far outliers that would pull average up.

Terminal Area Productivity Program

# Dynamic Spacing Human Factors

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Wake Vortex Dynamic Spacing Workshop
NASA Langley Research Center / May 13-15, 1997

## AGENDA

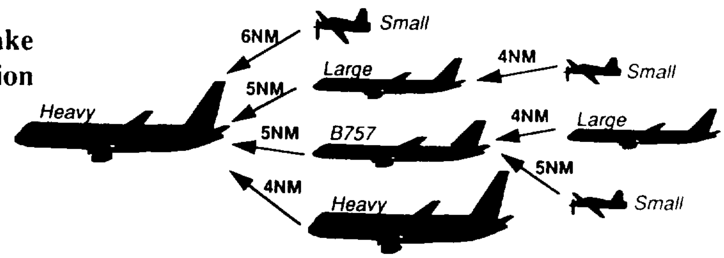
- Dynamic Spacing Human Factors Overview
- Preliminary Test
  - Specific Objectives
  - Measures & Variables
  - The Set Up
  - Results of Training Runs
  - Results of Test Runs
  - Summary
- Current Research Status & Plans

BGKanki NASA/ARC 5.97

# Dynamic Spacing Human Factors

**Background:**

AVOSS technologies will make it possible to reduce separation standards in the terminal area under certain meteorological conditions




**Human Factors Issues:**

- Define controller limits to incorporating dynamic changes in separation standards
  - Adequate transition time
  - Limited number & complexity of different separation standards
  - Acceptable levels of workload
- Identify timing, planning & coordination strategies
- Consider consistency with current practices, policies, regulations

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# Dynamic Spacing Human Factors: An Integrated Approach

**Simulation Approach:**

- DFW TRACON airspace
  - Realistic traffic flow & A/C mix
  - Participants: TRACON feeder & final; Pseudo pilots
- Training protocol
  - Use of online feedback
  - Consider team strategies
  - Consider operational practices
- Performance measures
  - AC separation, throughput,
  - Operational errors, workload
  - Communications

**Field Approach:**

- Observe DFW ATC operations
  - Traffic flow & A/C mix
  - TRACON feeder & final
  - Center, Towers, Pilots
- Observe training
  - Methods, goals,
  - Performance criteria
- Observe the coordination of controllers and support in the work environment
  - Normal conditions
  - Changing conditions
  - Special weather conditions

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# Preliminary Test: Specific Objectives

- Research Issues
  - Test how well controllers handle shift from reduced to standard separation matrix
  - Understand how widely controllers vary in their performance as final controller
  - Compare training vs. testing differences
- Test of Methods
  - Test out simulation variables: traffic flow, performance measures
  - Test out simulation set-up: scheduling, workload

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# Preliminary Test: Measures & Variables

- Measures:
  - FAF: separation at final approach fix
  - PAS: separation at threshold
  - Excess separation: (actual - required separation)
  - Communications: number com's to pseudo-pilots
- Traffic Flow
  - High: 95 sec between AC
  - Med: 105 sec between AC
  - Low: 115 sec between AC
- Matrices

| Following \ Leading | Small | Large | 757 | Heavy |
|---|---|---|---|---|
| Small | 2.5 | 4 | 5 | 6 |
| Large | 2.5 | 2.5 | 4 | 5 |
| Heavy | 2.5 | 2.5 | 4 | 4 |

M1: Standard Separation Matrix

| Following \ Leading | Small | Large | 757 | Heavy |
|---|---|---|---|---|
| Small | 2 | 2 | 4 | 5 |
| Large | 2 | 2 | 3 | 3 |
| Heavy | 2 | 2 | 3 | 3 |

M2: Reduced Separation Matrix

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## Preliminary Test: The Set Up

- 4 Days / controllers 1, 2, 3 & 4
  - C1 & C4 paired on Tues & Fri / C2 & C3 paired on Wed & Thurs
  - Each controller spends one day as feeder controller and one day as final controller
- 2 pseudo-pilots for all sessions
- Training vs. test runs
  - Training Runs: AC=14, TIME=30, low, med & high traffic flow rates, M1 & M2
  - Test Runs: AC=28, TIME=50, low & high traffic flow rates, M2 --> M1

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## Preliminary Test: Results of Training Runs

- Reduced separation achieved in reduced separation matrix condition
  - FAF & PAS: M2 < M1
  - Greater throughput & less total time for M2
- Variability among controllers on degree of separation achieved (PAS)
  - C3 doesn't achieve reduced separation
  - C1 shows decreased excess separation in M2
- More excess separation in low traffic flow
  - PAS: Med < Low

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## Preliminary Test: Results of Test Runs

- FAF & PAS: Reduced separation NOT achieved
- No differences in throughput
- More controller variability
  - (especially PAS measures) C1& C4 < C2 & C3
- FAF & PAS: Less excess separation in M1 than M2
  - controllers achieve "flow" in M2... no change in M1
- Communication greater for C2 & C3 indicating more vectoring, interaction with pseudo-pilots

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## Preliminary Test Summary:
### What did we learn about dynamic spacing?

QUESTIONS asked...

- Is reduced spacing achieved? Are there training vs. testing differences?
- How well do controllers handle the shift from reduced to standard matrix
- How widely do controllers vary in their performance as final controller?

ANSWERS.....

- Reduced separation achieved in training but not test runs; i.e., not with a M2 --> M1 shift within-run.
- Greater controller variability in test runs, are these skill or strategy differences? are there length of run effects?
- Less excess separation in M1 than M2; controllers achieve "flow" in M2... and don't change in M1
- More communication by some teams indicates more vectoring & interaction with pseudo-pilots

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## Preliminary Test Summary:
### What did we learn about our methods?

QUESTIONS asked...

- ➡ How well do the simulation variables work? e.g., traffic flow, performance measures
- ➡ How well does the simulation set-up work? e.g., feeder- final teamwork, pseudo-pilot workload, scheduling

ANSWERS.....

- ➡ Measures of separation, excess separation and communications describe different aspects of performance and workload
- ➡ Traffic must flow at a critical level in order to induce controllers to reduce separations....but
- ➡ In higher traffic flow, feeder and final may or may not have a joint strategy; workload for pseudo-pilots as well as controllers may increase

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## Preliminary Test Summary:
### Unresolved Issues

- To what extent can we generalize from a sample of retired controllers to active controllers who are familiar with a particular airspace?
- To what extent will simulation-induced performances generalize to real operations?
- How do current operations handle dynamic changes and anomalies? How do individuals, teams and facilities coordinate their work and planning in accommodating changes?

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# Current Research Status & Plans

√ **Initial Scenario/Simulation Development . . . . Completed**
  - Baselines, Training & Measures
  - Preliminary Test
  - Preliminary Test Analysis & Review
- **Operational Issues - Field Observations . . . . . . Ongoing**
  - DFW ATC system, training,
  - Live data feed
  - Identification of constraints
- **Full Simulation Experiment . . . . . . . . . . . . . . . . Planned**
  - Adaptation to Metroplex & multi-rwy scenario
  - DFW controllers
- **Consideration of Displays/Advisories . . . . . . . . . TBD**
  - Input from AVOSS, interface with FAST

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**Questions and Discussions Following Barbara Kanki's Presentation (NASA Ames)**

Jan Demuth (FAA)
Where did you get your reduced spacing matrix? Number two, why did you go from reduced to the standard in your testing?

Kanki
The reduced was based on best guess. We don't have answers for that and won't have for some time. We are looking at two different things. We are looking at payoff and we are also looking at where is reduced spacing possible. The focus on the test was the transition and so in some sense it didn't matter what the exact numbers were. We wanted to see how a change would be incorporated. The second question - we would want to do both directions of transitions, standard to reduced and vice versa. Reduced to standard seems more critical.

Demuth
What operational reality were you looking at for that?

Kanki
None, just the logic if you go from standard to reduced, you don't have to do anything special to the stream, but if you go from reduced to standard, you have to start shifting to longer spacing.

Dave Hinton (NASA Langley)
If I could add a few words, we must consider situations with AVOSS that due to changes in weather, thunderstorms approaching or whatever, controller may have to open up spacings during an operational period. We would like to know if that is feasible and safe to do.

Jerry Robinson (Boeing Company)
Was there a large percentage of small aircraft in your study?

Kanki
No, perhaps 2 out of about 28 aircraft.

Bill Rodgers (Honeywell)
You said you had reduced excess separations when you made your transition. Was that in relation to reduced separations or regular standard?

Kanki
That was with the standard, going back to the standard.

Rodgers
A comment - perhaps there could be some insight that can be gained by looking at real operations during a push, if you can catch them when they have to switch from VFR to IFR. There is probably the same kind of issue which you could observe to see

what happens.

Kanki
Right, there are shifts and transitions that normally occur and we could learn by observing those.

Kenny Kaulia (ALPA)
As far as your reduced separation table which you said was a best guess, I would just suggest that if you had a wider band, for instance if you went from 2.5 miles down to 2 miles. Rhonda, in her presentation, said controllers had difficulty with that half mile separation. You might get results if you do something, since it is a best guess, of going say from 2.5 to maybe 1.5 or something like that.

Hinton
We were partially to blame for that matrix, and one of the considerations we gave to all the categories was runway occupancy time. So that is one reason we thought that cell would have to be bounded by 2 miles. If we can do 1.5, we would like to do it. From the wake perspective, we would be able to, but from runway occupancy time it isn't certain that we can.

Charles McKulchen (National Institute of Health)
How old were these controllers who you were trying to teach new tricks? Because it strikes me that it would make a deal of difference if you were trying to teach these people conditioned reflexes, the young ones would be able to switch back and forth and the old one would take you, I suspect, forever.

Kanki
I don't know if age is an issue. The fact that they are retired is an issue, and they don't work at DFW today is an issue. They did achieve the reduced spacing in the training sessions. In that sense they reached the performance criteria.

Tom Doyle (Adsystech, Inc.)
I would say the biggest issue there was that the controllers were not real familiar with the DFW operation. It wasn't their age. They looked competent in what they were doing. They just didn't have a detailed grasp of DFW. Also, I would recommend that you actually get someone from DFW or somebody with an air traffic background to work with you and answer some of the questions raised. They could help a great deal in that area.

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# Wake Vortex Systems Cost/Benefits Analysis

First Wake Vortex Dynamic Spacing Workshop

Vicki K. Crisp
NASA-LaRC
SAB/ASAD

## NASA and FAA Join in Air Traffic Management (ATM) Research

NASA and FAA to improve the efficiency of NAS

- Joint activities include near and long-term requirements in areas such as:
  - Roles of flight crews and ATC
  - Cockpit situational awareness
  - Conflict detection and resolution
  - Flight restrictions
  - Safety analysis
  - Flight operations of all vehicle classes
  - Cost-benefit assessments

# Advanced Subsonics Technology Program

## Goal

Focus technologies to insure U.S. leadership in:

- Aircraft manufacturing
- Aviation system safety and efficiency
- Protection of the environment

## Part of the Answer

Advanced Air Transportation Technology (AATT) Program

Terminal Area Productivity (TAP) Program

# AATT

## Goal

Enable substantial increases in the efficiency and capacity of aircraft operations within the national and global air transportation system to:

- Improve the efficiency of the nation's air transportation infrastructure
- Provide greater operational flexibility
- Enable increased U.S. sales abroad

## Approach

Enable "free flight" within the constraints of safety and other users needs

# TAP

## Goal

Increase airport terminal area capacity in instrument-weather conditions while maintaining equitable safety to:

- Reduce the gap between industry's desired capacity and the ability of the NAS to handle future air traffic growth

## Approach

- Safely reduce aircraft spacing in the terminal area
- Improve low-visibility landing and surface operations
- Enhance ATM and reduce controller workload
- Integrate aircraft and air traffic systems as appropriate

# TAP Elements

- Safely reduce aircraft spacing in the terminal area
  - Reduced Spacing Operations
    - Aircraft Vortex Spacing System (AVOSS)
    - Airborne Information for Lateral Spacing (AILS)
    - FMS/CTAS Integration

- Improve low-visibility landing and surface operations
  - LowVisibility Landing and Surface Operations
    - Taxiway Navigation and Situation Awareness (T-NASA)
    - Roll-Out and Turn-Off (ROTO)
    - Dynamic Runway Occupancy Measurement (DROM)

## TAP Elements

- Enhance ATM and reduce controller workload
  - Air Traffic Management
    - Center/TRACON Automation System (CTAS) automation aids
    - FMS extended utilization
- Integrate aircraft and air traffic systems as appropriate
  - Aircraft-ATC System Integration
    - Cost and benefits studies
    - Sensitivity studies
    - Procedure and safety substantiation
    - 757 flight facility development

## The Behavior of the Dollar ($)

- Airframer
  - Does it reduce my design cycle costs?
  - Does it reduce my manufacturing costs?
  - Does it help me sell more aircraft?
- Airline
  - Does it reduce my operation costs?
  - Does it reduce personnel workload?
  - Does it help me sell more tickets?
- FAA/NASA:
  - Does it increase safety?
  - Does it increase the efficiency of the NAS?
- Consumer:
  - Does it reduce my ticket cost?

## Capacity

*Capacity* is an important variable in controlling the impact of future air traffic increases on the National Airspace System

- AATT: Efficient use of the airspace, “free flight”, provides potential increases in air traffic capacity.

- TAP: Reductions in aircraft separation requirements and runway occupancy time provide potential increases in terminal area capacity or throughput.

## Increase Terminal Area Throughput

- Studies of 10 major U.S. airports (Boston, LaGuardia, Kennedy, Newark, Atlanta Hartsfield, O’Hare, Detroit, San Francisco, LAX, Dallas-Fort-Worth)
  - Sites visited to understand airport operations
  - Airline and airfield personnel surveyed to define surface delay causes
  - Studies performed to define factors that impact ROT
  - Analytical modelling of approach and landing phases and fast-time simulation modelling of surface operations used to study the effects of the TAP technologies
- Impacting Factors
  - Aircraft separation requirements
  - Runway Occupancy Time (ROT)

## Wake Vortex Separation Requirement VS Runway Occupancy Time

- FAA Airfield Capacity Model
  - Decreases in capacity did NOT occur when ROTs increased from dry-runway values to wet-runway values
  - Minimal capacity loss with 20% increase on ROT to depict low-visibility conditions
  - Increases in capacity DID occur when in-trail separations were reduced (if capacity had leveled off, we could assume ROT is the capacity constraint)

In most cases of single-mode operations, wake vortex separations are the primary factor restricting airfield capacity

## Delay Factors of ROT

- Aircraft type/weight
- Surface conditions
- Exit designs/locations
- Runway exit locations
- Pilot motivation & technique
- Touchdown point
- Airline gate locations
- Airline policies

## Surface Delay Causes

- Gate-Hold Delays
  - Destination airport
  - Departure airport
- VMC Taxi-Out Delays
  - Waiting in departure queue
  - Ramp & taxiway congestion
  - Departure sequencing
- VMC Taxi-In Delay
  - Crossing runway/taxiway
  - Waiting for gate
  - Ramp and taxiway congestion

## AVOSS Design Criteria

Is an all weather system necessary?

- Factors affecting IMC Taxi-Out
  - Queue & Ramp
    - ATL - Thunderstorms; DTW - snow/sleet/hail; JFK - snow/sleet/hail & low-vis/fog; LAX - low-vis/fog
  - Taxiway
    - ATL - Snow/sleet/hail; DTW - snow/sleet/hail; JFK - low-vis/fog; LAX - low-vis/fog

Primary factors affecting IMC taxi-in and taxi-out are unique to each airport

Groundbased equipment requirements may vary

## AVOSS Benefits

- LMI Runway/Airport Capacity Model
  - ROTs at dry runway values of approximately 50 seconds
  - Minimum interarrival separation criteria is 3.0 nmi matrix
  - Interarrival time uncertainty 13 seconds
  - 120 second departure separation for heavy/small, heavy/large
- AVOSS
  - Separation criteria moderately reduced for large/small and heavy/all
  - 120 second departure separation reduced to 60 seconds
- AVOSS + ROTO + DROM
  - Minimum interarrival separation matrix reduced to 2.5 nmi
  - Arrival ROTs reduced 20% (average less than 50 seconds)

| | Delay saved 2015 (min) | Boston Logan 2006-2015 | Delay saved 2015 (min) | Detroit 2006-2015 |
|---|---|---|---|---|
| AVOSS | 1.3M | 92 - 165 $M | .2M | 14 - 24 $M |
| AVOSS+ROTO+DROM | 3.3M | 220- 401 $M | .6M | 49 - 86 $M |

## AVOSS Costs

- Preliminary estimates of several configurations
- Software is the "big ticket" item
- Sensor technology cutting-edge

## Summary

Goal of Cost/Benefit Assessments

- Provide quantitative and qualitative data to aid in the decision-making process

- Benefits derived from increased throughput (or decreased delays) used to balance life-cycle costs
- Packaging technologies together may provide greater gains (demonstrate higher ROI)
- LMI: "Estimating the Effects of the Terminal Area Productivity Program"(http://spock.lmi.org/qrswelcome.html)
- MCA Research Corp.: "Airport Surface Delays and Causes"

**Questions and Discussions Following Vicki Crisp's Presentation (NASA Langley)**

Dave Smith (SE-TAC International Airport)
The one slide you had up which showed the various people who needed to assess what they are getting out of it had airline, aircraft manufacturers and I was wondering if you should include airports on slides.

Crisp
Yes. I should have included them. That was an omission of haste. Definitely, airports should be there because they will be responsible for some of the cost. I am sure they are interested to see what their ROI (return on investment) are going to be as well.

Smith
That is a nice entry into one of my comments. On the last slide where you showed cost, one of the things that was not obvious but it has occurred to me, as an airport operator, that somewhere on there we should talk about maintenance in terms of cost benefit.

Crisp
Right, maintenance is being included in the life cycle cost of all our technologies.

Smith
Something that might be helpful. When you do airport surveys and you don't get a large return, you might consider using the FAA regional office, their capacity people. They have access to multiple airports and multiple information they could even themselves as individuals get back to you in terms of answers. The other, you were looking for some data on taxi-in and taxi-out times. There is hard data in a new system called CODES and ASQP on-time performance data that you can get the actual unimpeded times for that information if that is any use to you.

Crisp
OK. Dave, maybe you could comment on that. I think we are doing some simulations for taxi-in and taxi-out, certainly for T-NASA. I am not sure if we are comparing that to real data. Dave.

Dave Chin (MCA Research)
Just to elaborate on that point. We have been using ASQP to get the nominal taxi-in, taxi-out times, especially for T-NASA. We also have work with a new database compiled by the New York Port Authority called KADA, which is more encompassing and covers GA and small aircraft traffic, because ASQP only tracks commercial carriers.

Dan Vicroy (NASA Langley)
It sounds like you got a pretty good data set on some of the surface operations. As George Greene pointed out Tuesday, and also on the chart on separation two

speakers ago, there is a lot of interest in terms of separations during approach to landing today. What are we actually doing today? Are there any plans to collect that kind of data for your analysis? Or do you know of any data that is available for that kind of analysis?

Crisp
Is this under VFR and IFR?

Vicroy
yes

Crisp
We are having difficulty getting that, I think Leonard or Rose may want to respond. From what we are told, it is not captured anywhere in particular. We have talked to a number of pilots and air traffic controllers to get a feel for what they are doing in VFR which tends to be 1.9 miles or even below. Under IFR we assume that we're restricted to FAA standards.

Rose Ashford (NASA Ames)
This has been quite an issue for us. I understand that the actual separations on final approach that are in VFR have been kind of sensitive because of the B757 issue. So we are about to fund an effort by MIT Lincoln Lab to collect VFR separations data at a couple of airports. We're assuming for the AVOSS benefits that the separations currently used in VFR are probably reasonable minimum separations that we could get out of AVOSS. As we continue with cost benefit assessments we will use that until we get more real data out of AVOSS which should be sometime, Dave help me out here, the end of fiscal 98.

Hinton
Yes, we will have data from the deployment in late fiscal 98.

Crisp
We are also getting DROM data.

Ashford
We have not talked about DROM. DROM is another part of TAP which was just completed last month with an installation in Atlanta. What this does is actually measure runway occupancy time and collect a database of occupancy time by aircraft type and weather conditions, time of day, etc. We will be able to figure what is limiting with AVOSS, whether it's separation on approach or runway occupancy time. A second part of that effort is to use a heads-up display in the aircraft to help the pilot in low visibility landing conditions to maximize his safe braking, tell him where the runway exit is so we reduce the times runway occupancy is the limiting factor and maximize the potential benefit of AVOSS.

# Getting to Operational Deployment: Lessons from TDWR and ITWS

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# Outline

- FAA acquisition process
- Issues in development of "wake vortex" like systems
- Development strategy - use of prototypes
- Lessons learned
- Summary

## Old FAA System

- (Phase 0) Mission need and determination
  - Mission Need Statement by "sponsor"
- (KDP-1) Concept exploration / alternative analysis
  - Operational requirements
  - Test and evaluation master plan (TEMP)
- (KDP-2) Demonstration and validation
  - Integrate into NAS architecture
  - Acquisition plan
- (KDP-3) Full-scale development
  - Development specification
  - Procurement
  - Testing
- (KDP-4) Production Phase



## "New" FAA System

- "Sponsor*"
  - Mission Need Statement
- Mission need decision
  - (Operational) requirements document
  - Investment analysis
  - Cost/benefit
  - Acquisition program baseline
  - NAS architecture integration
- Investment decision
  - Solution implementation
- In service decision
  - In service management
  - Service life extension

**http://fast.faa.gov/**

* "Sponsors" - administration, air traffic services, airports, security, capacity, policy/planning, regulation/certification, research/acquisition, system safety, space transportation.

## Mission Need Statement

- Mission area (advisory, flight assistance, capacity, demand management)
- Needed functional capability
- Current capability
- Capability shortfall (quantified)
- Impact if not resolved
- Benefits
- Timeframe
- Criticality
- Long-range resource allocation plan estimate

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## Prototyping and Technology Transfer - The Terminal Weather System Experience

- Issues in development of systems
- How do field prototypes help get there faster and better
- Technology transfer to operational systems
- Updating the system as full scale development is underway
- Issues still to be resolved

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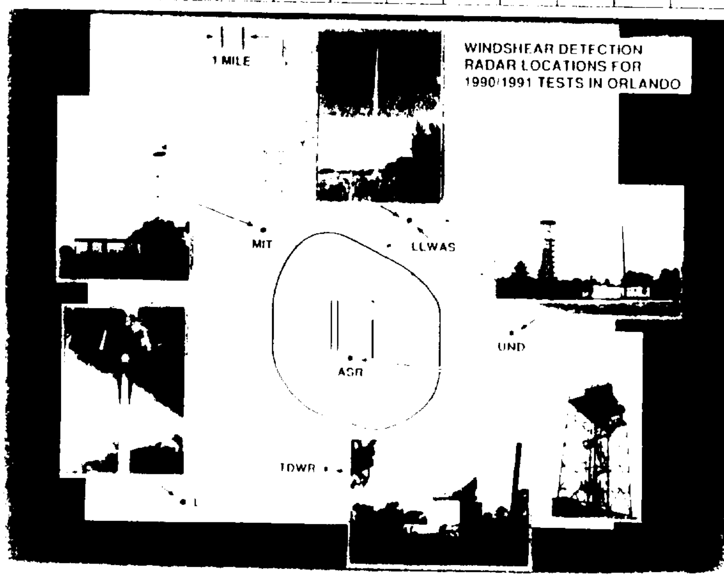
# FAA / LINCOLN LABORATORY AVIATION WEATHER PROGRAMS

| FIELD EXPERIMENTS | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TDWR TEST BED | MEM | HSV | DEN | DEN | MKC | MCO | MCO | MCO | MCO | | | |
| ASR 9 WSP | | | HSV | HSV | MKC | MCO | MCO | MCO | ABQ | ABQ | ABQ | |
| INTEGRATED TERMINAL WEATHER SYSTEM | | | | | | | | | MCO | MCO | MCO | |
| | | | | | | | | | | MEM | MEM | |
| | | | | | | | | | | | DFW | |




# Aviation Weather System Issues

- Improving safety requires addressing rare events
- Weather varies greatly in time, between locations, is not "controllable," nor easy to simulate
- Pilot is the final decision maker and "sees" a different world
- Concurrent evolution of needs, data sources and "science"
  - Air traffic is getting new capabilities with no prior usage
  - Automation, TFM and "free flight" evolving

  Ability to sense weather is limited, but improving

  Product generation "technology" rapidly changing

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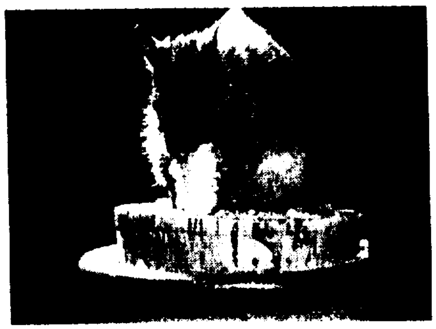
## The Classic Dilemma

**What the User Had in Mind**



**What the Developer Created**

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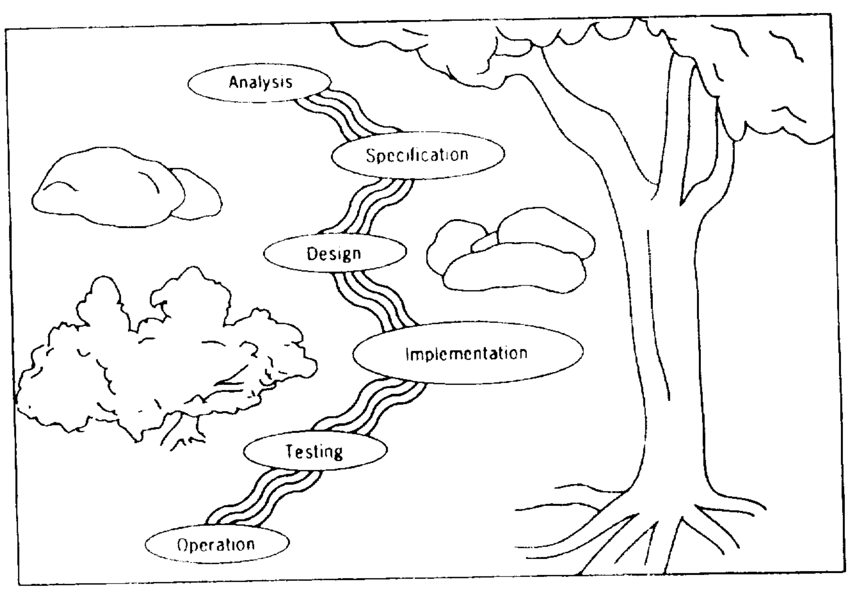
## The Waterfall Model of Software Development *




* From: Gregory W. Jones, *Software Engineering:* New York, John Wiley & Sons, 1990, P. 20

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## Types of Prototype

- "Rapid" prototype
  - Used to determine user needs. Reuse of other software is common. Efficiency, dependability are relatively unimportant. The "quick-and-dirty" software is then discarded and replaced by reliable, maintainable software tailored to the operational need.
- Functional prototype
  - Provides functionality desired. May not meet availability/reliability/maintainability/operations cost requirements
- Engineering prototype
  - Addresses key engineering risks with candidate hardware and software technologies
- Pre-production prototype
  - Addresses producibility as well as providing a system to use for full spectrum of testing

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## Weather Product Development and Technology Transfer

Determine user need / usage concept / benefit ↓

Evaluate scientific knowledge ↓

"Rapid Prototype" algorithm to automatically produce product ↓

Analyze experimental data (→ back to Evaluate scientific knowledge) ↓

User real time evaluation of product, display concept (→ back to Determine user need / usage concept / benefit) ↓

Develop specification for product algorithm ↓

Validate specification by recoding and comparison with "rapid prototype" software results for test cases

| | | |
|---|---|---|
| Government Implement and Test ↓ Commission | Select Contractor<br>Contractor Implement<br>Gov't. Test (DT&E, OT&E)<br>Commission | Firm Implements<br>? Tests<br>Firm Sells<br>Service |

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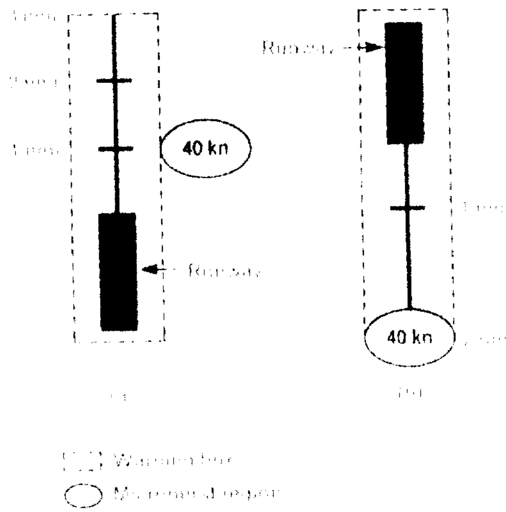
## Initial TDWR Approach to Microburst Warning Generation

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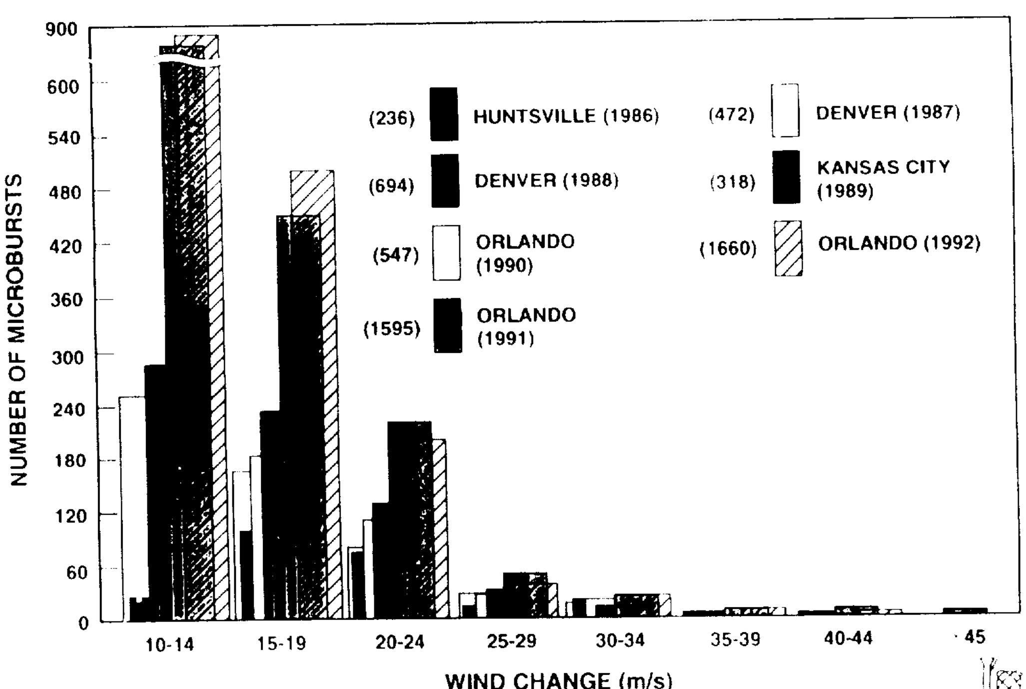
## DISTRIBUTION OF MICROBURST STRENGTHS



# ORLANDO MICROBURST "OVERWARNING" PROBLEM

- PILOT EVALUATION OF RECEIVED WIND SHEAR ALERTS

| | |
|---|---|
| $\Delta V > 30$ kts | 67% FALSE |
| $\Delta V > 20$ kts | 74% FALSE |

- PILOTS OFTEN IGNORED ALERTS ON APPROACH

| | |
|---|---|
| $\Delta V > 40$ kts | 44% LANDED |
| $\Delta V > 30$ kts | 50% LANDED |
| $\Delta V > 20$ kts | 88% LANDED |

- PILOTS OFTEN DEPARTED WITH DEVIATIONS WHEN MICROBURST ALERT ISSUED

| | |
|---|---|
| BEGINNING OF DEMONSTRATION | 20% DEPARTED |
| END OF DEMONSTRATION | 69% DEPARTED |

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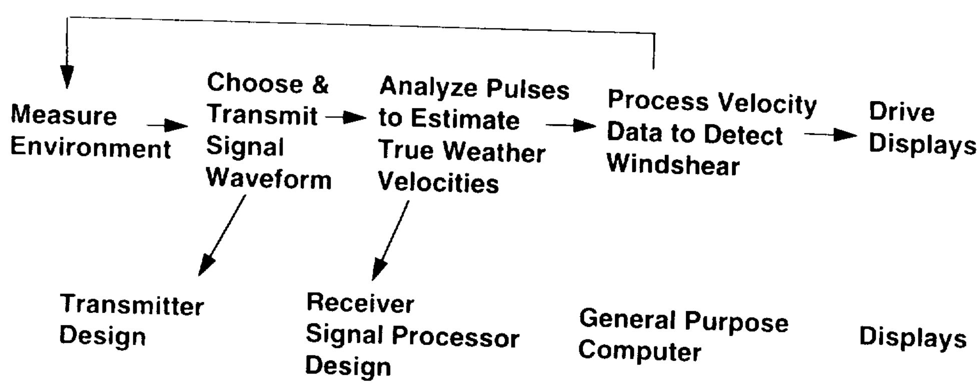
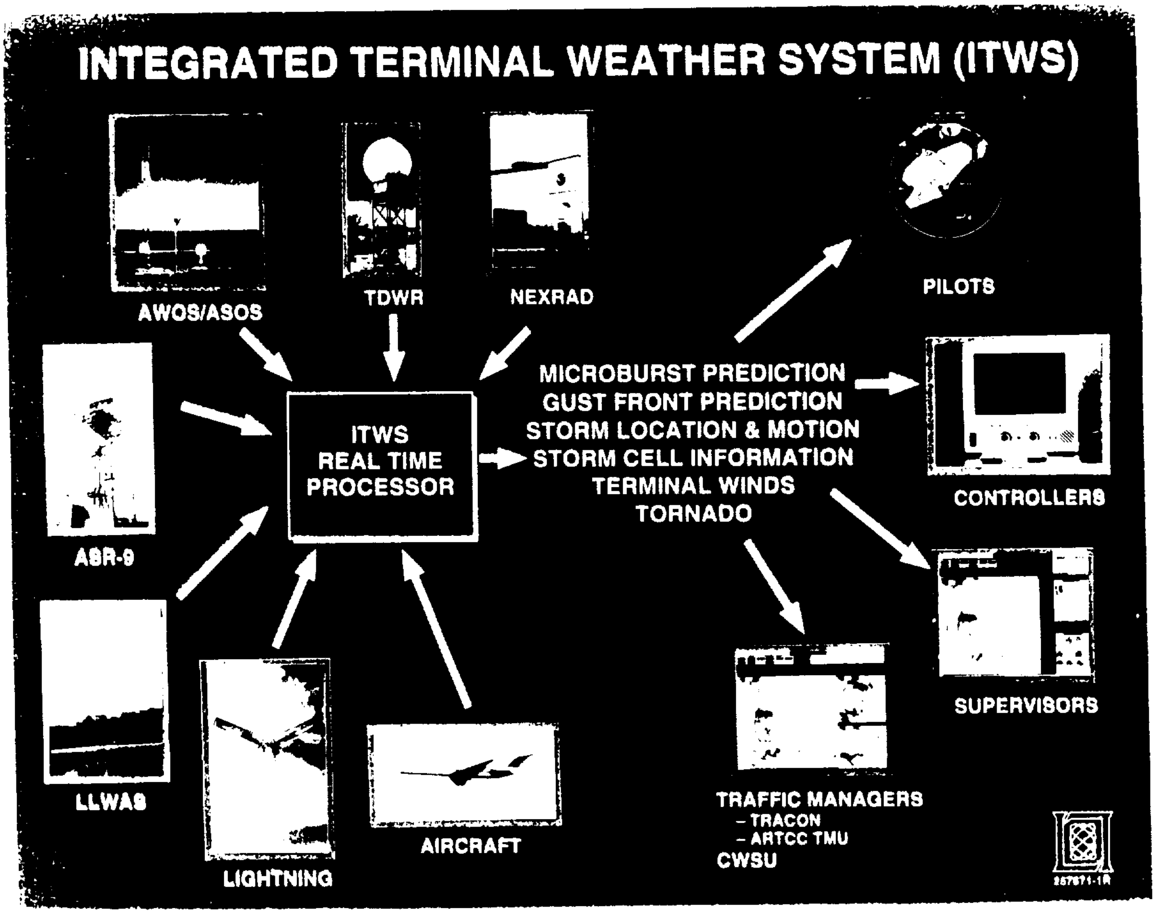
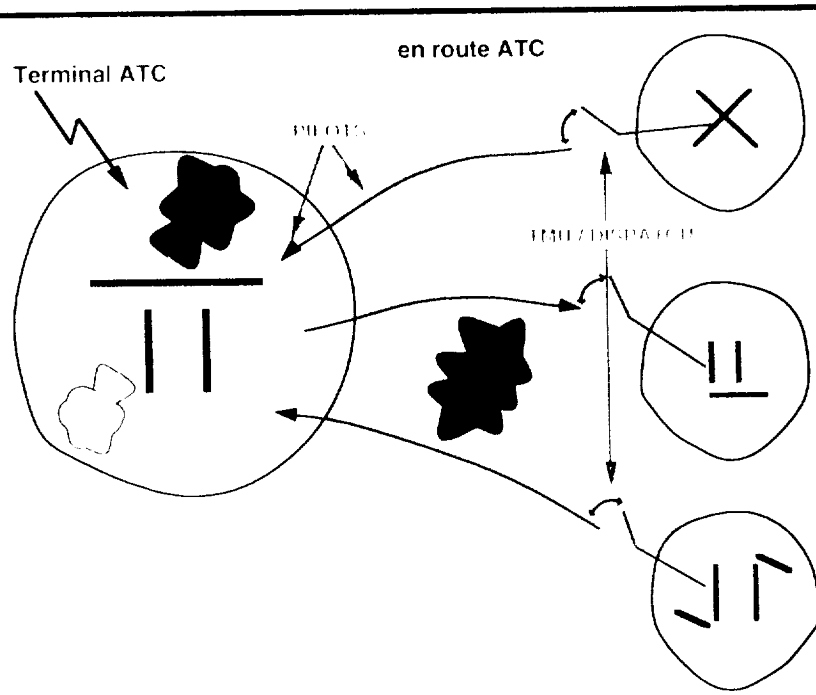
# A TDWR System Engineering Issue






## Effective Terminal Capacity Factors

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## ITWS NATIONAL IMPLEMENTATION BENEFITS FOR INITIAL PRODUCTS
### (BASED ON 1993-1994 DEMONSTRATION AT MEMPHIS, ORLANDO, AND DALLAS-FORT WORTH)

| User Identified Payoff Area | Order of Magnitude Yearly Benefit $M |
|---|---|
| Higher effective airport capacity during thunderstorm | 7 |
| Anticipating arrival and departure area closure/reopening | 51 |
| Anticipating runway impacts and shifts | 36 |
| Better terminal area traffic pattern | 3 |
| Optimizing traffic flow | 39 |
| Downstream delay reduction | 80 |
| Airline operations optimization (fuel, connections, ramp operation) | 19 |
| Total | 235 |

# Lessons Learned

- TDWR
  - More aggressive use of prototypes to locate and address unexpected deployed system problems
    - More prototypes (to address site specific issues)
    - Use FSD system elements (computer, communication boards, GFE modems, generators, etc.) in prototype
  - Provide prototype software as GFI exhibit
- ITWS
  - Have "parallel track" conversion of "rapid prototype" software to more nearly usable form once product success has been achieved

## Summary of Aviation Weather Experience with Prototypes

- Prototypes have been very successful in aviation weather system development
  - Clarifying user needs
  - Developing system specs
  - Quantifying and increasing benefits of system
  - User support from "quick" benefit flow
  - Reducing schedule(?) and risk
  - Solving problems with production systems
- Problems to date
  - Operations cost of prototypes
  - Upgrades when FSD is underway
  - Need "full up" product generation to meaningfully evaluate display format
- Areas of research
  - How to balance "rapid prototype" software with transition to "useful" GFI

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## Summary

- AVOSS has a number of similarities to FAA weather system development
  - Weather/atmosphere is a key factor
  - New ATC capability
  - "Concurrent" system development (e.g., ITWS, CTAS)
- AVOSS needs to get entrained into the FAA acquisition process at some point
  - Mission Need Statement
  - Operational requirements
- Prototypes used operationally can be very helpful
  - Clarify user needs
  - Quantify and improve benefits
  - Build operational user support
  - Reduce schedule and risk

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**Questions and Discussions Following Jim Evans' Presentation (MIT Lincoln Lab)**

Klaus Sievers (German Cockpit Assoc.)
If AVOSS is finished sometime in the future, it will reduce separations and thereby increase capacity during some time of the day, not 100%. It is not possible to predict at what time or when this excess or new capacity will come on stream. It is not possible to predict it in time for airline scheduling to take it into account. Could you comment on how this could be handled?

Evans
What you have is a significant real-time traffic management system that is trying to manipulate the supply to match up to the time changing capacity. You do this because, in this country, you assume that you are going to have fair weather when schedules are set up. For example, the numbers in Dallas, before they build the new runway, they would run up to 102 an hour, but when you went down to 2 runways, you went down to 66. Clearly somebody had to manipulate supply. It's similarly difficult at New York City, Chicago, Boston, and San Francisco. So that is part of the system. To the extent that you have something which can run in fair weather, and now what we are really trying to address is improving capacity in adverse weather. What you have to have is a prediction time that is something corresponding to plane transport time. That means you need predictions typically at the one to two hour category. The reason for that is the strategy for which flights get delayed. For example, I am familiar with San Francisco where we are operating a ceiling and visibility production system. What they do at San Francisco is let the long distance flights go, they don't use them in constraining capacity, they only use the flights on the west coast and to Salt Lake City, so they are only down to a 1 to 2 hour prediction, not a 6 or 7 hour prediction. The other thing you need is a prediction of the capacity. As long as you could get a prediction over the hour is going to be such and such, I don't necessarily have to predict 2 hours in advance what it will be every 2 minutes - within the hour. So you can in some sense deal more with a statistical approach. When it comes time to hit the terminal area, you do need a reliable prediction out in the 20 to 30 minutes time frame. I hope that is some help. But that is some real difference between U.S. and Europe. What happens in Europe is you don't really use visual flight rules. When the weather is fair, you essentially forfeit some capacity that you could have otherwise used. It is really a matter of approach to the problem.

Jerry Robinson (Boeing Company)
Upon learning what you just said, where does the command center enter into the picture? You have the TMU.

Evans
The command center is part of the interaction. The product we have dealt with so far, in a formal operational sense to this point, have dealt with thunderstorms. Thunderstorm stuff is pretty much managed at the nearest ARTCC because they will do a lot of what is called first year programs, second year programs. It is interesting because at Dallas I would have thought the national command center would want to

get our displays, but they didn't. They let Fort Worth Center do the control. Now where we are bringing in a visibility and ceiling prediction program for San Francisco, which gets more national delay than any place in the country, the command center is a lot more interested in that than they seem to be in Dallas.

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**Jan Demuth (FAA) - Presentation with no slides**

This will be short. By a show of hands, who is here from the FAA and Air Traffic? That's a zero. Obviously, I don't have to ask who is here from capacity within that organization. I say that so we don't forget those folks. You need to understand that I represent the regulations and certification side of the FAA, which is only one of the three of the triad that would get involved in anything of this magnitude. I'm responsible for the safety that carries through with anything that we do with the operations within the national airspace system. Wake vortex is something that is near and dear to us and has been for some time. And we just finished last August with an adjustment to the classification system. What you need to understand regardless of whether, Regs and Certs, Procurement and Research, or Air Traffic, the FAA right now has only one wedge in the 1997 management plan that relates to wake vortex. That is 2.6.1 if anyone wants to find that. But the important thing that you will notice when you see that, you'll notice that it's TBD. It's unplanned, unscheduled, and unfunded. This particular piece is a generic statement of our recognition of the importance of wake vortex as it relates to airport capacity and safety, and includes both the elements of procedure and technology. Just very quickly my message, since we have had a lot of technology, is to talk about procedures and how that works, not that we haven't talked about some procedures here.

If we can get aircraft on an electronic glide at 3 miles, all coming in at the same altitude, we could probably virtually eliminate encounters that would impact safety of flight. Not entirely, we are not minimizing the importance of how we get airplanes queued up for that position. I say that to make the point that what we're doing here in AVOSS, such as economic analysis and getting ready for a procurement cycle. I think it will be equally important that we look at the procedures that go into the traffic equation that are being supported now. It is not clear to me yet that we are getting all the pieces together in one program. That is strange coming from an organization that doesn't have a plan. But, as a systems engineer, I can't help but make those observations. And I won't fail to say those things when I get back home. We need to work on the procedural aspects of air traffic control. Even those of you who are looking at the guts of what a vortex is, you need to have a little perception of what it is that goes on in controlling aircraft. I am a pilot and I have really got an education in the last 3 years, and its all been very positive.

The second thing I want to say, comes back to Tim's challenge he threw out the first day. Tim said that the FAA ought to be able to show what's going on at these airports (almost in real time). We had a couple of presentations that related to that today and that is very important to understand. I think the FAA is just beginning to scratch the surface on what we need in order to model what needs to go on in our airport system. We just finished, as I said at outset, an adjustment to the wake vortex classification system for final approach, making the adjustment at the threshold. We did that last August and we're still looking for the impact of that. Even though we can find a couple of airports where there has been drastic changes in factors that reflect capacity, it is not clear what the cause and effect of that is.

What the real separation had to do with it. And I am even more confused when Barbara takes a picture from Dallas-Fort Worth and says that nominally at the outer marker, giving at least a mile if not two miles more separation than is required. Somehow we have to relate to that. We have got to have real operational procedures well understood and go and collect the data to see what is actually happening. We have to have not only one airport model, but we have to have all 10 or 11 or 15 modeled with some kind of interrelationship with weather patterns. That is where we have to go.

I can't tell anybody even today what the impact has been of changing the weight classification system from 12,500 to 41,000 from Small to Large in any kind of objective way. We could probably pick out some anecdotes and say we suspect, but we don't know. And we certainly had no way of projecting or forecasting what that was at the outset. And when I say we, I am including the industry in that because we took a long hard look at the folks who were working the problem and it just wasn't, to an objective level, that would give us that kind of visibility.

The third thing and then I'll sit down, is we have to do a better job of talking to each other. We are going to have to put all those pieces together one way or the other whether it's informally with what is going on in our daily lives, or whether it is some kind of formal structure that I don't see anywhere going on that manages the likes of airport capacity and safety. To put the issues and the pieces of this puzzle together that we have seen pieces of here. That message I'll take back to my organization as well. As far as communication is concerned, you still owe us a letter. We were asked early on, as early as August. Flight Standards put a position letter on the table for NASA, as far as what an acceptable threat was relative to wake vortex. That letter essentially says that no encounter perceptible to a pilot is the only acceptable threat. And yet we have yet to hear from you on that.

## Questions and Discussion Following Jan Demuth's Presentation

Brad Perry (NASA Langley)
That letter was directed to TAP program management.

Demuth
You are making another point I just made. Good enough. We will work that together, I am sure. I think that probably a lot of that is going on. We get caught up in our daily life where somebody has a piece of information or an idea I heard, that I ought to go talk to them. I'll try to do better too. That is all the words I had.

Bob Zoldos (Air Transportation Association America)
You said "I can't tell anyone what the effect of wake turbulence separation has cost so far". In LA and San Francisco alone, the airlines have paid over $700,000 in the last 6 months due to the separation standards that were implemented last year. That is only a 6 month look at a couple of airports, so the separation standard didn't do anything to enhance safety as far as we are concerned, but it did cost us a ton of dollars.

Demuth
So noted.

Kenny Kaulia (Airline Pilot Association)
I would like to thank you for being you usual frank self this morning. I would say that there may be some problems with the increase in the separation standards. At some of the airports air traffic controllers are now changing their procedures and having the turbo prop aircraft, slowing the turbo prop down, and then having the jet aircraft fly above and pass the turbo prop before reaching the marker and beginning their descent into the airport. That is one of the problems and I wanted to mention it while I had the opportunity.

Demuth
Thanks Kenny. That's Chicago and again I say we need to take a look at the procedures from a capacity and safety standpoint. There may be a lot of room for stuff we can do without waiting for AVOSS for how ever many years.

Jerry Robinson (Boeing Company)
Much of what I've heard addresses the technological solutions in separation. There is more to the picture than technology to get this bought off and implemented. What do you see as the sequence of events from your position in the FAA?

Demuth
I just wrote a cc mail message about a week and a half ago that got to part of that. Thanks for the question. The FAA is going to have to take the three associate administrators that have bearing on the question. They will have to decide what it is they want to do with this situation. How are we going to reduce accidents and at the

same time look at a triple capacity. For us, we know that is going to be bigger airplanes as well that don't exist today. And that we need to be thinking about. To your question, those three associate administrators are going to have to get in a room and figure out what it is they want to do and start managing a program at our level. It is not anything that I can do or my other cohorts from Flight Standards that are here, or even at my level at the Air Traffic side of the house, or Research and Acquisitions. The first thing that has to happen is that the three associate administrators are going to have to do something with that wedge in the 97 plan. They are going to institute some kind of a steering committee that we had but that no longer exists for wake vortex. Then they are going to have to make some work assignments within the FAA, and I would think geographic in this case, not just Headquarters, to start focusing on what is happening here in this room.

Robinson
In your response I believe I heard a concern for large aircraft that might be manufactured in the future. Is that a concern to the FAA when talking about wake vortex?

Demuth
It is a concern of mine that I would put on the table. If you are looking to triple capacity, we don't know of any major facilities that are on the drawing table right now. So part of that will have to be handled with larger aircraft and scheduling.

Rose Ashford (TAP Level II Program Office NASA Ames)
This is not a question so much as a comment, Jan. You mentioned the letter that the FAA wrote to NASA some time June or July last year taking the position that the only good encounter was no encounter. The letter also mentions a nuisance encounter. I think some of the work we saw yesterday, where we saw encounter of aircraft, I think what will come out of that is a definition of an encounter that becomes a nuisance encounter. Yes, we do have your letter and yes we should reply. Langley did draft a reply and it was held up in my office for quite some time. We decided some time ago to hold off with a reply until after this workshop. The response is not greatly controversial. It simply says we're going to continue our work. We expect that the early AVOSS deployments will be based on transport only until there is sufficient comfort with the system that we can go to a decay plus transport. Also, for most weather conditions the vortices do transport out of the corridor quick enough that that is what will control the separation. It may be that the arguments become that it is not enough pay back in reduced separation to ever go to a decay plus separation criteria. That's a maybe. We will find out more after the summer deployment. Perhaps we should talk to each other privately. I do have your letter.

Demuth
Thanks Rose.

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# WVWS

**The**
**Wake Vortices Warning System**
**- WVWS-**
**for Frankfurt Airport**

**Parallel Runway System 25**



## WVWS Objectives

**Reduce / suspend increased wake vortex separation minima between staggered aircraft on final approach to the two parallel runways 25 at Frankfurt airport**

- **in order to increase arrival capacity**
- **whilst maintaining or increasing safety**

**Aircraft approaching the same runway will continue to be separated according to the increased (ICAO) wake vortex separation minima.**

## WVWS — Tasks

Identify meteorological conditions
under which there will be no risk of hazard to arriving staggered aircraft
caused by wake vortex propagation from one runway into the safety area of the adjacent runway

- ⇨ measure and predict wind vectors
- ⇨ model the wake vortex self-propagation
- ⇨ model the wake vortex transport
- ⇨ determine the risk of vortices infringing the safety area of the adjacent runway
- ⇨ process meteorological warning messages provided by meteorological services

H. Lafferton, Head of Future Technologies & Systems — DFS Deutsche Flugsicherung — WVWS 3

## WVWS — User Participation

Involvement of controller and pilot representatives throughout the WVWS programme

Broad user information before and during the operational testing & evaluation phases

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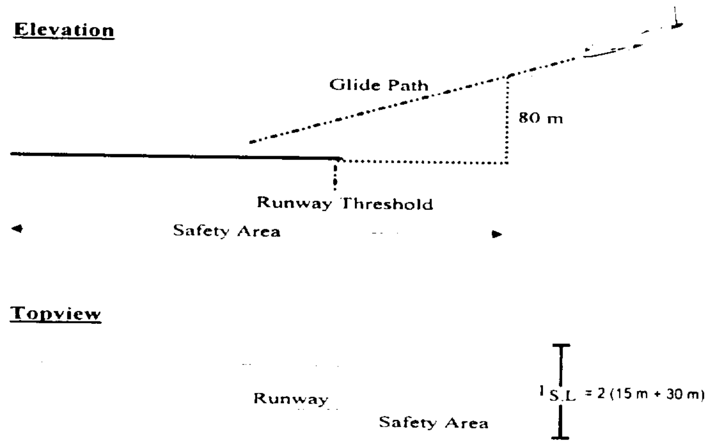
## WVWS Safety Area

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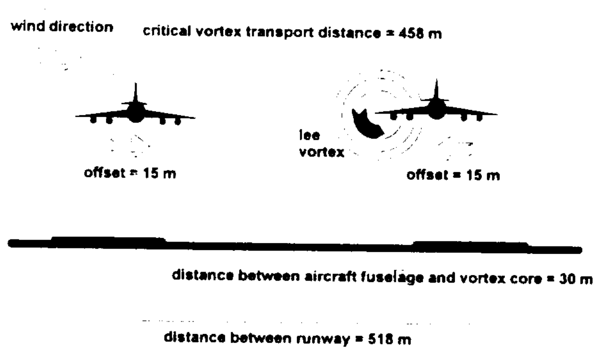
## WVWS Safety Area

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## WVWS — Operational Procedures

- staggered approach:
  no vortex transport from left to right nor vice versa;
  > HEAVY aircraft on either runway
- modified staggered approach 25 L:
  possible vortex transport from right to left but not vice versa;
  > all HEAVY aircraft landing on RWY 25 L = downwind runway
- modified staggered approach 25 R:
  - vice versa -
- modified missed approach procedure

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## WVWS — Result of Risk Analysis (1)

The probability of accident caused by wake vortices being transported from one runway to the other runway under WVWS operation

is less than

the accepted probability of accident estimated for operation without WVWS applying the encreased wake vortex separation minima for single runway operation

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## WVWS Result of Risk Analysis (2)

| Accident probability per landing | | |
|---|---|---|
| caused by wake vortices | | |
| | | Accident probability |
| WVWS | | <1,57 * exp-6 |
| | | |
| Reference | Single Runway Operation, | 1,9 * exp-6 |
| [CAA] | wake vortex staggering | |
| | any a/c behind B747 | |



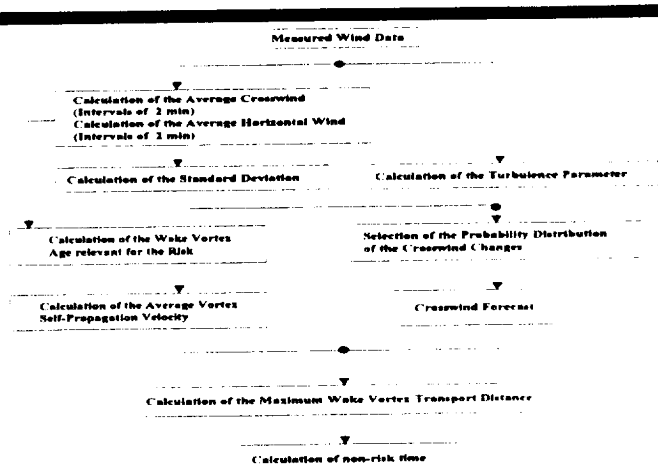
## WVWS Result of Cost/Benefit Analysis

**Enhancement of arrival capacity due to reduced wake vortex separation between staggered approaches for runways 25:**

- **min. 1.1 additional landings per hour**
- **max. 3 additional landings per hour**

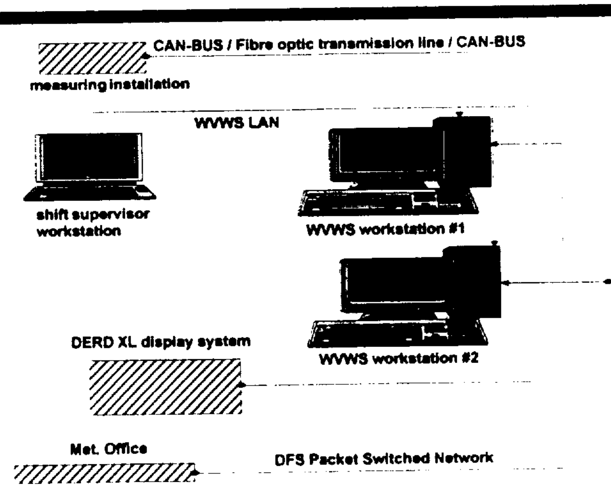
**(Variations with time of day and season)**

## WVWS Functional Components

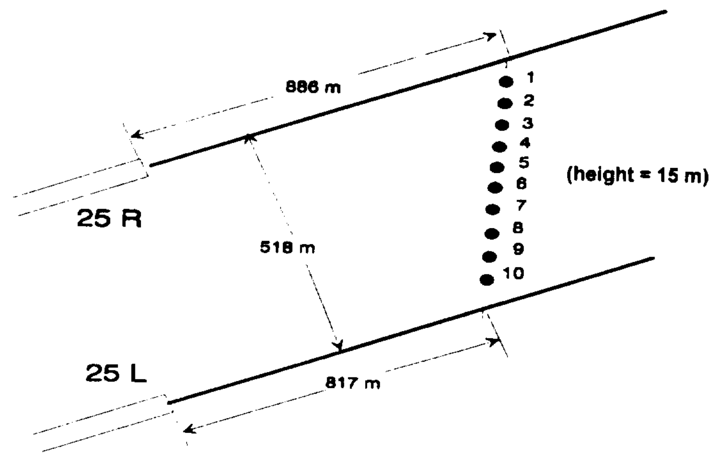





## WVWS Physical Components



## WVWS Location of Wind Sensors

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## WVWS Objectives of Operational Field Trial

Evaluation of operational procedures

Stepwise approach to operational introduction and use

Broad user acceptance

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## WVWS Preparation of Operational Field Trial

Involvement of Lufthansa German Airlines and the German Cockpit Association

Possible extensions of the present system design identified

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# Wind Prognosis

- Forecast each Minute, 20 Minutes ahead
- Gives interval of future crosswind with probability of 95%
- Prob.distribution for different wind classes
- Wind class selected according to measured turbulence parameter
- Wind classes derived from measurement campaigns (Summer/Winter sample)

# Wake Vortex Transport

- Based on Vortex Model taking into account
  - Vortex life time
  - Vortex self-propagation velocity
  - Tangential velocity of vortex
  - Vortex core altitude as function of age
  - wind profile in atmosperic boundary layer
- take vortex self-propagation towards parallel runway
- add forecasted crosswind
- multiply with max. expected vortex life

# Vortex Life

- Life ends, if tangential velocity does not present hazard to LIGHT aircraft
- Tangential velocity of 4 m/s here
- Life expectancy formula derived from vortex measurement campaign in Frankfurt
- actual life prediction derived from horizontal wind measurements

# What we get

- due to predicted wind situation, a vortex can reach the safety box of lee runway
- a point in time when this is to be expected
- in the meantime the lee runway is regarded safe
- controllers can reduce spacing until that point in time

**Questions and Discussions Following Joerg Rankenburg's and Ralph Rudolph's Presentation (DFS)**

David Chin (MCA Research)
Please put back the slide that shows the accident probabilities that you derived. My general question relates to how those probabilities were derived for your reference as well as for your enhanced case when you had the system in.

Rankenburg
These are some figures, but I don't have to admit that some scientists were after those figures, and I really can't explain or analyze how they came to those figures. In case someone is interested, I have some papers dealing with risk analysis. These are the figures and all we could do was trust them.

Tim Dasey (Lincoln Lab)
Can you put up the transparency of the safety monitoring area you chose. I am not sure I understood the reasons you chose that particular region. I am interested in understanding what was the reason for using 80 meters as top of the corridor.

Rankenburg
In fact it wasn't money. Our meteorological specialists told us the end of the measurement, let us say parameter of the safety box, have some physical reason. When they measured the wake vortices at the Frankfort Airport, in the vicinity of the thresholds of runway 25 left and 25 right, they discovered out of a thousand models that passed by, they did it with laser, and tracked those vortices, there was no activity beyond 70 meters. So they said, above this level the wake sinks. They have to sink, that is physics. If there are no vertical wind fields, no corrective weather situation, we estimate these weaker vortices to sink at a certain rate, that is between 300 to 500 feet per minutes. In this weather situation, aircraft staying on the glide path would always be a little above the sinking wake vortices because we have at least 3 nautical miles separation. That means that at speed 180kts you still have 1 minute. In 1 minute the wake of preceding aircraft are expected to be about 300 feet, even a little more, below the glide path. Unless there is a weather situation which could infringe on sink rate, we are considering that aircraft that stay on glide path are safe. What we are evaluating together with meteorological staff as well as airline representatives, is trying to identify weather situations which could influence the sink rate of the vortices created by aircraft on final approach.

Peter Zwack (University of Quebec at Montreal)
I was interested in your forecast of the wind. Were you forecasting a change in the wind, or do you just use wind and assume it's not going to change during the next 20 minutes?

Rankenburg
Yes, we take both into consideration. There was a model on the crosswind component that is to be expected in the next 20 minutes. To develop this model on

the future crosswind, we take the actual horizontal wind into consideration. There is some formula, I don't have it handy here. As I said before the meteorology staff, they came up with this stochastic crosswind component taking into consideration the actual wind. The prognosis is renewed every minute. So every minute there is a new prognosis of the future crosswind component. The stochastic crosswind component model and the model on the wake vortex transport are the main two components that are running into the prognosis of the future crosswind component, let us say. And considering this crosswind component gives us an indication of how to react within the next time limit, let us say up to 20 minutes. Twenty minutes would be perfect to have some planning because our final approach starts at 10 nautical miles and so we need at least 10 minutes timescale ahead to get into some planning; 20 would be better. We got some problems on that, on the dynamical graphical display, but we are working on that. The operational evaluation of the system is still in progress. The technical things are done, the algorithms are validated and technically it is ready to go, but we are still in negotiation with airlines.

Klaus Sievers (German Cockpit Association)
Not a question but maybe a statement or remark. We have taken a look at the system in Frankfurt and the forecasting part and everything is fine science. Unfortunately, the only weather sensor that is active is a wind line between the two runways. While it may adequate to cover up to 80 meters, we think 80 meters is a little low and we prefer to extend coverage to outer marker if not more. And also we see that the WVWS system is the first system of its kind in Europe. In Chicago there was something in the 70's. The system is going to be operational and basically is using forecast of the wind and it is a weather forecast. We would like some hard facts to back up the forecast like an operational lidar system which makes sure the vortices follow the forecasting behavior. If that is ok then maybe we go.

Rankenburg
Yes, thank you. We know those comments and we are working on that. It would be nice if we had resolutions to all questions. We heard a lot here and see that there is a lot of work to be done. I have to always stress that we are in specific situations, that we are looking into the final approach. It was of interest how the wakes behave in the landing phase or in the vicinity of the threshold, to exclude either one or both vortices. Of course we would be glad if we could prove the prognosis, but for the time being we cannot prove this prognosis by real time measurements. We are trying to get some kind of other prognosis to reveal some vertical winds or convective weather situation on the whole final approach area and we are negotiating with some people running the lidar as well. We are thinking it over and I think we are going to have a trial to see if it is of use. Perhaps we can confirm our prognosis by some real-time measurements.

# VORTEX

# FORECASTING

# SYSTEM

529-03
018124
318784
22P.

SYD RENNICK

TRANSPORT CANADA

AIRSPACE

STANDARDS
&
PROCEDURES

# OUTLINE

PERSPECTIVE

ASSUMPTIONS

TYPES OF OPERATION

TIME FRAME

RECOMMENDATIONS

# PERSPECTIVE

PILOT AND CONTROLLER

KISS

PRINCIPLE

# ASSUMPTIONS

THE MODEL WORKS

WEATHER DATA MEETS

REQUIREMENTS

# TYPES OF OPERATION

SINGLE RUNWAY

PARALLEL RUNWAYS

INTERSECTING RUNWAYS

# TIME FRAME

NEAR TERM

MEDIUM TERM

LONG TERM

# RECOMMENDATIONS

CONFIRM FINDINGS/COMMENTS

CONTINUE EXAMINATION OF SYSTEM

UTILIZE WORLD-WIDE DATA & RESULTS

SHARE TEST RESULTS

# VFS EVALUATION

- Focused effort towards operational real-time system
- Near-wake database (NWDB)
  - Specified vortex locations (typically 100 vortices)
  - Computed vortex circulations (lift, angle of attack, inboard flap, outboard flap, sideslip angle)
- Far-wake evolution using Lagrangian cross-plane vortex method
  - Transport (including wind)
  - Decay (through effective viscosity)

# VFS EVALUATION (Cont'd)

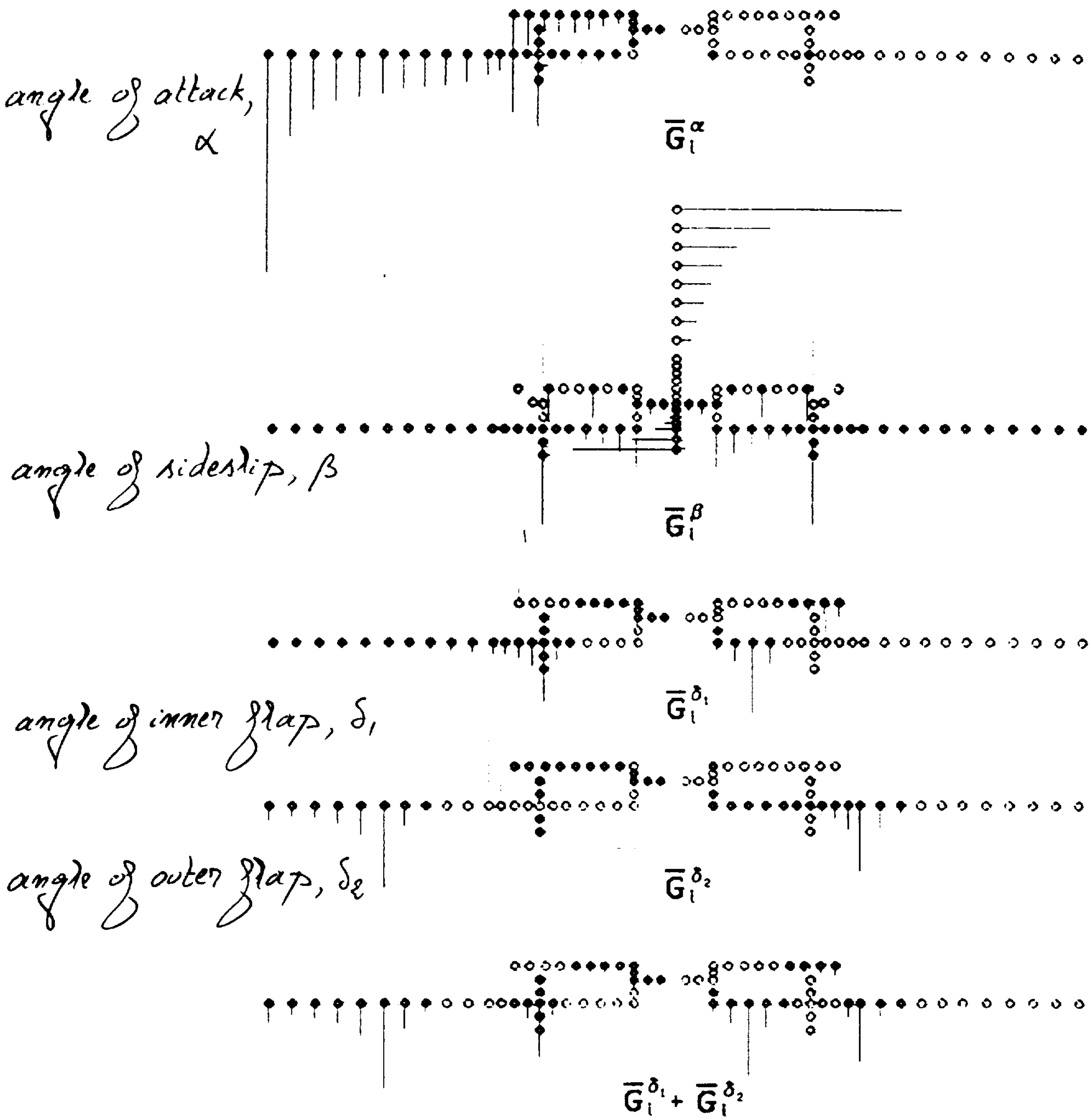
- IDF and Memphis data
- Enhancement considerations
  - Accurate diffusion scheme (vortex circulation exchange instead of core spreading)
  - Vortex redistribution scheme
  - Zero slip velocity at ground (vortex sheet+ diffusion instead of image vortices)
  - Production/destruction of vorticity due to stratification
  - Fast computation (require ? times faster than real-time)

S. M. Belotserkovsky, SABIGO, 1995

Near-wake database of B-767 OGE

Vortex locations $(x_i, y_i)$ in cross-plane (here 99 vortices)

Vortex circulations $\Gamma_i$ per unit:




The database of B-767.

S.M. Belotserkovsky, SABIGO, 1995

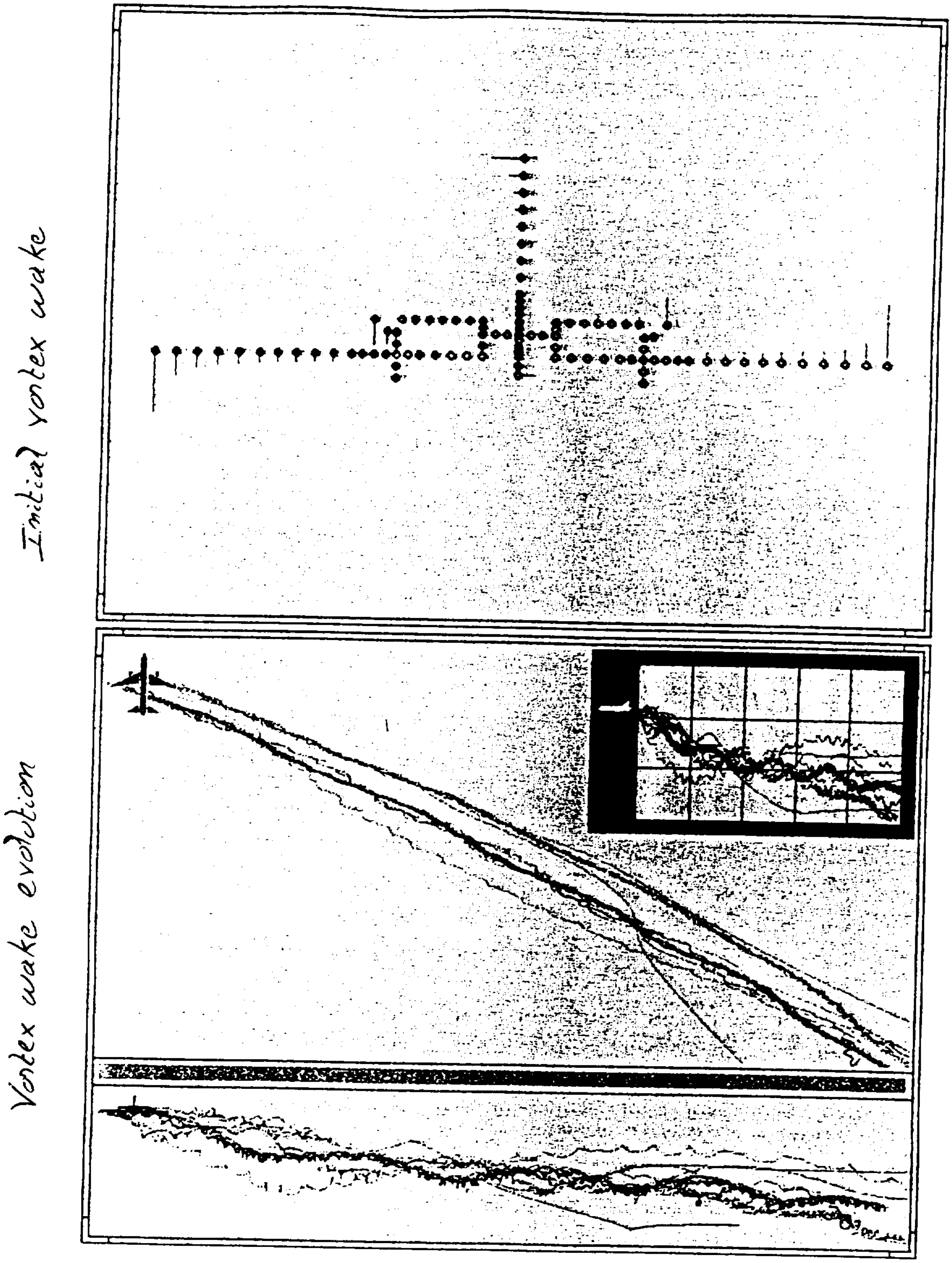
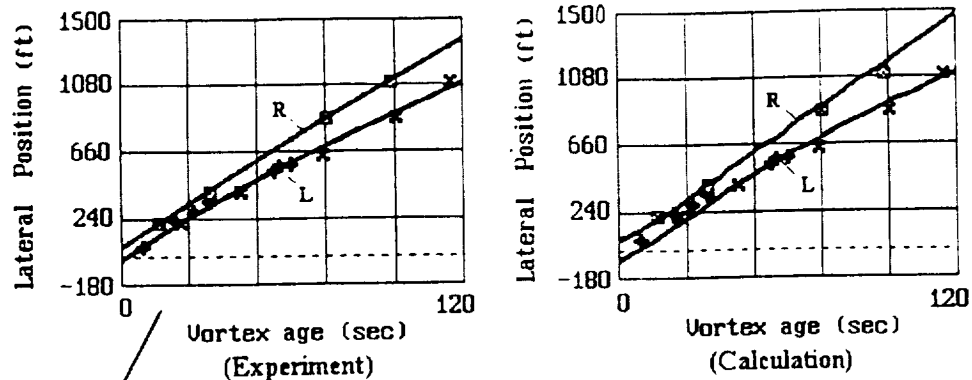



Fig. B-767, flight 5. Idaho Falls
Flight at a lower angle of attack (at a greater speed) and $\delta=0$; $t=120$ sec

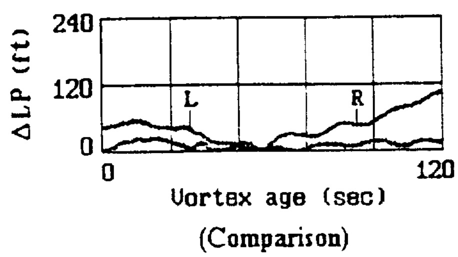
S.M. Belotserkovsky, SABIGO, 1996

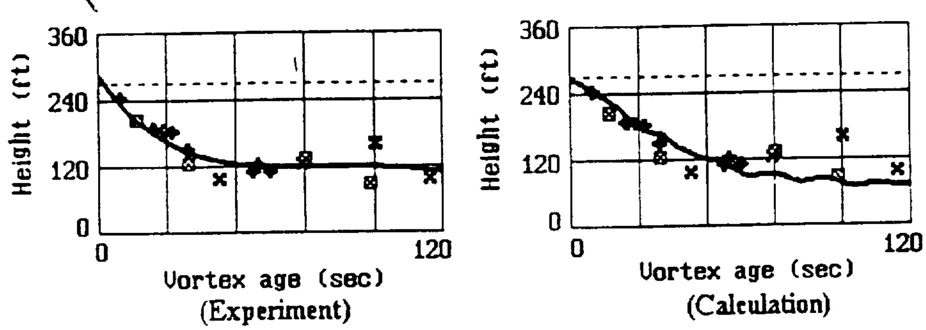
Boeing 767 - #1 Idaho Falls (IDF)

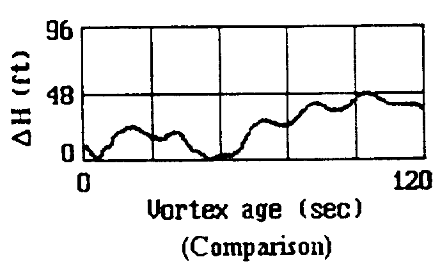
| | | | |
|---|---|---|---|
| Height (ft): | 270 | Angle of attack (deg): | 8.7 |
| Flight speed (kts): | 140 | Flap angle (deg): | 20 |




Note: the solid lines are a polynomial fit of the data using least squares



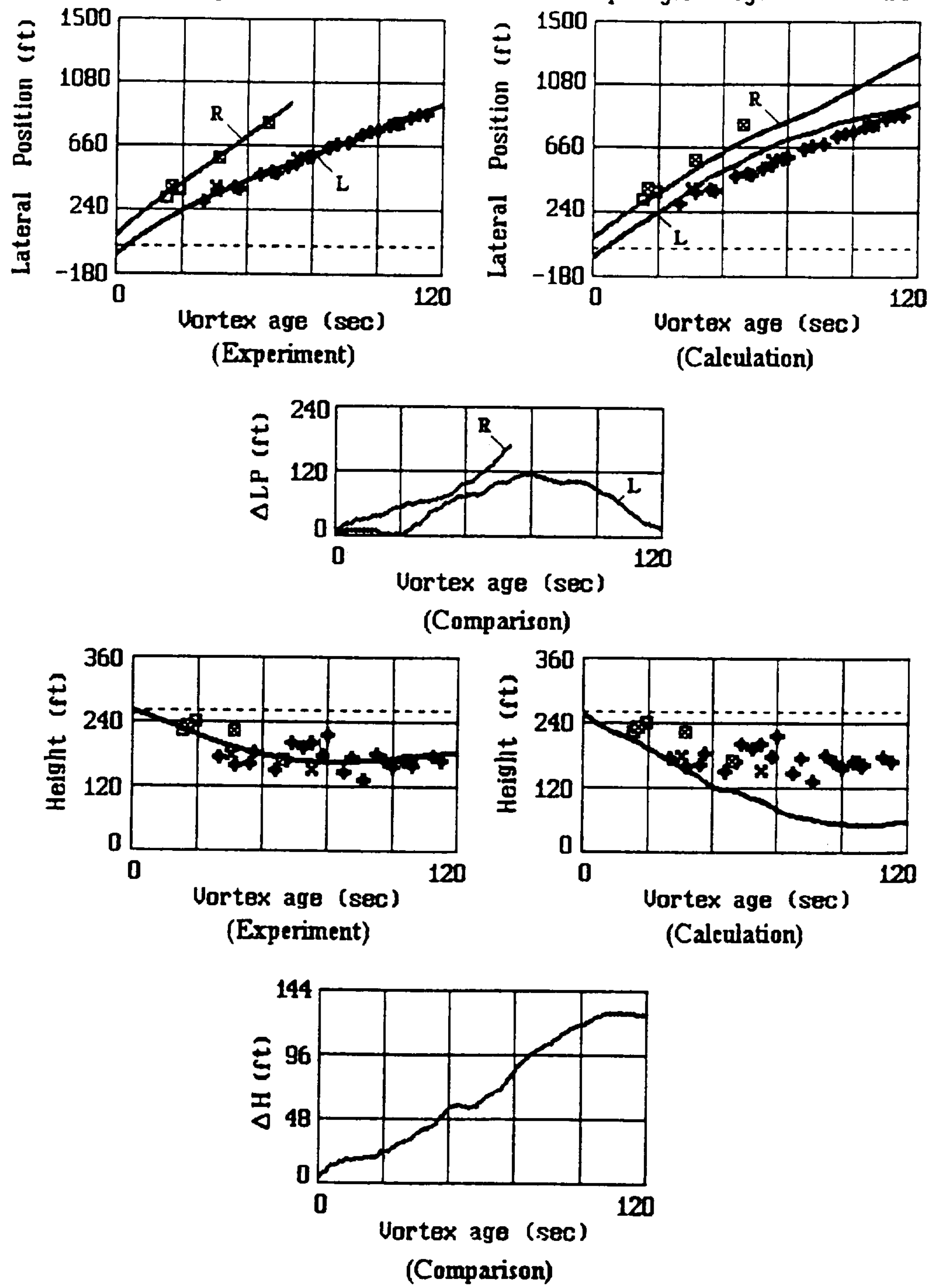



S.M. Belotserkovsky, SABIGO, 1996

Boeing 767 - # 9 IDF

| | | | |
|---|---|---|---|
| Height (ft): | 260 | Angle of attack (deg): | 7.2 |
| Flight speed (kts): | 140 | Flap angle (deg): | 25 |



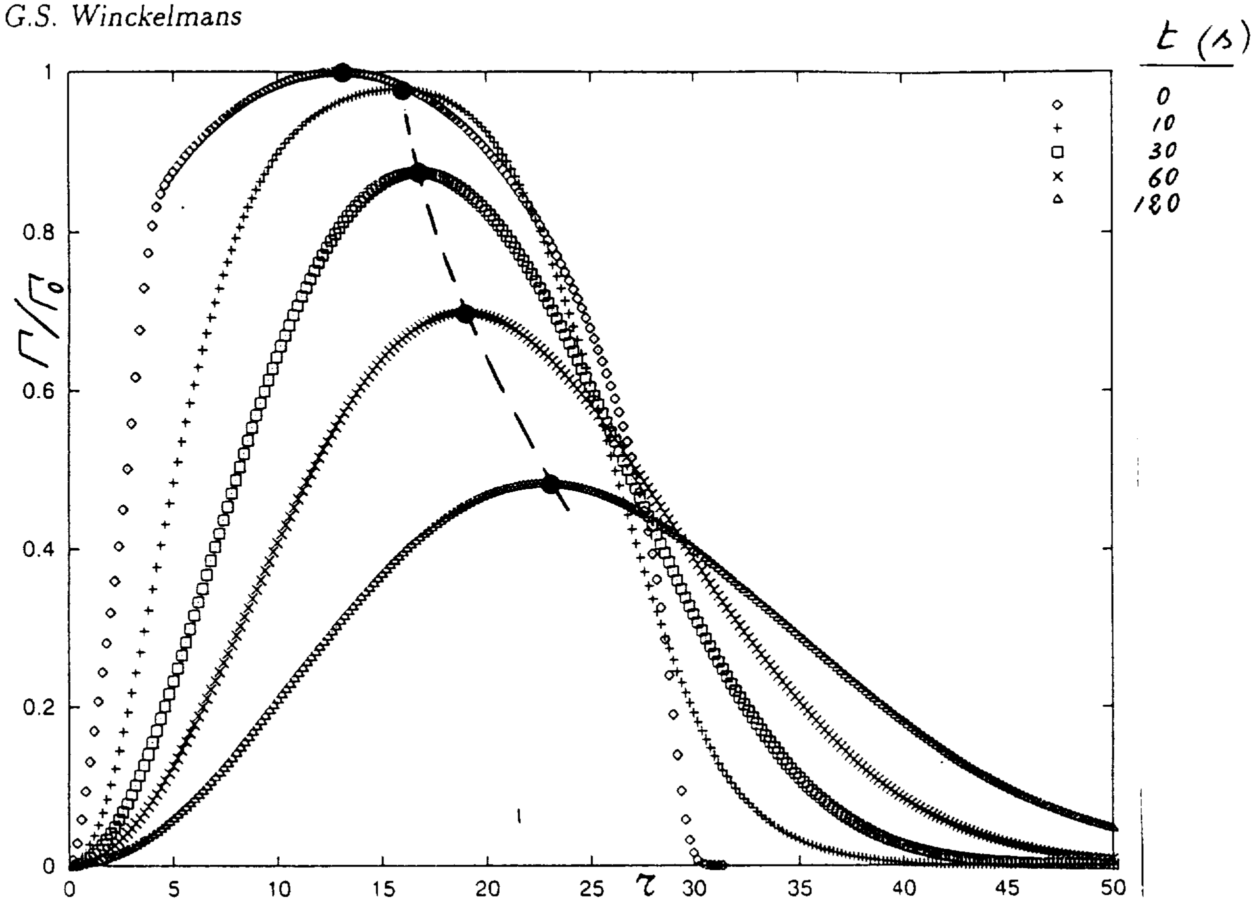



Figure : Simulation of a simplified B-727 vortex wake using the MDV with core spreading; circulation within a circle of radius $r$ centered at the vorticity centroid.

Method of discrete vortices (MDV), with Gaussian cores and diffusion by core spreading.

Simplified B-727 vortex wake: elliptical loading, $V_\infty = 72.1\ m/s$,

$\Gamma_0 = 885\ m^2/s$, no wind, OGE, $b = 33\ m$, $A_R = 6.86$, $C_L = 1.29$

Run conditions: 256 vortices, $\nu^* = 0.68\ m^2/s$, $\delta t = 0.1\ s$

Enhancement considerations:
- accurate diffusion scheme
- redistribution of vortex particles



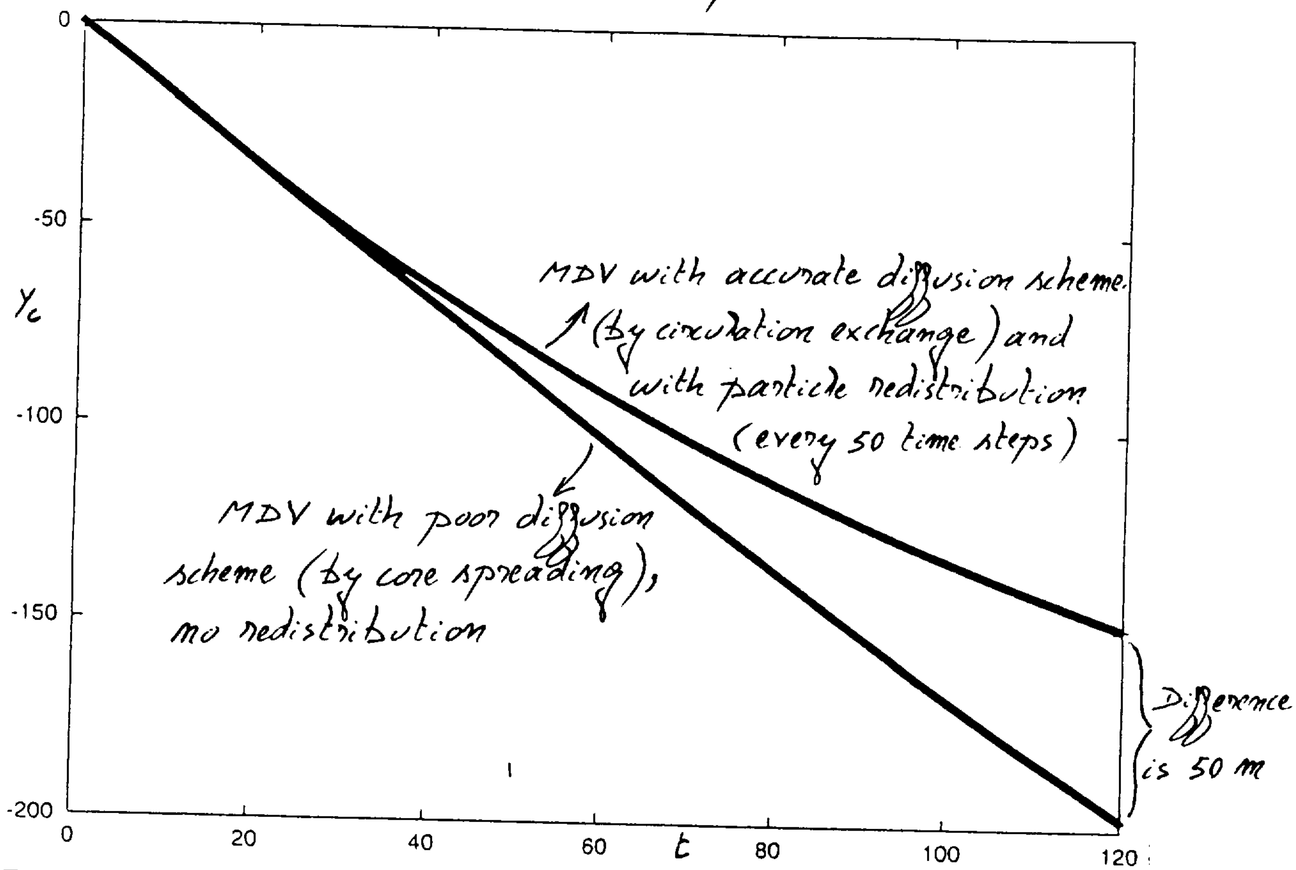



Figure : Simulation of a simplified B-727 vortex wake using the MDV with circulation exchange; evolution of the vorticity centroid, $y_c(t)$, and comparison with results obtained using MDV with core spreading.

Same run conditions as before

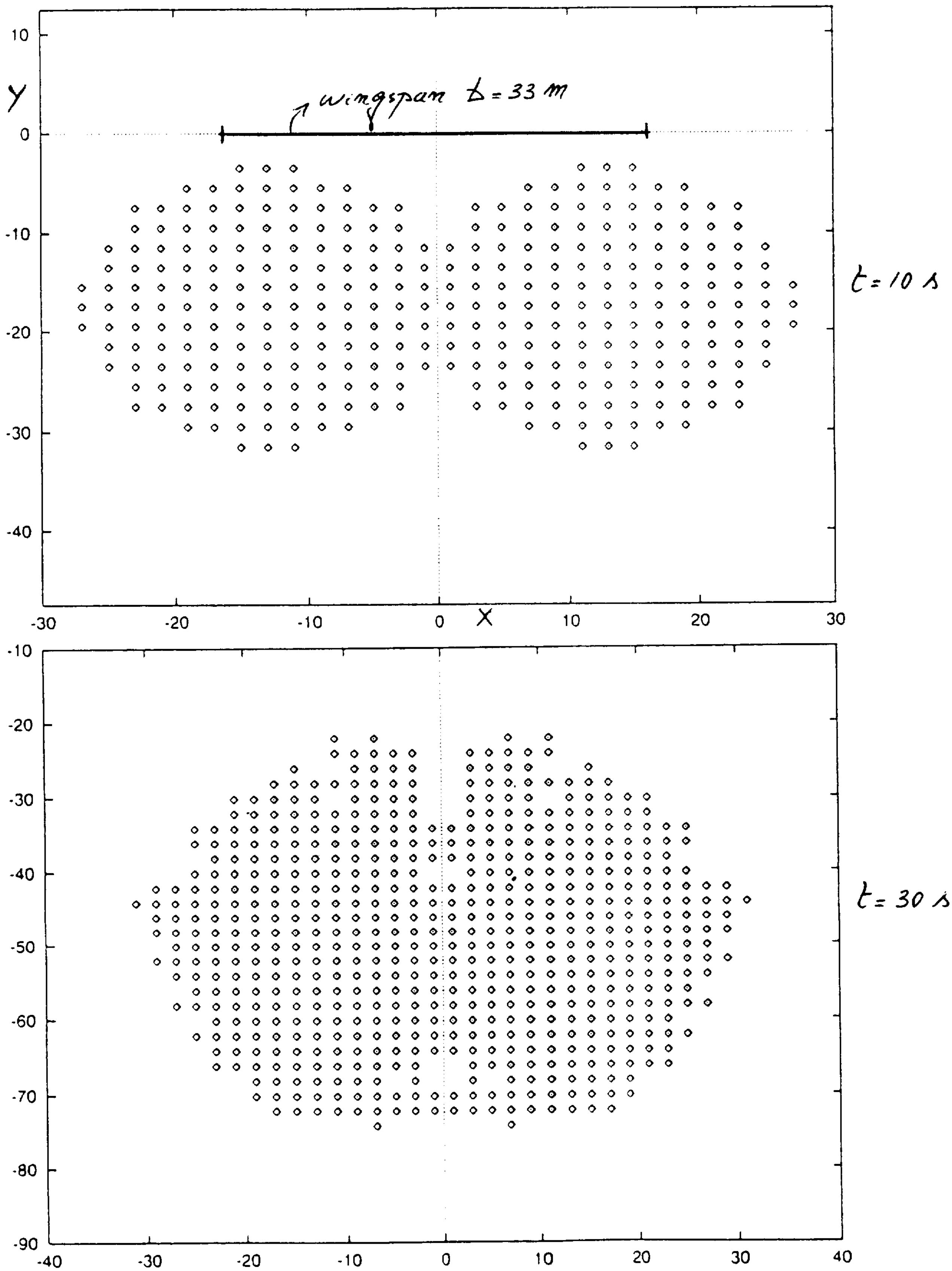



Figure : Simulation of a simplified B-727 vortex wake using the MDV with circulation exchange and particle redistribution; particle positions at $t = 10$ and 30 s.

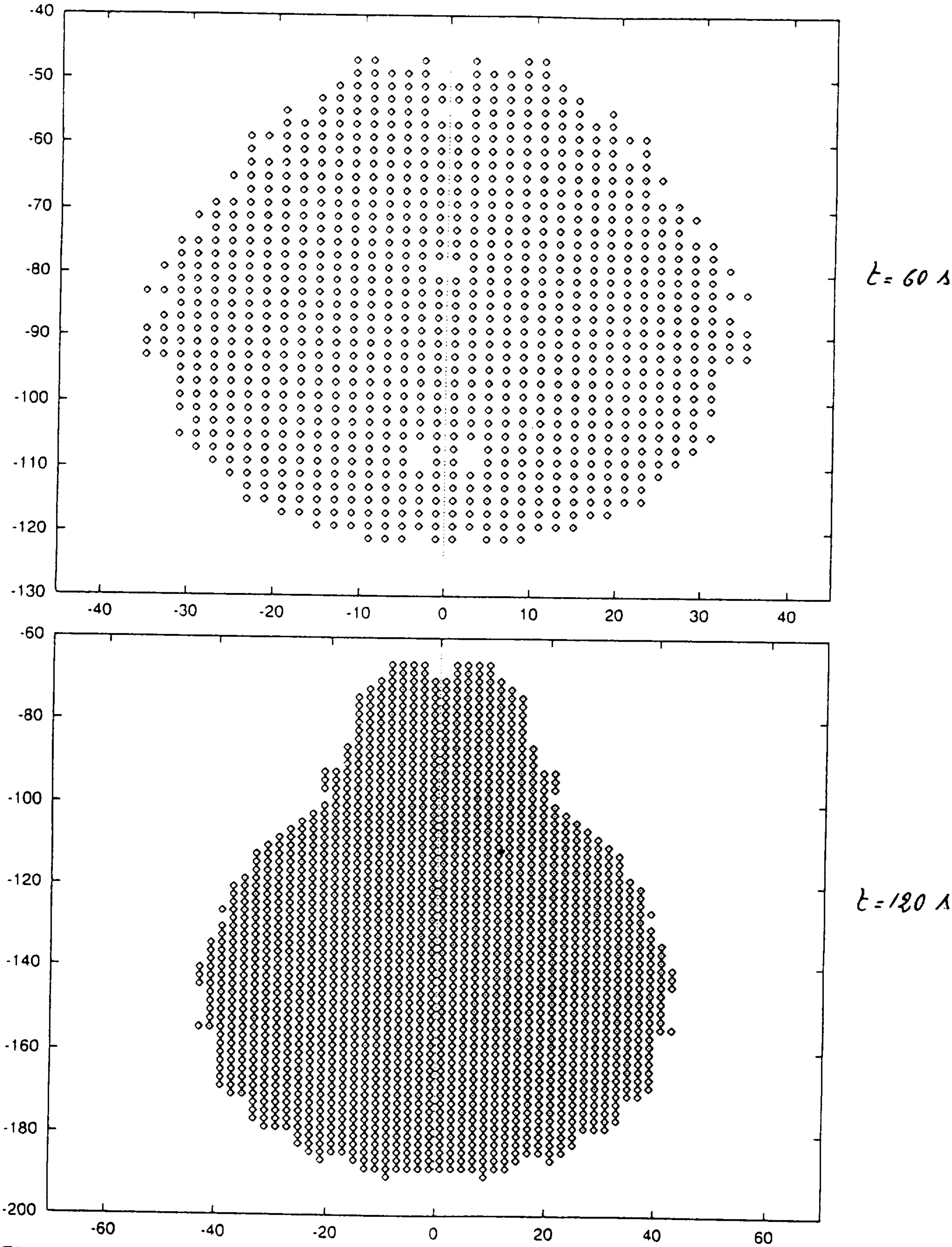



Figure : Simulation of a simplified B-727 vortex wake using the MDV with circulation exchange and particle redistribution: particle positions at $t = 60$ and 120 s.

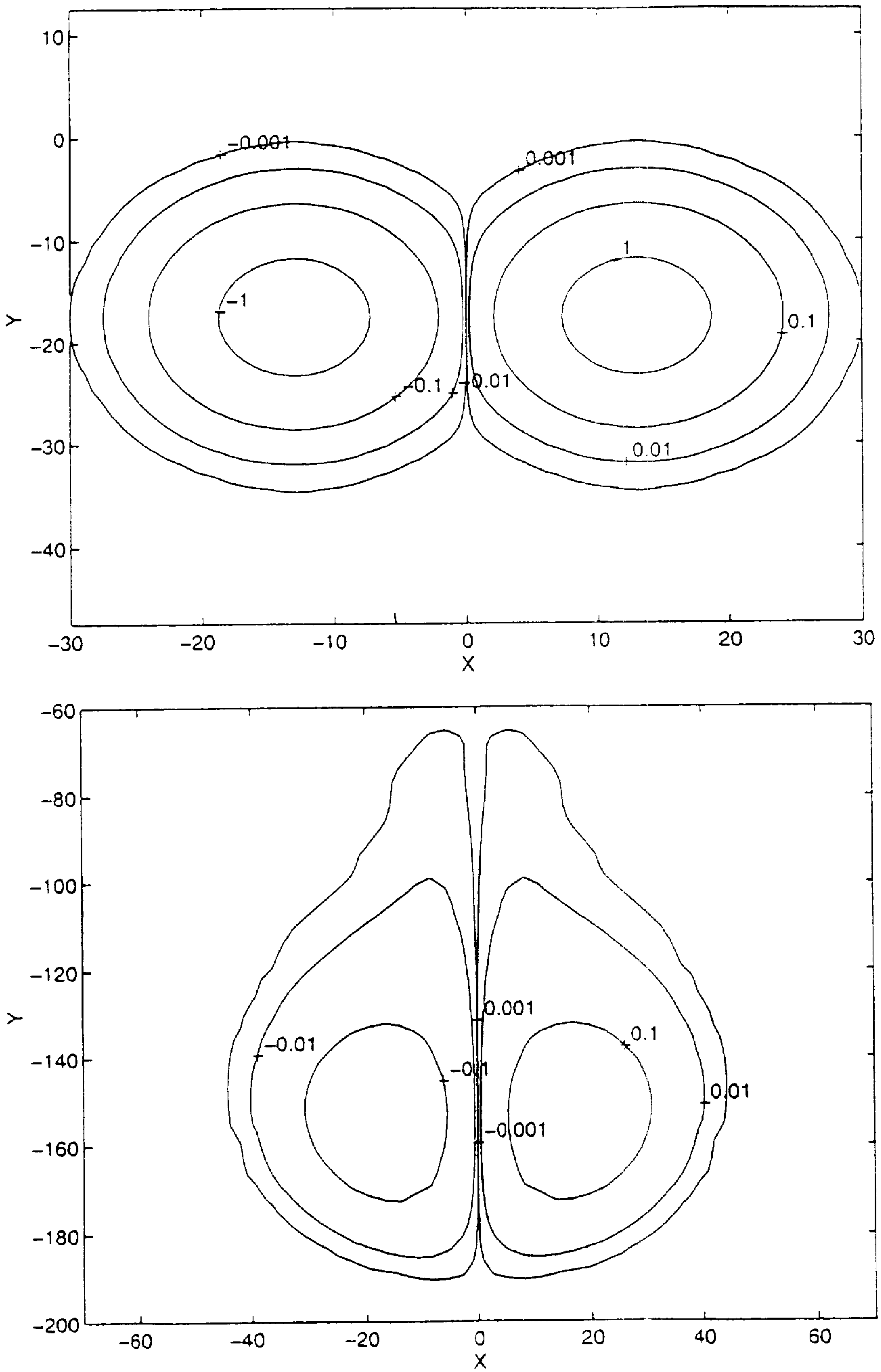



Figure : Simulation of a simplified B-727 vortex wake using the MDV with circulation exchange and particle redistribution; vorticity contours (in 1/s) at $t$ = 10 and 120 s.

Enhancement considerations : Vortex wake IGE : strong interaction with the ground

Notes: • Same simplified B-727 vortex wake as before.



• accurate viscous scheme + particle redistribution used in both A & B.

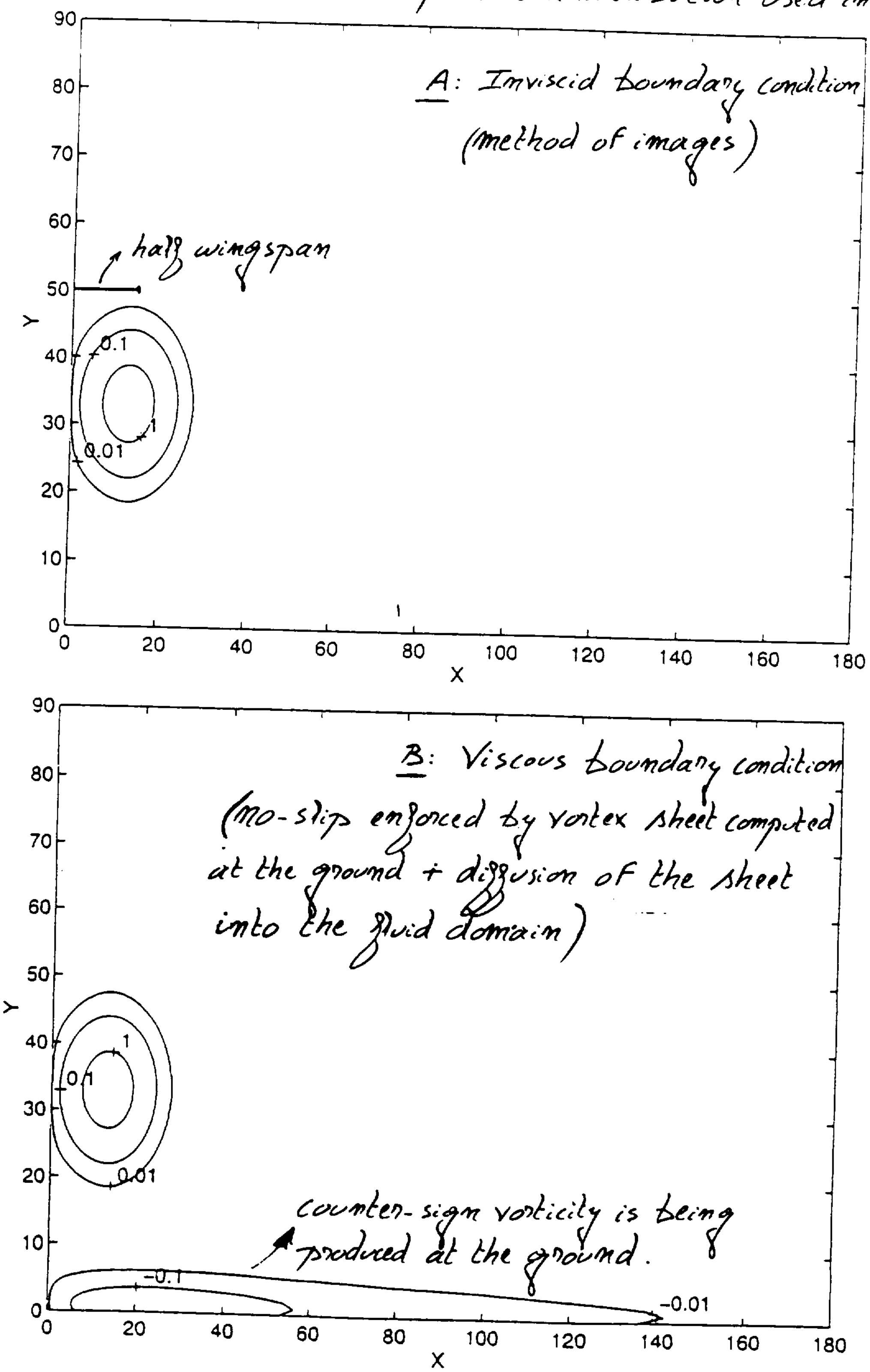



Figure : Contours of vorticity, $\omega(x, y)$, at $t = 0$ s. Comparison of Approachs A and B.

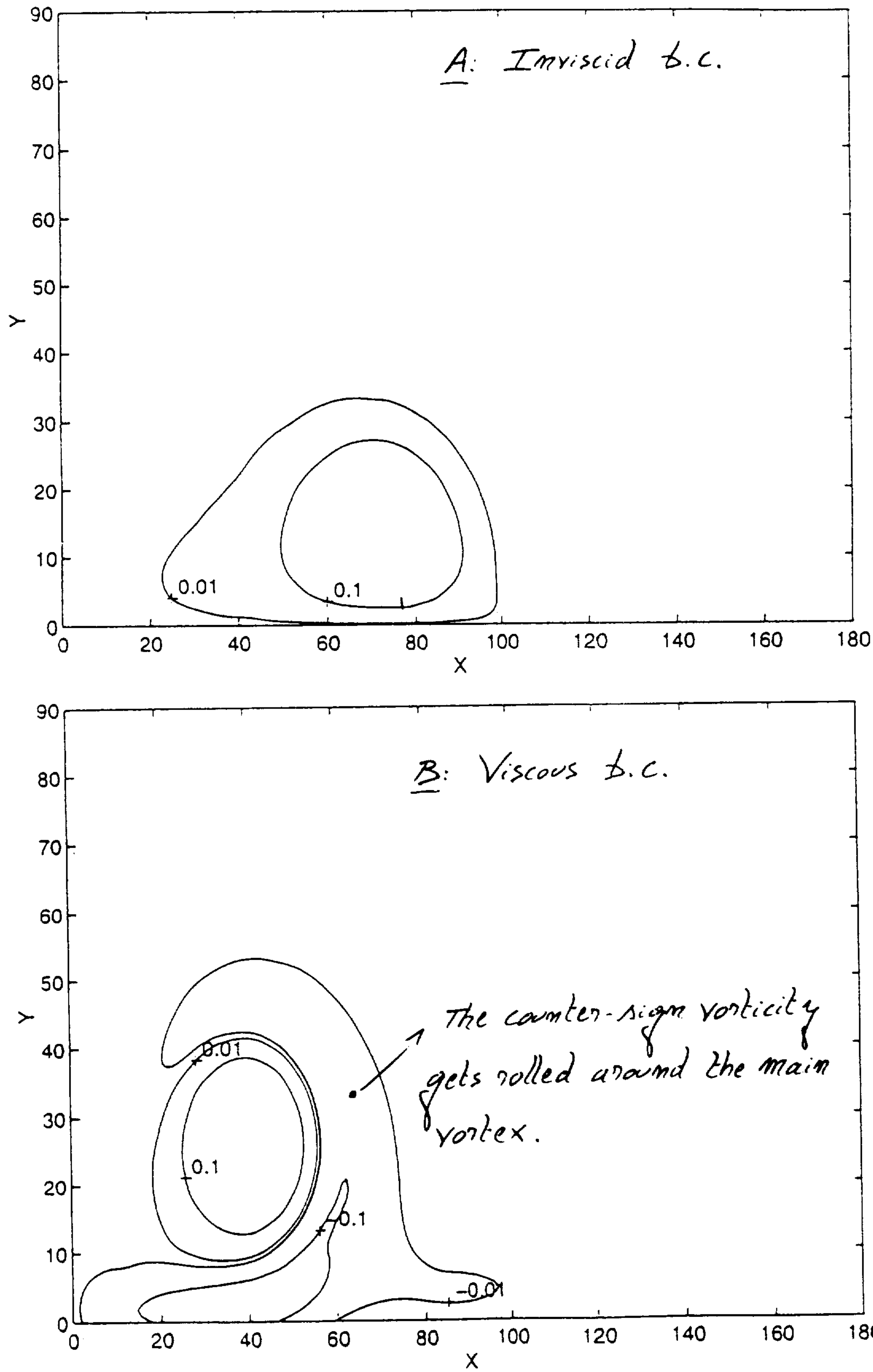



Figure : Contours of vorticity, $\omega(x, y)$, at $t = 60$ s. Comparison of Approachs A and B.

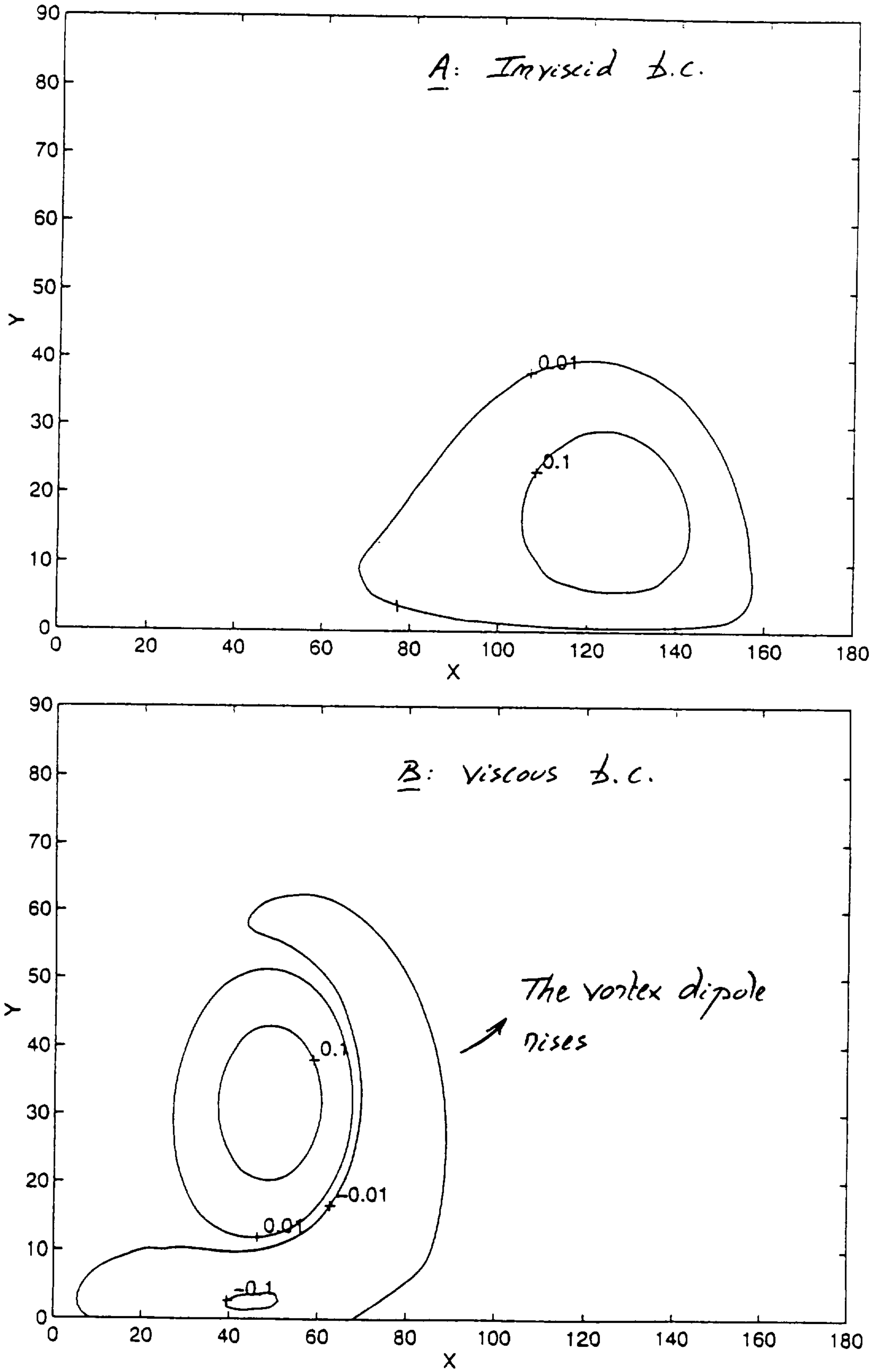



Figure : Contours of vorticity, $\omega(x, y)$, at $t = 120$ s. Comparison of Approachs A and B.

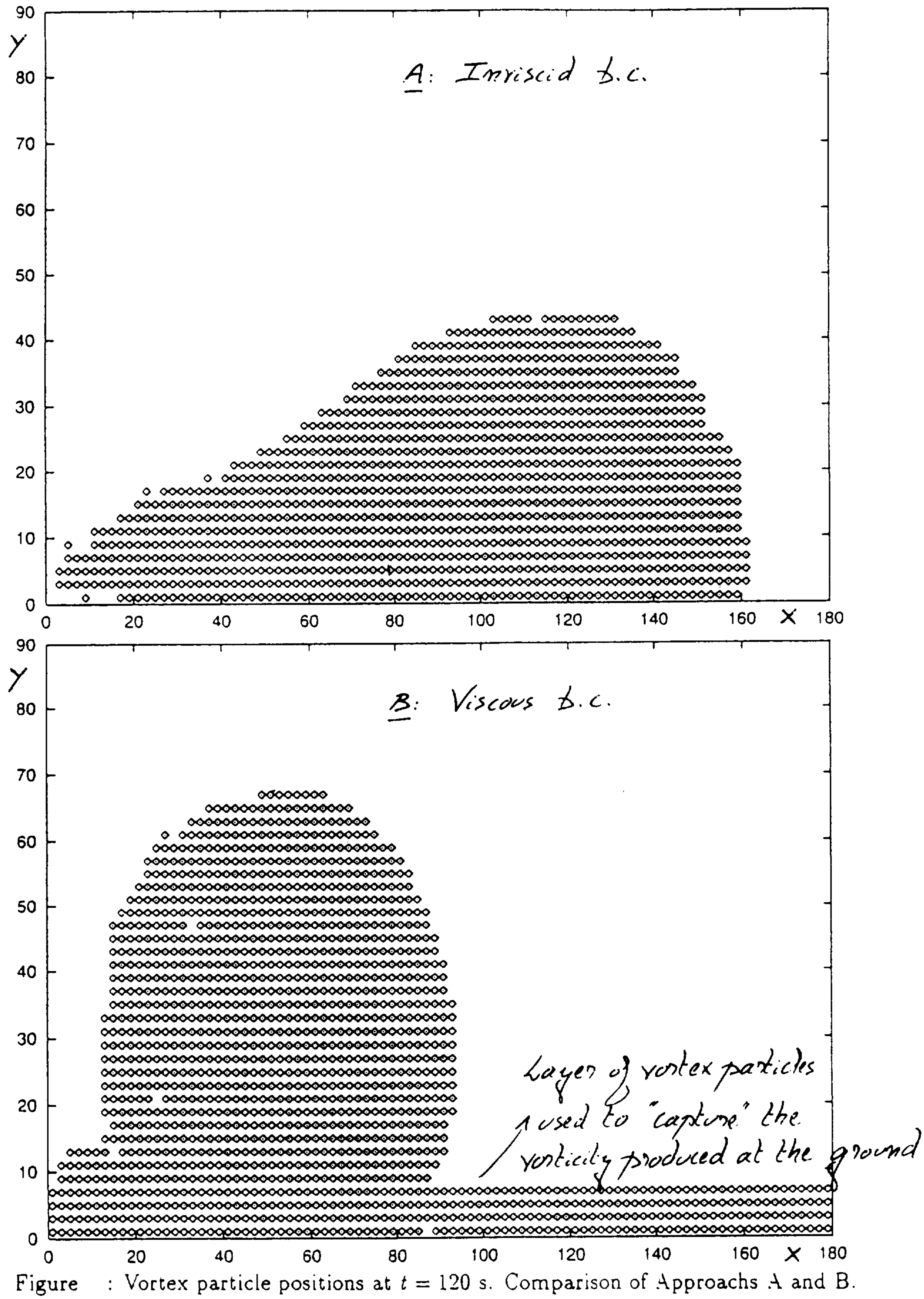



Figure : Vortex particle positions at $t = 120$ s. Comparison of Approachs A and B.

Centroid here defined as: $x_c = \dfrac{\sum_i x_i |\Gamma_i|}{\sum_i |\Gamma_i|}$

$$y_c = \frac{\sum_i y_i |\Gamma_i|}{\sum_i |\Gamma_i|}$$

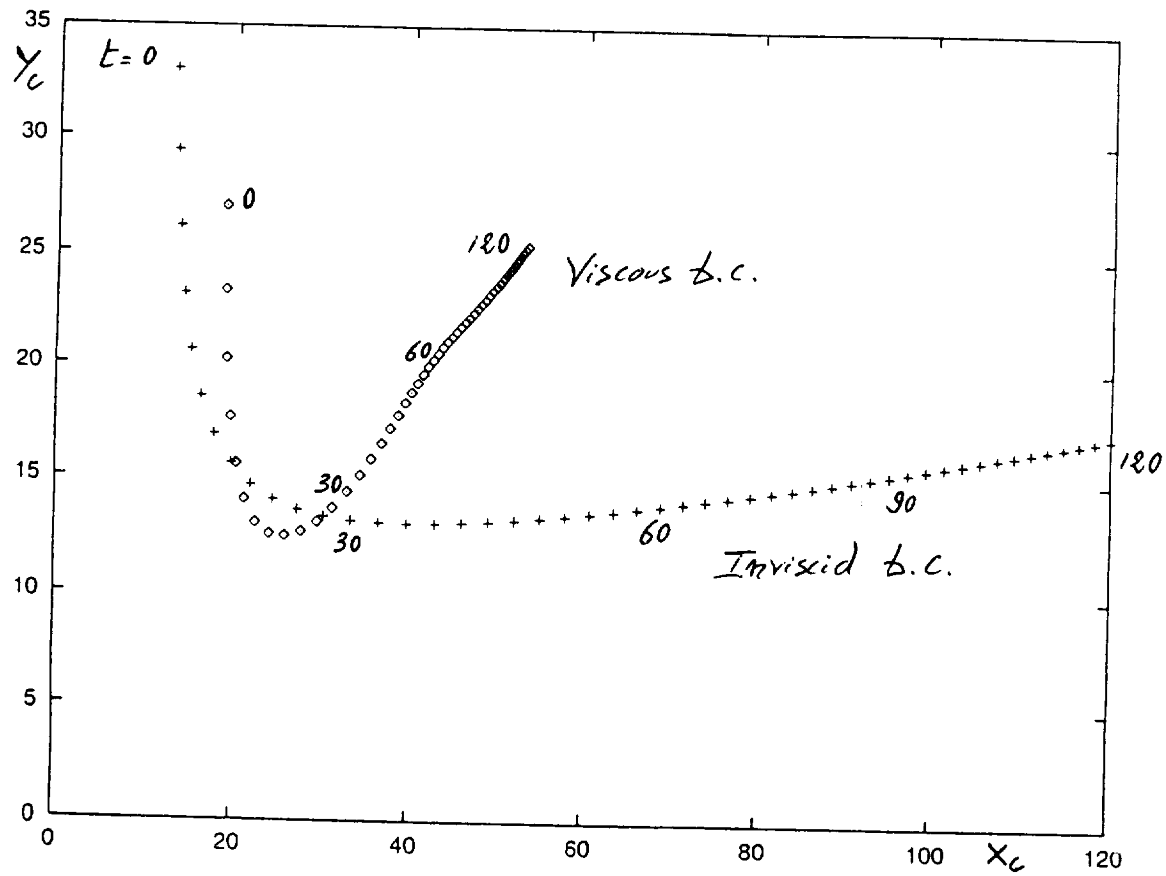



Figure : Trajectory of vorticity centroid, $(x_c(t), y_c(t))$. Comparison of Approachs A and B. The time interval between two consecutive points is 2.5 s.

Vortex trajectories are quite different. The viscous boundary condition here leads to vortex rebound.

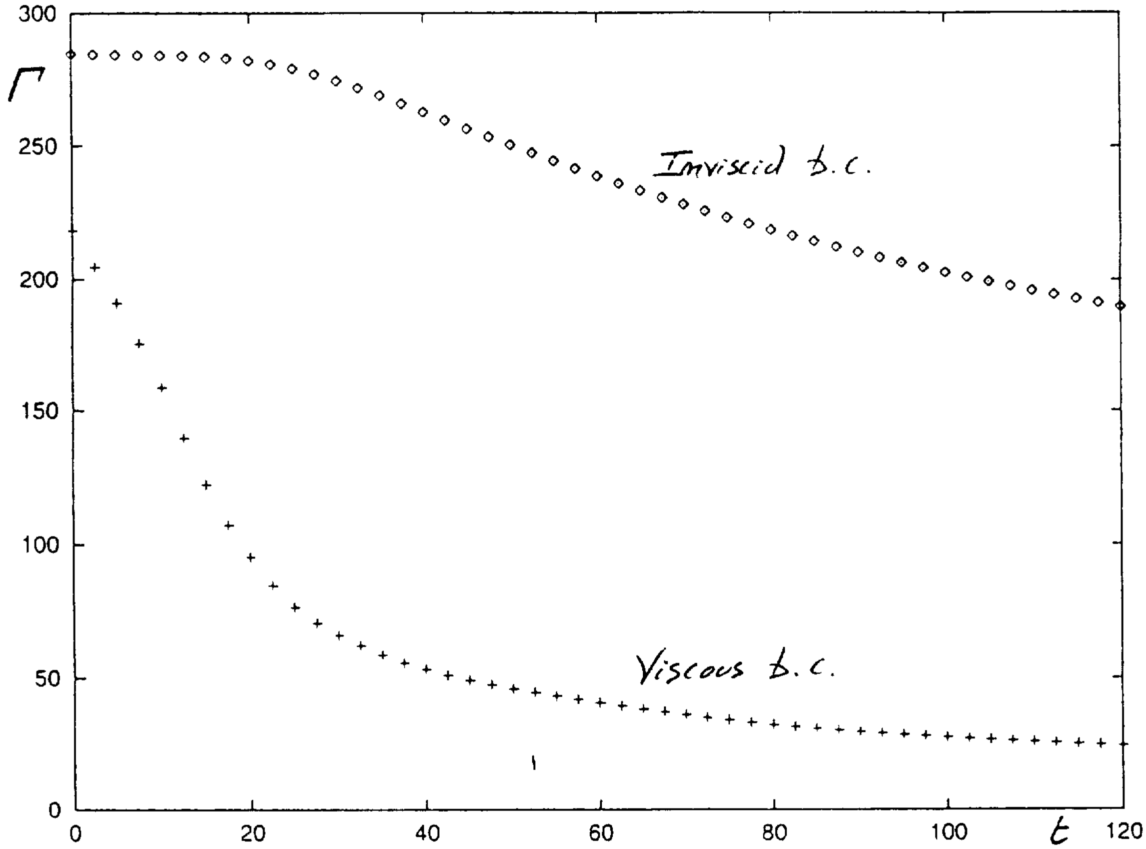



Figure : Evolution of total circulation, $\Gamma(t) = \sum_i \Gamma_i(t)$, in the first quadrant. Comparison of Approachs A and B.

Note: t = 0 corresponds to 10 s after aircraft

Vortex decay is much enhanced by using the proper viscous b.c. at the ground.

**Questions and Discussions Following Sydney Rennick's (Transport Canada) and Gregoire Winckelmans' Presentation (GSW)**

Charles Zheng (University of South Alabama)
In your near wake database you said typically it's 100 vortices. Based on what kind of criteria do you say it's 100 vortices instead of some other number?

Winckelmans
No, no, I am not saying it should be 100 vortices. I am saying so far, SABIGO, from what I have seen, seems to be using 100 vortices to describe the near wake. But in the computation, for instance I create out of the viscous interaction of the wake with the ground, I start with maybe 100 or 200 vortices. But because you produce vorticity at the ground, you end up with much more. If you are to capture the details of the vortex wake, a 100 vortices is usually not enough. But you might get away globally with 500 or maybe 300.

Zheng
Yes, that is my question. Based on what criteria can you determine 300 or 500 is enough?

Winckelmans
I would say its based on the criteria that you probably want to have a reduction on the order of 1 meter and you want to cover the region when there is significant vorticity. So depending on the evolution of the significant vorticity and the size of this, you know how many vortices you need for that. You don't want to carry out vortex particles up to when the vorticity is $10^{-3}$ seconds minus one. So you want restrict yourself to where it is really doing something. You want to use your vortex particles wisely. You don't want to use a whole bunch of data of a value which is $10^{-3}$ with respect to the most significant ones. So there is a trade off there you can play.

Klaus Sievers (German Cockpit Association)
What is the relevance of this work? Is it one more algorithm to predict vortex movement. If so, how do you get real aircraft data. Do you do wind tunnel testing to see if 100 or 200 would be proper to model one aircraft's behavior? How is this done?

Winckelmans
There are lots of simpler models that basically represent the vortex with two vortices. So having 200 of them is quite an improvement. I would not want to put a number bound on that. Concerning the flight test and airplane flight velocity of the airplane, you know its weight, and you know from the wind profile the side slip angle. So you can compute the angle of attack and you also suppose to know about the flap deflection for a typical landing. So a 727 lands you would like to know the flap deflection is typically, I don't know, say 30 degrees or something like that. That is information you would have to feed the system. This is something in real time. This would be a typical flap setting for landing for instance.

Rennick
This system in evaluation right now incorporates all the Boeing fleet and this year they will be developing a near wake database for other aircraft; the Airbus series and Douglas. It is aircraft specific and configuration specific and that information is fed into the model.

Winckelmans
So you want to get as much as you can from the flight manual and the tower. Of course some things you have to compute. So far, the angle of attack they compute it, because it is not measured.

George Greene (NASA Langley)
I am looking forward to seeing your work play out. Because there is sort of a fundamental difference and opinion between the approach we take here and your approach. The near wake database takes a lot of work to develop and they have done a fantastic job of it. It is after all an inviscid database. You have engines on airplanes and you dump it in an atmosphere that you don't always know to great precision. You can get a lot of precision in the near wake and it may not improve your accuracy. I think one of the things you will help us, as an international community to pull together, is to see what degree of precision versus accuracy you need to get a single or bottom line answer where the vortices go and how long they stay around.

Winckelmans
Yes, in our opinion the new wake database is not that critical. I just showed you what they have done, we didn't specifically ask them to do that. You could probably get away with much less work on near-wake database and put more work on the far-wake evolution. Personally, I am not pushing Transport Canada to develop with SABIGO any more near-wake databases. I don't think that is useful way of spending money. So you want to spend money on the far-wake. But they had near-wake database already, so they did not spend much time on that. But they like to do it because it is a fairly automatic thing to do, when you have done one you can do 10 then 100. Personally I don't think there is more work to be done on that side.

The Met.Office



# Development of a Wake Vortex Incident Reporting System and Database

Presentation to the
**1st Wake Vortex Dynamic Spacing Workshop**
May 1997

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## Introduction

It was recently identified that wake vortex separation regulations where an increasing limitation on capacity at European airports. Studies showed that with sufficient incident data, the potential to decrease separations under favourable meteorological conditions could be realised.

The European Commission has recently contracted the UK Met. Office and aviation telematics specialists RED Scientific Ltd. to develop and implement a Europe-wide wake vortex incident reporting system, utilising both automatic and human data sources. The aim is to create and maintain a database of wake vortex incident reports with associated meteorological data, which may then be used by researchers and operational aviation community to further understand of wake vortex behaviour.

This presentation will summarise the motivation, aims and future uses of the reporting log, and is an opportunity for potential users or contributors to discuss their thoughts and requirements for the use of the database products both in Europe and the US.

## Summary

- Background to project
  - Existing wake vortex incident data
  - European Commission
- Objectives of the project
- Project structure
  - Contributors
  - Proposed reporting system
- Database content
  - 3-D profiles
  - Turbulence estimation
- Database products and users
  - Confidentiality issues
- US involvement and benefits
- Future considerations

## Background

- Separation rules a major constraint on capacity in a growing number of European airports
- 'Worst case' separations, due to insufficient understanding of environmental factors
- Fully equipped measurement sites at single airports extremely costly
- A European wake vortex and met. monitoring incident reporting system identified as an affordable way of collecting necessary data

With the continued increase in air traffic, capacity problems are an increasingly important issue to international airports. Across Europe, in excess of 15 airports regularly operate more than 500 departures daily. For example, Heathrow departures frequently exceed 600 per day, with two runways operating in segregated mode.

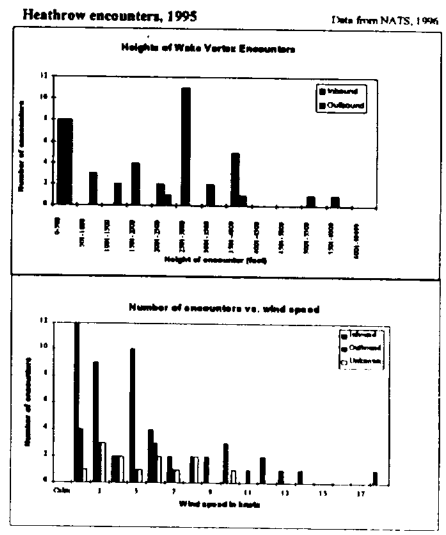
Current separation regulations take no account of meteorological conditions, save for subjective pilot reports to ATCs, whereby separations may temporarily be reduced. A system to measure the effects of environmental conditions on the persistence and movement of turbulent wakes is clearly required.

Fully equipped meteorological monitoring systems are extremely expensive and can cost up to $1m to install at a single airport. An incident reporting system and database was identified in a European study in 1994 as a viable and economic solution to the problem of capturing a sufficient quantity of objective data

## Existing Wake Vortex Incident Data

- National Air Traffic Services (NATS) have held an incident database for over 20 years
- Reports mainly from Heathrow and other UK airports
- Insufficient Met. data held
- Unsuitable for validation of models

## Incident statistics




The UK are the only European country to regularly monitor wake vortex incidents. The CAA's air traffic division, hold a database of reports covering many years. The purpose of the NATS database is largely to provide statistical summaries of incident rates and their relation to the aircraft involved, rather than to further research into objective methods of separation reductions

The system is UK based, and over 90% of reported encounters are at Heathrow airport. There is clearly a need for data from airports with a diverse range of runway configurations, meteorological phenomena and capacity in order to assess the global problem.

Meteorological information consists of relevant METARS. Since turbulent conditions and rapidly changing wind speeds and directions are significant to the wake vortex problem, this alone is insufficient.

Examples of the data provide an illustration of the motivation to introduce condition-dependent separations. Based on observed encounters at Heathrow, where departures and arrivals operate on separate runways, the vast majority of encounters are experienced by inbound traffic. Two distinct peaks in encounter rates occur; at low levels (< 500 ft) where any encounter is critical and 2500 - 3000 ft, the height at which aircraft join the glide slope

A strong meteorological dependence is clear from analyses of windspeeds and crosswinds at the time of the encounters. Hence there is clearly a case for more comprehensive met. data to be collected in relation to these encounters.

## The European Commission

- Body of representatives from European member states, financed by their governments
- Provide funding for research projects which are in the interests of the European Community
- Group DGVII (Transport) identified airport capacity problem
- Group DGXIII (Telematics) funding contract to implement a **E**uropean **T**urbulent **W**ake **I**ncident **R**eporting **L**og (**ETWIRL**)

## Objectives of **ETWIRL**

- To design and implement a wake vortex incident reporting system (2 year program)
- To gather incident and associated met. data from across Europe into a central database
- To disseminate this data to the research community for validation of models
- To provide information for the development of Wake Vortex Advisory Systems (WVAS)

The European Commission is the central funding body for this work, having previously contracted the initial investigative studies into the feasibility of implementing a pan-European reporting system.

The EC has contracted RED Scientific and UKMO to implement the two year program to develop the database and reporting system. Alan Woodfield is also contracted to UKMO for his expertise in wake vortex identification from flight data recorders and turbulence estimation.

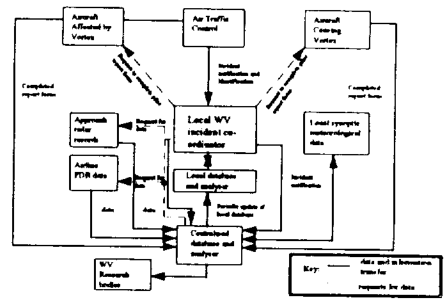
The two-year plan will cover trial reporting systems at a small selection of airports, leading to a fully functional reporting system which can then be further automated and maintained in line with user requirements

# Project Structure: Contributors

- **UK Met. Office**
  - Data specification, management and dissemination
- **RED Scientific Ltd.**
  - Project co-ordinators, software design, reporting system logistics
- The aviation community

| Contributor | Parameters |
|---|---|
| Pilots | Initial reporting of any encounter; Completing reporting forms |
| Airlines | Providing FDR data, briefing pilots |
| Air Traffic Controllers/ Airports | Provision of approach radar information |
| Met. Services | Airport METARS, surface sensor data, turbulence measurements |

# **ETWIRL** Reporting system schematic




The current project may be seen as two distinct entities:

1. Initial communication with co-operating bodies (i.e. airlines, airports, aviation authorities and researchers), leading to development of a European reporting system enabling prompt and efficient data to be sent to a central point from a number of sources.

2. To design and construct a comprehensive database which will contain as much information as possible for each incident. The data held will be stored centrally, and methods for disseminating information from it will be established for users

The co-operation of airlines, airport authorities and government aviation authorities is vital to the success of the reporting system. Information gathered will be a mix of electronic data (FDR, radar, synoptic met.) and human input (pilot reporting forms, ATC notification)

A number of local incident co-ordinators collect incident data for communication to the central database. Electronic data transfer is highly desirable.

In addition, the Met. Office aims to undertake analysis of data relating to turbulence, in order to provide turbulence estimates.

## Database Content

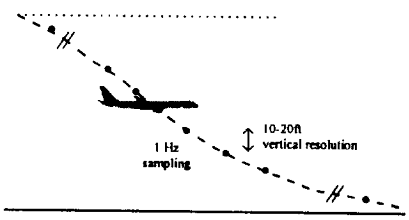
| Category | Source | Parameters |
|---|---|---|
| Leader / follower aircraft details | Pilots report form; ATC radar | Aircraft type and size, speed, altitude, flight phase, degree of buffeting and stick shake |
| 3-D position of aircraft | Pilots report form; ATC radar; FDR | Locations of leader and follower aircraft over a time period covering the incident, speed, altitude, yaw, pitch and roll of follower |
| Met profiles from affected aircraft | FDR | Profiles of temperature and wind on descent / climb, normal acceleration |
| Surface Met. data | UK Met Office, airports | Airport METARS, surface sensor data |
| Turbulence measurement | FDR, Met. Office, local instruments | Estimates of turbulent dissipation rate using different algorithms |

The aim is to build up a comprehensive database of incidents containing as much meteorological detail as possible. Aircraft details will be collected via pilot reporting forms, and from Air Traffic Controllers. Approach radar data will also be used for separation, speeds and altitude information.

The principle additions to the system currently operated by NATS are the inclusion of vertical profiles from Flight Data Recorders, and the estimation of turbulence parameters from vertical accelerations.

More detailed synoptic reports will be included, along with additional surface measurements for incidents occurring at airports where instrumentation is installed.

## 3-D Met Profiles from FDR data




- Profiles of wind, temperature and normal acceleration
- Minimum 2 minute profile for all encounters (1 Hz sampling)
- Profiles from 300ft above incident position
- Complete incident-to-ground profile for all incidents at <1000 ft

## Turbulence estimation

- Turbulent dissipation rate algorithms
  - US algorithm (Cornman)
  - UK algorithm (Woodfield)
    - using normal accelerations from FDR data
  - de Bruin method
    - from surface synoptic measurements
- Direct measurements
  - Instrumentation at Schiphol airport, Netherlands

Vertical profiles of wind and temperatures will be taken from affected aircraft which have fast access FDRs. It is estimated that this data will be available for around 20% of the incidents.

Raw data is sampled at 4 Hz, but limitations on the response of instruments indicate that profiles of 1 second average are sufficient for analysis. Typically a 2-minute timeslice will be stored, covering a height range of approx 1000ft . Where incidents occur within the lowest 1000 ft, a complete profile to the surface will be stored. This data is only an approximation to a vertical profile of the conditions, due to the angle of the glide slope.

Normal accelerations will be used to produce estimates of turbulent dissipation rates using two algorithms. These will be used to compare with direct turbulence measures where available, as an assessment of the effectiveness. A further approximation using surface observations will also be available for the comparison.

## Database users and products

- Model validation data
  - User-defined datasets
  - Standardised regular outputs
- Operational users
  - Incident statistics for airlines/airports
  - Statistical analysis of environmental factors affecting incident risk
- Electronic data transfer: E-mail, internet etc.

## Confidentiality of data

- No data will be used for investigation purposes
- All incidents de-identified before entry
  - e.g. Date/time information omitted
- Individually negotiated confidentiality agreements may be arranged

The stored data will be made available to those parties interested in its use for wake vortex characterisation studies or the compilation of statistics for airlines, aviation authorities etc. The content and format of the supplied information will vary between users, and at this stage any suggestions or requirements from potential users is welcomed.

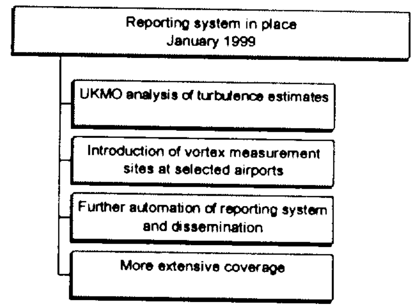
It is anticipated that a number of standard packages of data will be output regularly, for users to access. There will also be a need for specific requirements to be met for individuals within the field. Statistical summaries and analyses may also form a significant proportion of the products, particularly to operational users.

The data held on this database is purely for research and information to the aviation community. It will not be used in any way for investigative purposes into specific incidents. All incidents will be stored with identifying information removed.

## US Involvement

- US airlines reporting incidents at European terminals
- Modelling work supported/validated by incident reports from ETWIRL
- Future expansion to cover US terminals?

## **ETWIRL**: Future developments




The data collected from ETWIRL will be made available to all researchers of wake vortex behaviour, and developers of dynamic separation systems. We welcome any comments from the US community in the design of the database. Objective incident data is vital in the progress of theoretical work into wake vortices.

Once the reporting system is in place, it is a relatively simple step to expand the scheme to include non-European airlines using European airports. This would involve the co-operation of pilots of these airlines. Similarly, the system may be extended to further European airports for which wake vortices are a problem.

It is anticipated that the comparison of empirical turbulence estimates will show a case for more direct measurements at a number of terminals. The system may then be expanded to accommodate improvements in met. monitoring.

After the initial 2 year project, the database maintenance will require further funding. It is possible that contributors and users of the system will also contribute funds to this aim, leaving scope for further involvement by non-European countries.

**Questions and Discussions Following Julie Turner's Presentation (U.K. Met Office)**

Jim Evans (MIT Lincoln Lab)
How do you get information on the preceding plane? It sounds like your flight recorder is for the plane that had the incident. How are you going to get detailed information on the plane which generated the vortex?

Turner
We don't envision being able to get flight data from that plane. We will certainly get information on the size, weight, and position when the encounter occurred from the terminal radar and air traffic reports, and possibly from pilots as well. This information is already collected by the Heathrow system by NATS.

Tim Dasey (MIT Lincoln Lab)
This is smashing work.

Turner
Thank you.

Dasey
I understand the confidentiality concerns about the information as sent out. But I would try and retain as much as possible. For instance, information about incidents as a function of time of day statistically would be very interesting. You may be able to retain that information and create statistics without disseminating specific flight and times to outside organizations. Just a comment.

Turner
Thank you for the comment. One of the reasons for recording time of day is to correlate the instant information with the meteorological situation. And since we will be already attaching as much of the NATS data as we possibly can to each incident, that invalidates the need for time of day to be recorded.

Kenny Kaulia (ALPA)
I also find your presentation, I won't use the word smashing but interesting. British Airways has a program where they use quick access recorders and has had a very good program for a long time. We are just beginning to do that here in the States, although it is limited to a small number of aircraft in the U.S. fleet, but I think that is something that is coming. We will be able to do similar work to what has been done at British Airways. My suggestion as far as FDR data, if at all possible, to get data from preceding aircraft. That will give you valuable information as to the configuration of aircraft in addition to weight, etc. You also get as much data as possible from the following aircraft such as control wheel position, and such to see pilot inputs which are going on. That would be useful and helpful. The expanded FDRs are going to be coming out in the U.S. soon, due to NTSB recommendations, that data will be readily available.

Turner

I hope so. Ideally we would get flight data recorders from both the leader and following aircraft. At the moment, we think that is going to be our biggest problem. So initially we aim to get at least data from aircraft that actually encounter and any information that pilots can give us on the degree of buffeting or turbulence encounted that goes with the incident will also be recorded. Yes, in an ideal world we would get all FDR data we want but this is the real world unfortunately. Can I just add if any of you have to rush off, please do leave me your cards, I will be in touch with you. If you have any further inputs to make as to what you can gain from this database that would be useful to you and ultimately to everybody concerned. Thanks.

**Workshop Session Chairmens Panel Wrap-Up Discussions and Questions**

Brad Perry (Moderator NASA LaRC)
I will ask the session chairmen to join me and also George Greene and also Leonard Credeur, the Deputy Level III Manager for Reduced Spacing Operations. Going down the line, Fred Proctor from day 1 with the predictive modeling; George Greene who we heard from on day 1 and again yesterday, Dave Hinton, Dan Vicroy, Mike Kaplan and on the far end, Ben Barker.

I'll put a slide up just to get some discussion going. This chart we already saw, it was from Dave Hinton's presentation on Day 1. It is particularly interesting to go back and review these questions as we wrap up our workshop, to look at challenges. First of all what useful knowledge can each discipline provide today in working together to build a dynamic wake spacing system? What knowledge gap must still be filled for a minimally useful system? We had a lot of discussion of where transport is and where decay is. The fact is we will have transport capability well ahead of the time when we will be able to model and include decay. What features should and can be introduced as enhancements to an operational system? There are many aspects of that in the community such as pilot perspective, and regulation and certification perspectives, etc. And lastly, we invite anyone to entertain the bottom question which is simply, is there a better or simpler or different or preferable system that we might be doing in lieu of AVOSS? Or something we would build into AVOSS to make it stronger?

I would like to point out one other thing before we get into general discussion. We've enjoyed a good working relationship with the FAA and look forward to continuing that. We have been working very closely, in addition to Jan Demuth up in Washington at FAA Headquarters, we have been working continually at Langley with Hugh Bergeron who heads the local FAA Field Office, and who is in the back of the room holding his hand up. Hugh has been very interested and supportive of what we are doing, and we appreciate it. We are dedicated to do the best we can to be successful. This is a complex area involving many disciplines and technologies which, as we have seen over the last two and one-half days, are in various stages of maturity. Using a can-do attitude and using the smart people that are working on this, we can and will be successful. I look out in the audience, I see many of you sitting out there that are working with us in one way or another and we are appreciative to have you on our team. I would like to turn the corner here and let us ask questions to pick up further things that need clarification. If you had a question from a previous session you didn't get a chance to ask, now is the time.

David Smith (SETAC Airport)
I am the generalist; I agree with the gentlemen from Canada. I don't understand 75% of the physics. I believe I heard, in the cost-benefit presentation, that it is difficult to establish flight tracks down to the threshold and exactly where they were and what they were doing. You may, I don't know for sure, be able to use some of the larger airports that have noise abatement system. They have downloads of their ARTS data.

You can identify aircraft spacing or just about anything you want in a real-time situation. That might work if someone will check into that. I'll leave a discussion item for the panel. We spent a lot of time focusing at the conference on how we are going to deal with arrivals and arrival wake vortices. There has been some buzzing mostly in the corridor and afterward at diner on possibility doing departures first. Intuitively, it seems that setting up a wake vortex effort to get your departures off is better than trying to fix the approach wake vortex problem. There are airports out there, not necessarily SETAC in this case, but there are airports out there who can use that immediately. And that gets to the issue of what the FAA gentlemen had. One, you have this simpler version to deal with departures, you get people saying can you do this or what about this? Your approach to the wake vortex situation may begin to solve itself. Could you guys talk to that.

Brad Perry
I have an initial comment I would like to make on that, then I'll turn it over to the panel. I think Dave Hinton will have further comments to make as well. We are very interested in the departure problem. The approach problem in many regards can be seen as more challenging. We would like to work the departure problem and devote some resources there as well. Ultimately, we think we need to solve both areas. We think what we are learning today for the approach solution set, portions of that will apply to the departure. Dave.

Dave Hinton (NASA Langley)
Yes, we have had an ongoing discussion with a number of people about the departure situation. As Brad said, we are interested. The reason we are going at arrivals first is the great base of knowledge we can build upon exists in the approach regime. There are recognized benefits of both, but the arrival is that of getting those airplanes on the ground while they are burning their fuel. More importantly, there is a shift of emphasis in some of the research in departure versus approach. Some aspects of the system become simpler in the departure scenario. For example, the system does not have to produce 30 minute predictions. We may only need a 2 minute prediction. Other aspects become more difficult, particularly the procedural aspect. The reason for that is on approach we have very precise, consistent navigation paths through space. On departure we have different aircraft rotation points, different climb angles, and there is no precision navigation for a straight out departure to stay in a narrow corridor. So we have to couple any departure efforts much more closely with the operational community. We also have to couple arrival with the operational community, but it becomes an upfront issue much more rapidly in the departure scenario. I do agree we want to look at departures.

Ben Barker (NASA Langley)
One of the reasons I have focused my team, in the lidar effort to look at higher pulse repetition rate lidar system, up to 1 kilo hertz pulse system that Grady Koch told you about yesterday, is to be able to look at departures better. We know with a lower pulse system, you have to be homed in on a particular approach corridor because you need to get a good velocity profile of the wakes. I believe that working on the higher

pulse rate system will put us in a position to be able to look at the departure situation better.

David Hinton (NASA Langley)
I guess I would like to use the opportunity since we have some fairly good representation from ALPA and other organizations. It's fairly easy to define a departure corridor that only extends a few hundred feet above ground. The question is if we protect the aircraft from wakes in that domain, can we safely ignore what's happening at 500 feet or 1000 feet? How do you get the airplane away from that protected corridor into the terminal and enroute airspace? If there are any ideas from the floor on that, I would like to know.

Sydney Rennick (Transport Canada)
In response to your question, David. My belief is that information, for a simplistic approach, can be data linked from the aircraft to the ground. If you want whatever the wind speed and directions are as a simplified first start, you can get it at 200 miles and whatever altitude. Where my premise comes from is the requirement and a requirement that will increase in the future to maintain defined exact departure routes or arrival routes particular with FMS approaches where the system is doing it to 5 feet. That will happen in the future with Standard Instrument Departures where you will be obligated to follow that exactly and you will be following that exactly based on GPS navigation. If that information, if the wind speed and direction as a start, is data linked to the ground and incorporated and spit back up to the aircraft, the pilot could have a visual indication in the cockpit of the wake vortex location from the aircraft in front of him. Maybe my approach is too simple and I don't understand the problem, but to me that is a very quick, very effective approach.

The second part of my comment is that the concentration is on the resolution of the accuracy of the wake vortex location. From what I have seen and listened to here and over the last couple of years, it seems there is pretty reasonable accuracy with respect to the lateral position of the wake vortex. For the moment, any reduction in capacity at an airport is being driven by trying to determine the exact location of both the lateral and vertical positions. Could we, as a community for the moment, say to hell with vertical position and as long as I have got lateral freedom, then go with that and work on that vertical resolution. But for the moment address the capacity problem.

Brad Perry
Any comments on that from the panel?

David Hinton
Certainly, AVOSS will not give freedom based on lateral transport in the sense that aircraft can choose to stay a dot to the left or right of centerline. I am not proposing that. But AVOSS in Dallas will use both lateral and vertical motion, so if vertical is not known but the lateral is in fact transporting outside the corridor, it will do exactly as you say. It will provide a reduced separation matrix based only on that lateral motion. I don't know if that answers the question, but if we don't know the vertical but do know

the lateral, we are home free.

Wayne Jackson (Transport Canada)
I may have missed it, but the only thing I saw in terms of a definition of dynamic spacing and how it would be implemented at the operational level was one of the presentations this morning showing a second separation matrix which had reduced values. Is that the intention for the short period, for this phase of your work, or do you have another concept as to how you would actually change the spacing?

David Hinton
The interface to the control system is evolving as we work with folks like Barbara and Rhonda at Ames to define exactly what that should look like. For the purposes of Barbara's study we needed some changed matrix to give controllers to evaluate controller performance. So that matrix is based on an educated guess as to what the output of the system may actually be, limited by runway occupancy time. The actual matrix, when we say dynamic spacing, what we mean is that it is not static and published in a handbook, but is a function of the weather conditions. Now how dynamic it can be is going to be a function of what the ATC system can accept. Obviously we can't change it every 5 minutes or 10 minutes. We are looking at a planning horizon of 30 to 60 minutes. The additional logic that has to be put in place is going to be a function of what we get back from the ATC community. They may ask us, for example, give me a matrix that I can use for the noon balloon and if for some reason that changes, don't change it on me twice, once but not twice. We have heard those kinds of feedback.

Tim Dasey (Lincoln Lab)
In the spirit of thinking of alternative system concepts, I talk to pilots and ask what is the difference between VFR and IFR and what makes you more comfortable about flying closer in VFR? What always comes up is that they can stay above the glidescope of the plane in front of them. I guess the question I am asking, is there a way, if a tool could be provided to pilots, so in instrument conditions they could use a cockpit-based tool to allow them to make sure they are above the glideslope of the airplane in front of them? Could procedural changes be made? Would this tool increase the level of confidence of pilots so that procedural changes could be made to reduce separations?

Dan Vicroy (NASA Langley)
I think the problem you run into, if you start flying above the glidescope of the plane in front of you, is that the next guy has to fly above that, and the next guy above that, then somewhere along the line somebody just flies the normal glidescope and smacks into the wake from others which have been stairstepping up the glidescope. That is one of the problems with trying to fly above the guy preceding you. Also, the touchdown point will march up the runway.

Jerry Robinson (Boeing)
I just want to add, that in light of the discussion mentioned earlier, relative to

relationship of demand and local weather, it appears that TRACON, the Center and the Command Center all need to be linked together in providing input from ATC to establish the size of your look ahead window. Another point that I would make is that so far all the discussions have centered around the outer marker. I would recommend that you include the final approach fix. My understanding is that the outer marker might be a disappearing point of reference.

Dave Hinton
I want to clarify one thing. We have been using the term outer marker in a somewhat imprecise sense relative to your comment. We are talking essentially of the glidescope intercept point.

Jerry Robinson
Ok, and I do remember one other question I have. Some times controllers will feed an aircraft in on a short final or insert it between two aircraft, that is change the sequence. What happens to the system in that circumstance? Because I think the sequence of aircraft is an input to the AVOSS. What happens if the controller decides to change that sequence by say putting one in short?

David Hinton
Unless you are talking about visual approaches where people are doing curved approaches and intercepting the localizer at two miles, that is a type of arrival approach maneuver that AVOSS will not support for reduced spacing. We can accommodate that. If ATC wants to do that, but they have to go back to default spacing, because it violates the AVOSS concept of flying a protected corridor. If the system studies show it is more efficient to put everybody in that corridor than to allow visual approaches, then I expect visual approaches would tend to wane in popularity.

Second, the sequecing changes that Rhonda talked about, correct me if I'm wrong, are really taking place further out. You don't have the option inside the final approach fix to be changing the sequence unless possibly you are diverting one aircraft off the approach to a parallel runway or something of that nature. But the AVOSS concept is going to require relatively stable conditions, on the approach path, flight from the final approach fix to the runway.

Jerry Robinson
That is what I was thinking. So you will require stability.

David Hinton
It is to be worked out with Air Traffic. Do we have AVOSS on full-time, or shut it off in clear conditions and allow them to do what they have done previously?

Klaus Sievers (Vereinigung Cockpit)
You asked the question earlier about departure wakes. What comes to my mind is that departing aircraft tend to be heavier than arriving aircraft because of fuel load. As wakes are dependent in some fashion on the aircraft weight, I guess the wakes

would be stronger on the departure than on the arrival, generally speaking. I don't know how those stronger wakes behave, what they do. I guess that is a subject of future research. I would not be too confident that you can move to a 500 feet AVOSS for departures right away.

James Hallock (Volpe Center)
On the last statement, we have measured the wakes on departure and the one thing we found is that they do decay faster on departure. Yes, they initially tend to have a stronger wake, but not that much because even though the weight is higher, the speed is a bit higher because you are only using a small amount of flaps. The effect of vortex separations are larger. All that plays together in a sense of making it less of a problem on departure.

The other point I wanted to make is we have been talking about just using the presence of a vortex as being the thing to look at. Based only on lateral position is something we were doing years ago and based on measurement of something like seventy thousand landing airplanes, we found that it is around 8 to 10% of the time there will be a vortex within plus or minus 150 feet of the extended runway center line after 80 seconds, which is our infamous 3 miles. It would be nice to have some other way of saying there is a vortex there, but it doesn't have the strength to cause a problem. Knowing that the vortex was right at 150 feet away may be enough to say something. But it is the size of the corridor that is critical. If you define that well and make it less than 150 feet, then I think you have the possibility of doing a pure location of a vortex type system.

Kenny Kaulia (Airline Pilots Association)
I guess I'll start off by hitting the overhead bullet number four. "Will the community accept less than full approach path prediction and monitoring, given current data?" I can tell you that we are in the same position as the FAA right now. That there is no acceptable wake vortex encounter. That is not coming from me personally but from the pilots that I work for. Being a realist I think that is going to change and I think the AVOSS system will be something that will allow it some time in the future, I will not guess when, which would give us the opportunity to enhance capacity.

On the departure case, I think it is different as far as the aircraft's energy state. I think the incident and accident data bears that out. The aircraft is climbing with a lot of power applied, and an encounter would not be as severe.

I would like to say I appreciate the opportunity to come to the workshop. I think that there is still a lot of research work to be done to really understand the wake characteristics. And I am happy to hear that in the initial phase of what we will be looking at is the lateral and vertical movement of the wake rather than trying to rely on wake vortex strength predictions.

George Greene (NASA Langley)
Kenny, I would like to follow up on a comment you made either earlier today or earlier

in the week that bears a little on that. I guess I am a little more humble every time I think I know more about the technology and I find out more about the people issues. You brought up the case that perhaps when separation standards were changed, the controllers being intelligent people, thought of new ways of increasing capacity on their own, given the constraints placed on them. I wonder if we have addressed an educational program, since I don't know of any controller other than Tom Doyle here. I kind of wonder what you think of an educational program for controllers that would try and transfer this technology to them?

Kenny Kaulia
It's funny that you you bring that up. I have been in discussion with more of our regional pilots. Of course I represent the national association, but the problem has already been introduced as far as the lack of training of the controllers and to a large extent, the lack of training of the pilots. The genesis of the Wake Turbulence Government/Industry Team was to first of all put together a training aid. My understanding is that this training aid on wake turbulence has not really gotten the exposure we had hoped. I agree with you that the training issue is something that needs to be addressed, which would probably do a lot to increase the capacity just based on the plot we saw this morning showing excess margin as far as spacing is concerned. Obviously, the real data at the threshold is going to be somewhat less than that, but controllers are like everyone else. They have a certain rule they have to maintain and they are going to put in a certain amount of conservatism to make sure they don't get in trouble for having two aircraft being below the minimum separation standard. I think that is an area we will need to pursue on the Government/Industry Team.

Brad Perry
There is a question down here. While waiting for the microphone, there's one input I would like to make. We talked a few moments ago about the departure domain. I also want to reiterate that I said on day one that we are also interested in applying lateral solutions to our AILS, Airborne Information for Lateral Spacing, closely spaced parallel runways research. That has got to be part of the solution set for AILS for runway spacings less than 2500 feet. We have already shown good initial simulation study results for being able to do AILS at 1700 feet, perhaps a little less spacing. We are down in the domain where wake vortex will definitely be a part of what we are looking to bring forward as a closely spaced parallel solution set within the Terminal Area Productive Program as well.

Jan Demuth (FAA)
I would like to address the training part of that. Our purpose for the training aid was to increase awareness for both the pilot and controller communities. I am keenly aware that we did not get dissemination to either community to the extent that we would like. Part of the problem is the fact that it was primarily a paper distribution. That we are taking care of; we'll do a secondary distribution electronically very soon. Second, we are making an opportunity to work through NTIS with something that's reasonable from a price standpoint for distribution by CD-ROM. And something that you are

probably not aware of, we are in the process of producing a computer based instruction model. It would be less than 30 minutes for an average pilot or air traffic controller and designed for both communities. We will be making distribution and availability in the August/September time frame.

Myron Clark (FAA Flight Standards)
I have heard some discussion of where the coverage need to be and I don't know if I have heard anybody mention the magic word GPS yet. I think you need to keep that in the back of your mind as you worry about what you are going to do. If that comes full force like it looks like it's going to, we are going to do point-in-space approaches to all kinds of points. I think you gentlemen need to keep that in your planning.

Al deGraffenried (Aero Electronic Leasing)
First of all, you might wonder what is a leasing company doing here. Pull out the word leasing and put in research. One of the earlier papers on day one I think counseled very gravely not to try and retrofit the airplanes. I notice later in his paper he said with the advent of new science and technology and left himself an out. Well, we have some new technical approaches to boundary layer on the molecular level. Although it's prenatal, in other words not mature yet, it looks like we can get increased lift and decreased drag. We were aiming originally at the fuel consumption problem. In keeping with the phrase "fools rush in where angels fear to thread," we are looking at the problem of retrofit. Briefly the concept is if you can reduce the drag and increase the lift on the central 75% of the wingspan, then the circulation locally at the tips should be less for the same gross weight and airspeed. If that is the case, we don't have what the last question says, a simpler system, but we will have something which may attenuate the problem for the AVOSS people and it will help a little bit if we are successful and the gods smile upon us.

Jerry Robinson
I heard the comment of GPS. I understand there is a technical paper out on the ability to establish some separation of flying aircraft in a smaller corridor because of the navigational accuracy of GPS. Have you taken that into consideration in your programs?

Dave Hinton
We have not at this point. It would be premature to try to look at the sensitivity of that. We plan to look at the sensitivity of system performance to the corridor size. There are many factors that may change the corridor size, navigation accuracy, autopilots, pilot training, you name it. We will be looking at the sensitivity of performance to corridor size. What may open up a whole new bucket of worms, so to speak, would be if we have point-in-space approaches which do not follow one path, but different aircraft follow different paths. That is another twist on the problem. I want to demonstrate that the system can work today before trying specific adaptations to other proposed systems.

Klaus Sievers (German Cockpit Association)

I think that the last comment of the gentleman from Boeing was aimed at packing aircraft into a tight space and packing them tighter and tighter. That is happening in the North Atlantic with the reduced vertical separation now. And believe it or not, I have heard reports that aircraft have encounted wake vortex at level 350 or whatever with 1000 feet separation and 25 degrees of bank is what I have heard, in the cruise mode when everybody is running around having coffee and eating. Hum, boy that's another research topic. Thank you for letting me participate in this workshop.

Myron Clark
Yes, we have had reports of wake encounters due to reduced separations, but there have been no reports of 25 degrees of roll. The only reports that have been fed back to the project leader, Mr. Grimes, if you know the name, who has worked hard with the international group on RVSM, were that it has not been rolling moment but it's been chop. All the pilots reporting back to us have said it is a surprise, they could see the airplane ahead of them, it happened within 10 miles. Primarily the reports have come from overtakers, who have aircraft about 10 miles ahead on TCAS and all of a sudden they will get the rumble, rumble. There were no reports of extreme rolls, but they were hitting the vortices. In fact, I have had discussion with some of the panel members on what might be happening up there at that altitude. But it is happening, you are correct, but I haven't heard of any reports with severe rolling.

George Greene (NASA Langley)
Let me comment on some of the discussion we had. Some of the flight tests from back 20 years ago sort of established a thousand feet is how far a wake could descend. One of the things we learned is that when you have quiescent conditions, the wakes ultimately go through the Crow instability and form vortex rings and some people would think that when you form those rings the wake would rapidly disintegrate. The observations are just the opposite, those rings are a more stable form of vorticity and so these rings may descend quite a bit further. It depends on the size or wingspan of the generating airplane, but it may be another 1000 feet or so if you had a quiescent enough atmosphere. And so it would account for chop but not rolling moment if you encounted something like that which was decaying.

Brad Perry
Ok, we will call this a complete point. I would like to thank everyone for being here to participate with us. This has been an extensive two and one-half day technical exchange covering the many facets of our NASA wake vortex research.

We are currently working toward the first field deployment of AVOSS at DFW in September, and beyond that to the analysis of the data attained during the deployment. We anticipate our next workshop will be in the Spring 1998 timeframe as the results of our initial DFW deployment become available.

If you have not yet completed a workshop evaluation form, I would appreciate you taking a few moments to do so before leaving today. Alternately, you may elect to complete the evaluation form within the next couple of weeks and mail it to me at the address on the form. We place a serious emphasis on the research and workshop feedback you provide us and plan to include this feedback in the proceedings we publish from the workshop.

Thank you again for participating with us during the NASA First Wake Vortex Dynamic Spacing Workshop. The workshop is now adjourned.

# Appendix A

# NASA *First* Wake Vortex Dynamic Spacing Workshop, Day 1 - May 13, 1997

- **7:00am - Registration**
- **8:00am - Welcome (H. Lee Beach, Deputy Director, NASA Langley Research Center)**
- **8:10am - Program Description & Overview (Chairperson - Brad Perry, NASA LaRC)**
  - 8:20am - TAP Overview (Rose Ashford, NASA Level 2 Deputy Manager, Terminal Area Productivity)
  - 8:35am - RSO Overview (R. Brad Perry, NASA Level 3 Manager, Reduced Spacing Operations)
  - 8:50am - AVOSS Concept and Status (David Hinton, AVOSS Principle Investigator)
- **9:20am - BREAK**
- **9:45am - Historical Background (Chairperson - Fred Proctor, NASA LaRC)**
  - 9:50am - History of Wake Vortex Research: Problems and Accomplishments (George Greene, NASA LaRC)
  - 10:20am - Wake Vortex Physics: The Great Controversies (Philippe Spalart, Boeing)
  - 10:50am - Past Wake Vortex Investigations and Dynamic Spacing Systems (Ed Spitzer, James Hallock, Dave Burnham, and R. Rudis; Volpe Center)
- **11:20am - Wake Vortex Characterization and Physics (Chairperson - Fred Proctor, NASA LaRC)**
  - 11:25am - From Initial to Threshold Vorticity Distributions: Definition of an Acceptable Encounter (Turgut Sarpkaya, Naval Post Graduate School)
  - 11:55pm - The LaRC Wake Vortex Modelling Effort (Fred Proctor, NASA LaRC)
- **12:20am - Morning Questions**
- **12:35pm - LUNCH**
  - 1:50pm - Two-Dimensional Parametric Studies of Wake Vortex Interaction With the Atmosphere (Fred Proctor, NASA LaRC)
  - 2:15pm - Toward Understanding Aircraft Wake Vortex and Planetary Boundary Layer Turbulence Interactions Using Large-Eddy Simulations (D. DeCroix, D. Showalter, Y-L. Lin, and S. Arya; North Carolina State University)
  - 2:40pm - Large-Eddy Simulations of Aircraft Wake Vortices: Atmospheric Turbulence Effects (J. Han, Y.L. Lin, and S. Arya; NC State University)
- **3:05pm -BREAK**
  - 3:20pm - Large-Eddy Simulations of Rebound and Aging of 3-D Wake Vortices Within the Atmospheric Boundary Layer (Alexandre Corjon, CERFACS, France)
  - 3:45pm - Aircraft Wake Vortices in the Atmosphere (Frank Holzapfel and Thomas Gerz, DLR OberpfaffenHoffen)
  - 4:05pm - Effects of Stratification on 3-D Trailing Vortex Evolution (Bob Robins, Northwest Research Associates)
  - 4:25pm - Initialization and Computation of Three-Dimensional Wake Vortices (Charlie Zheng, University of South Alabama)
  - 4:45pm - Two-Dimensional Simulations of Wake Vortex Interactions from Multiple Aircraft (George Switzer, RTI)
- **5:05pm - Afternoon Questions**
- **5:30pm - Adjourn for the Day**

# NASA *First* Wake Vortex Dynamic Spacing Workshop, Day 2 - May 14, 1997

- **8:00am - Wake Sensor Technologies (Chairperson - Ben Barker, NASA LaRC)**
  - 8:05am - Wake Sensor Subsystem Requirements Overview (David Hinton, NASA LaRC)
  - 8:15am - Wake Vortex Measurements Using a CW Lidar System (Rick Heinrichs, MIT Lincoln Laboratory)
  - 8:40am - Overview of Pulsed Lidar Measurements at LaRC (Phil Brockman, NASA LaRC)
  - 9:00am - Pulsed Coherent Lidar Wake Vortex Detection, Tracking and Strength Estimation in Support of AVOSS (S. Hannon, CTI)
  - 9:40am - Estimation of Aircraft Wake Vortex Characteristics from Coherent Pulsed Lidar Measurements (Les Britt, RTI)
- **10:10am - BREAK**
  - 10:25am - A 1000Hz Pulsed Solid-state Raman Shifted Laser for Coherent Laser Radar Measurement of Wake Vortices (Grady J. Koch, NASA LaRC)
  - 10:45am - Overview of Wake Vortex Radar System Development at LaRC (Robert T. Neece, NASA LaRC)
  - 11:10am - Simulation Results for Wake Vortex Radar Systems (Rob Marshall, RTI)
  - 11:45pm - Wake Sensor Evaluation Program and Results of JFK-1 Wake Vortex Sensor Intercomparisons (B. C. Barker/LaRC, D. C. Burnham/SESI, R. P. Rudis/Volpe Center)
- **12:20pm - LUNCH**
- **1:30pm - Aircraft/Wake Encounter Session (Chairperson - Dan Vicroy, NASA LaRC)**
  - 1:35pm- Current Status and Application of Hazard Definition Technology (George Greene, NASA LaRC)
  - 2:05pm- Piloted Simulation Study of Wake Encounters (Eric Stewart, NASA LaRC)
  - 2:35pm- Wake Encounter Validation Experiments (Dan Vicroy, NASA LaRC)
- **3:05pm - BREAK**
- **3:15pm - Terminal Area Weather Characterization and Prediction (Chair - Mike Kaplan, North Carolina State University)**
  - 3:20pm - Meteorological Instrumentation at the Memphis and DFW Airports (Mike Matthews, MIT Lincoln Laboratory)
  - 3:50pm - AVOSS Wind Profiling Algorithm (Rod Cole, MIT Lincoln Laboratory)
  - 4:20pm - The COBEL PBL Model (Peter Zwack, University of Quebec at Montreal)
  - 4:40pm - The Application of Mesoscale Numerical Weather Prediction Models to the Terminal Area and Examples from Memphis-1995 Field Data (Mike Kaplan, Ronald P. Weglarz, Y-L Lin, Adam H. Langmaid, and David Hamilton; NC State University)
- **5:10pm - Afternoon Questions**
- **5:30pm - Adjourn for the Day**

# NASA *First* Wake Vortex Dynamic Spacing Workshop, Day 3 - May 15, 1997

- **8:00am - Wake Vortex Systems Integration and Implementation (Chairperson - David Hinton, LaRC)**
  - 8:00am - AVOSS Field Development Approach (David Hinton, LaRC)
  - 8:25am - Development of Wake Prediction Algorithms (Don Delisi, Northwest Research Associates)
  - 8:50am - Center-TRACON Automation System (Rhonda Slattery, NASA Ames)
  - 9:20am - Dynamic Spacing Human Factors Investigation (Barbara Kanki, NASA Ames)
  - 9:45am - Wake Vortex Systems Cost Benefit Analysis (Vicki Crisp, LaRC)
  - 10:05am - Getting to Operational Deployment: Lessons from TDWR and ITWS (Jim Evans, MIT Lincoln Laboratory)
- **10:30am - BREAK**
- **10:45am - Government/Industry Perspective (Chairperson - David Hinton, LaRC)***
  - 10:50am - FAA Regulatory & Certification Perspective on Dynamical Wake Vortex Spacing (Jan Demuth - FAA)
  - 11:05am - Frankfurt Germany Wake Vortex System (Joerg Rankenburg, DFS)
  - 11:25pm - Transport Canada Wake Vortex Activity (Howard Posluns, Transport Canada)
  - 11:45pm - Development of a Wake Vortex Incident Reporting System and Database (Julie Turner, UK Met Office)
- **12:05pm- Wrap-up Panel (Session Chairpersons - Open to Questions from Participants)****
- **1:00pm - ADJOURN WORKSHOP*****

*** Personal Computer Stations with Microsoft PowerPoint will be made available for Speakers prior to this session to modify or make additional slides for their presentations.**

**** Workshop participants planning to stay for the Wrap-up panel can obtain a lunch sandwich order form from the workshop administrators. Your sandwich order will be available in the small cafeteria in building 1202 immediately following workshop adjournment.**

***** A meeting of the AVOSS Sensor Working Group (AVSWG) will be held beginning at approximately 1:30pm on day 3 to address JFK-2 test preparations and plans for future sensor developments and evaluations. Workshop attendees interested in attending this meeting should indicate their interest to Ben Barker prior to day 3.**

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**13-15 May 1997**

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# Appendix B

## Compilation of the Workshop Evaluation Forms

*Note: A total of 35 workshop evaluation forms were received following the workshop. The evaluation form responses are tabulated below by question number. Transport Canada's comments follow the tabulated evaluation responses.*

**REGARDING THE WORKSHOP -**

**Was it informative?**

1. Yes.
2. Yes. I broadened my knowledge as well as my contacts. Very rewarding.
3. Yes.
4. Yes.
5. Yes.
6. Yes.
7. Absolutely!
8. Yes, very.
9. Yes, definitely.
10. Very good balance of physics and engineering.
11. Very.
12. Yes.
13. Yes.
14. Yes, but not in the way I expected.
15. A solid mix of theory, sensors technology, and operational topics.
16. Yes, it does.
17. Yes, very good for me to learn about the whole program.
18. Yes.
19. Yes. Lots of good, new information.
20. Yes.
21. Yes, very informative.
22. I felt the sessions were very informative.
23. Yes.
24. Yes.
25. Yes - excellent.
26. Yes.
27. This was a good overview and introduction to the key components and players.
28. Yes.
29. Yes.
30. Yes, very informative.
31. Yes.
32. Yes.
33. Extremely.
34. Very.
35. I found the workshop to be very informative.

**Did it accomplish what you expected?**

1. Yes.
2. I didn't know what to expect, but it was certainly worthwhile for me.
3. Yes.

4. More.
5. Yes.
6. Yes.
7. Partially.
8. Yes.
9. Exceeded my expectations which were already very high.
10. No response.
11. Yes.
12. Yes.
13. Yes.
14. No.
15. Yes indeed.
16. To some extent.
17. Somewhat. For a first workshop it covered what it needed to cover.
18. For the most part.
19. It exceeded my expectations.
20. Yes.
21. Mostly yes.
22. I wanted to learn more about AVOSS and I certainly came away with a lot of information.
23. Yes.
24. Yes and no.
25. Yes.
26. Yes.
27. Yes.
28. Yes.
29. Almost!
30. Yes, I think so.
31. Probably. It's too early to know what action NASA will take as its result.
32. Yes.
33. Yes.
34. Yes.
35. The forum provided much more information than I really desired, but for the first workshop, I guess you needed to provide all areas of concerns.

**Why or why not?**

1. Got an update on who is doing what - led to many outside-of-meeting discussions.
2. See comment to first question above.
3. The meeting provided me a very good overall view of the objectives.
4. I got to see the large picture and all the real world issues involved.
5. We received a lot of information on the current work done for AVOSS development.
6. Got a lot of information and met the right people.
7. Some talks too specific.
8. No response.
9. The excellent scope and the cross-section of people. Really impressed with the presence of pilots, airport managers, avionics firms, and so on.
10. No response.
11. It provided a broad scope of AVOSS activity.
12. Brought various groups together, pointed out non-technical aspects.
13. Good, broad range of interests covered. Good introduction to current work programs.
14. I expected to learn about vortex wakes, but found that little was known about them, and what was known was not mentioned.
15. Was perfect timing to adjust European efforts to U.S. activities.

16. Clear definition of wake vortex hazard still lacking. At what stage is the wake considered to be hazardless?
17. No response.
18. I work for an airport planning firm so I was more interested in the impacts of AVOSS on capacity, not the physics.
19. Although AVOSS is only a technology program, it considers many systems aspects of the problem that will be required for implementation.
20. It covered all aspects of the wake vortex issue and provided very good insight to the problems.
21. I would have liked much more time for questions and discussions.
22. I understand the concept and have an appreciation for the issues.
23. I learned some things about wakes in general and about AVOSS.
24. Insufficient time for questions, and almost no time for discussions.
25. Technical, lidar, pilots, FAA, operations, weather - excellent depth!
26. No response.
27. No response.
28. It did because I was primarily interested in status and progress to date.
29. A little too much focus on past and not enough on the technical hurdles to be jumped in the future.
30. No response.
31. I was hoping for more FAA presence. NASA honestly opened its door. Hinton's presentations are clear.
32. I expected and received a reasonable introduction to AVOSS.
33. It offered a wide spectrum of views and status of on-going work.
34. Excellent presentations, opportunity to meet key persons.
35. No response.

**Any subject area(s) that should have been covered in more depth?**

1. Hazard definition - what it is (not just simulations).
2. No, for a novice in the field, it seemed nicely balanced.
3. On-board sensors, pilot's perspectives.
4. Representatives from the FAA Capacity Office should have been present.
5. No response.
6. Operational aspects, procedures to fly under wake vortex constraints.
7. Weather characteristics in relation to needs for accurate vortex behavior characterization.
8. No response.
9. I am new to this field. An overview of how air traffic is managed, airport control system, etc.
10. The upset aerodynamics and hazard definition.
11. No.
12. No.
13. Current operational practices and evidence that improvements could be made to capacity.
14. The accumulated experience of encounters.
15. No response.
16. Wake hazard definition.
17. Day 3 topics can be expanded - more participants.
18. Capacity impacts.
19. No.
20. No response.
21. I would have liked to learn about the actual accidents.
22. In the next session I am anxious to hear about the field trials.
23. Sensors, particularly range and weather.
24. The user needs and requirements.
25. No response.

26. I have No responses on the AVOSS program. However, I strongly feel that there should be more emphasis on understanding the basic phenomena such as bursting, dissipation, ground effects, atmospheric effects, etc. It is true that the present day capabilities will not permit us to understand the complete theory of the two trailing vortices together, but the understanding generated of isolated phenomenon will go a long way to design and interpret the mass of data that will be collected in the AVOSS program. Attempts in the 1960's to develop simple theories are still the basis of understanding trailing vortices. A little more effort on the theoretical side is desirable.
27. Working groups on sensing and prediction need to be separately held.
28. Difference between optical and microwave sensing.
29. No response.
30. No response.
31. The next generation empirical wake model.
32. Maybe some discussions of measures of how well the current spacing requirements work.
33. Field experiments.
34. Yes, pilot/aircraft reaction to vortex encounters.
35. No response.

**Any subject area(s) that should have received less attention?**

1. Radar. Suggest you reassess this area - doubt it will be useful for vortex measurements.
2. No.
3. Numerical simulation of the weather.
4. No response.
5. I think all (of the workshop) was ok.
6. Research into wake vortex behavior and modeling.
7. No.
8. No response.
9. I think modeling received too much attention, but questions really drew out the issues.
10. No response.
11. No.
12. No.
13. No response.
14. Yes. The endless succession of slides describing the organization of projects.
15. No response.
16. No response.
17. Day 1 and 2 technical topics can be focus groups now that the big overview has been accomplished.
18. Formulas, physics, etc.
19. No.
20. No response.
21. The papers that have already been published!
22. No response.
23. No.
24. Technical details of numerical modeling.
25. No response.
26. No response.
27. No response.
28. I cannot think of any.
29. No response.
30. No response.
31. Yes, too many results of narrow-focused simulations, TASS and others.
32. No.
33. Simulation studies.
34. No.

35. No response.

**Any suggestions for improving future workshops?**

1. Could try a brainstorming session on hazard definition.
2. A list of attendees with their affiliations would facilitate later personal correspondence.
3. None.
4. Test out the video equipment before using it.
5. No response.
6. Shorten the daily duration, like 8:00 a.m. - 16:00 p.m. Too much stuff to digest.
7. Make sure speakers fully understand the context of workshop and the audience they are addressing.
8. The general sessions were good to give a general idea of each component. We could then split up into parallel sessions to deal in detail with specific components: wake vortex physics, meteorology, cost/benefit, etc.
9. No controllers present as far as I knew. Aircraft Safety Reporting System (ASRS) in Mountain View, CA should have had a presentation , at a minimum.
10. No response.
11. Maybe one less paper in each area allowing more time.
12. No, keep up the good work.
13. Include more discussion time, perhaps more tables for displays of work, handouts, etc.
14. Remind presenters that descriptions of organizations are uninteresting - especially if endlessly repeated.
15. Current structure of workshop is ok.
16. No response.
17. No response.
18. Break it into two sessions - capacity impacts and physics, etc. People can then decide which to attend.
19. No.
20. Continue as is with updates to the topics/issues.
21. Fewer papers, only the most recent work, time for questions.
22. No response.
23. No response.
24. Leave more time for questions and discussions; include presentations from potential users.
25. No response.
26. No response.
27. No response.
28. Excellent workshop.
29. No response.
30. No response.
31. Do not give up foreign involvement (scientists ad governments)!
32. No response.
33. Show how the sponsored research attains the AVOSS objectives.
34. No, great organization, good facilities.
35. I would suggest that in future forums that those interested in specific detail areas be provided the opportunity to select what areas you want to gain insight on and not have to listen to all of the presentations.

**REGARDING NASA's AVOSS PROGRAM -**

**Does it address the capacity problem?**

1. It should, but was not very clear via the Ames presentations.
2. Yes. Plenty of analysis, plenty of measurements, simulations, and evaluations.
3. Probably not.

4. Maybe.
5. The time of forecasting was not clear and must be the most important parameter.
6. Yes.
7. Not qualified to answer (this question) at this point.
8. Yes.
9. I think so.
10. Yes.
11. Maybe.
12. Yes.
13. Yes, but has some ambitious aims.
14. Theoretically yes.
15. Yes, it does.
16. Not really.
17. To some extent, but I think we need the FAA, airlines, and ATC operators represented. Their perspectives described.
18. If spacing can be reduced, then yes.
19. Yes. Plan is for incremental approach based initially on transport only.
20. Not completely.
21. Yes.
22. No response.
23. Yes.
24. Yes.
25. Yes.
26. No response.
27. No response.
28. With proper sensing, capacity should improve.
29. Not yet.
30. Yes.
31. Yes.
32. Yes.
33. Somewhat.
34. It covers a significant item, namely wake separation while maintaining safety.
35. The AVOSS program addresses the capacity problem and I realize the importance of modeling AVOSS, but insofar as the airlines are concerned, it is needed now.

**Why or why not?**

1. A vortex motion AVOSS is likely to be implemented differently than a full AVOSS.
2. It clearly is what is needed at this stage of our understanding of the problem.
3. Combined uncertainties in weather prediction, vortex motion, weights in aircraft pairs, etc. May force the system to go back to the existing separation requirements.
4. You need to show that accurate information on the presence of vortices in the corridor will allow reduced spacing.
5. A more simple system is sufficient to address capacity, but safety needs such a complex system.
6. No response.
7. No response.
8. No response.
9. No response.
10. No response.
11. We don't yet know what answer we'll get as to vortex transport/decay versus acceptable hazard.
12. Will eliminate many needless delays.
13. I think more detailed information on current standards/safety analysis is needed.

14. It is a heavy weight program with all the inflexibility that that suggests, involving planning far too far into the future.
15. No response.
16. The detect and avoid strategy provides a short-term prediction capability (on order of hours). Long-term airlines flight schedules cannot be altered (to increase capacity) based on this capability.
17. No response.
18. No response.
19. No response.
20. As Dr. Jim Evans pointed out, the issue of how to use the added capacity has to be addressed.
21. It does because I personally cannot think of a better engineering/scientific approach to the problem.
22. No response.
23. No response.
24. No response.
25. No response.
26. No response.
27. No response.
28. By improving our understanding of wake vortices, we should be able to reduce spacing.
29. Need a better understanding of vortex diffusion and breakdown. Also, need more robust all-weather sensor.
30. No response.
31. Under most weather conditions, it should give 1 or 2 nautical miles. Forecast failures or insufficient lead times are a big concern. I was told ATC would prefer hours,
32. But it appears a lot of work remains before AVOSS is likely to be successful.
33. Not clear if AVOSS addresses capacity or safety or both.
34. Focus the program is ok; however, I have doubts that the required prediction time horizon can be achieved. Maybe I am wrong.
35. No response.

**Any suggestions for future AVOSS direction?**
1. In these trying budget times, (you) might think about some near term outputs.
2. No. My own "retrofit of aircraft" approach arises out of my personal expertise, aerodynamic boundary layers.
3. Emphasize more on-board sensor development. Analyze and apply AVOSS to all available existing incident and accident data to guide AVOSS future development.
4. You need to show that the prediction algorithm to be used is reliable for all conditions where the system would be used.
5. No response.
6. Cover full ILS approach beyond outer marker, include departure.
7. More focus on weather effects and implementation of readily available weather characterization and prediction/tools.
8. No response.
9. Good introduction to and overview of how airports work and also overview of actual wake vortex incidents and other safety incidents for comparison. Put cost/benefit, economic return, safety overviews up front and have them lead into more technical sessions. Set the stage. Questions were good in getting handle to overriding issues.
10. No response.
11. I like the current plan.
12. Define current spacing situation, evaluate which airports will benefit most.
13. No response.
14. Try to learn more about vortex behavior on the cheap before freezing fancy and very expensive vortex detection systems. In particular, NASA should get the Air Force or the Navy to fit smoke generators to the wingtips of heavily-used heavy airplanes - say B-52's, C-141's, or C-5a's - to be used whenever they land

at selected airports, and videotape the smoke-marked vortices via tail-mounted cameras and perhaps from the ground. As a professional scientist, what I find lacking in the AVOSS program is the atmosphere in which one bites and scratches one's way to understanding with quick and dirty methods, where each bite or scratch is directed by what one learned from the last one. A typical bite would be to find out where in the landing or take-off sequence vortices have been encountered. Nobody mentioned this at the workshop, except as a previous project. Is there really no information available now? There must be some, or there would not have been a workshop. But the fact that it was not mentioned reinforced the impression that the AVOSS program comes before the vortex problem in people's minds. My preference for visualizing the flow results from experience. I have used dye streamers to visualize flows around swimming fish, and better, shadow graphs of stratified water for the same purpose. No other methods so quickly disprove false assumptions.

15. No response.
16. I believe in the long-term active control of wake vortices should be brought into the program.
17. Safety issues must be addressed, critical to program success.
18. Involve the airports, airlines, FAA, ATC, etc.
19. FAA/ALPA make comments about planning now for implementation and for training with a prototype.
20. Include FAA flow management people and find a user customer for it.
21. I would like to see the work further accelerated and field data acquisition instruments considerably improved.
22. No response.
23. No response.
24. More attention to real-time detection and tracking of wakes.
25. No response.
26. No response.
27. No response.
28. Look at integration of optical and microwave sensors.
29. No response.
30. No response.
31. Do everything to involve the FAA and JAA. Fund scientists outside your backyard. Attempt to declassify Navy work.
32. Work on determining the statistics of events which can be hazardous even when measurements at a few points in space indicate acceptable conditions.
33. Show relationship (cause and effect) between AVOSS and airport/airspace capacity.
34. Program focus and direction are ok.
35. I suggest that all of the prototype programs be used together in a real-time basis at DFW to understand if they will work together. I also suggest early deployment of those portions of programs that have proven to work. Let's get them fielded ASAP.

**ADDITIONAL COMMENTS RECEIVED FROM TRANSPORT CANADA**

This note is to provide a few comments regarding the workshop and is in comment to your request.

The Workshop on 13-15 May was very worthwhile, in that I was able in 2.5 days to get a good overview of your plans, activities and issues. This is most important because I believe Transport Canada should integrate our effort with yours. More on that later.

Perhaps the main deficiency was who was not there (i.e. the FAA (Research and Acquisition, and ATC)). I understand that this is beyond your control, but it may constitute your greatest area of risk. The talk by Jim Evans should be taken seriously. CTAS is having success with the FAA by starting with operational demos at DFW and Denver. That approach may not work for AVOSS. Could the FAA allow different separations at different airports? Would the users accept that? Is the FAA involved in the cost benefit activity. Are air traffic controllers involved in the human factors investigations? I conclude this point by saying that the participation of the FAA and the presentation of their views and activities in these areas would be an important improvement to the next workshop.

Perhaps in future workshops you may want parallel sessions with tutorials or executive summaries provided at a plenary session.

The definition of "dynamic spacing" should have been presented clearly early in the workshop. There are many different views on what is meant by "dynamic spacing".

I look forward to receiving the proceedings and to further discussions with you about how we can best work together.

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**13. ABSTRACT** *(Maximum 200 words)*

A Government and Industry workshop on wake vortex dynamic spacing systems was conducted on May 13-15, 1997, at the NASA Langley Research Center. The purpose of the workshop was to disclose the status of ongoing NASA wake vortex R&D to the international community and to seek feedback on the direction of future work to assure an optimized research approach. Workshop sessions examined wake vortex characterization and physics, wake sensor technologies, aircraft/wake encounters, terminal area weather characterization and prediction, and wake vortex systems integration and implementation. A final workshop session surveyed the Government and Industry perspectives on the NASA research underway and related international wake vortex activities. This document contains the proceedings of the workshop including the presenters' slides, the discussion following each presentation, the wrap-up panel discussion, and the attendees' evaluation feedback.

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