Wake Turbulence Measurements

Practical Experience, Considerations, Contribution Made to NAS and Science To Date

WakeNet 3 – Greenwake Dedicated Workshop on "Wake Vortex & Wind Monitoring Sensors in All Weather Conditions"

29th and 30th March 2010
Palaiseau, France

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U.S. Department of Transportation

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Acknowledgement

- FAA ATO-R (Sponsor)
- Thomas Seliga (Retired DOT Volpe)

Facts of Life

- Wake Vortex Understanding Has In Part Depended on Available Vortex Sensors.
- There is No Perfect Sensor / Processing
- Thus Potentially, There is Philosophically No Perfect Wake Understanding, If Ever.
- But Wake Vortex Understanding Has Advanced Substantially Since the 1970s
- Sufficient Understanding Exists in Aspects of Wake Turbulence to Provide Near-Term and Mid-Term Wake Mediation Solutions via Procedure Changes and Wind Based ConOps.

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Status of the Science and Data Needs

- To Support These Objectives, the Necessary Data Collection Are Made in Offline, Non Real-Time Research Mode
- There is Currently No Well Defined Operational Concept for a Wake Advisory / Avoidance / Warning Systems, Thus No Operational Requirement for a Wake Sensor or Sensors.
- Research and Operational Wake Sensors Have Different Requirements (More Later)
- The Present Talk Highlights Some User Experience and Retrospectives on the Contributions Made to Capacity and Safety Topics and Wake Turbulence Science
- The Presentation is Not Intended to be a Complete Survey, and is Biased by the Experience / Involvement of the Volpe Center.

DOT Volpe Center

- Located in Cambridge, MA, USA (On the Campus of NASA's Former Electronics Research Center)
- Part of the United States Department of Transportation – Federal, But Fee-for-Service
- An Integral Part of the Wake Turbulence Field/Flight Research Activities in the U.S. Since 1971.
- Experienced in International Wake Turbulence Collaboration.

Measurement Campaign Involvements

TEST CONFIGURATION						REFERENCE/BASELINE SENSORS FROM VOLPE			
SITE	DESIGNATION	SPONSOR	TASK	OPERATION	YEAR	WINDLINE	SODAR	CW LIDAR	PULSED LIDAR
KENNEDY	JFK	FAA	WTR	LANDING	73-77	X	X	X	
STAPLETON	CEN	FAA	WTR	LANDGIND	73	X	X		
HEATHROW	LHR	FAA	WTR	LANDING	74-75	X	X		
ROSAMOND LAKE		FAA	WTR	B747	75	X	X	X	
O'HARE	ORD	FAA	WTR	LANDING	76-77	X	X	X	
TORONTO	YYZ	FAA	WTR	TAKEOFF	76-77	X	X	X	
MOSES LAKE	MWH	FAA	WTR	B747,L1011	79-80	X		X	
NASA DRYDEN		FAA	WTR	B747,L1011	79-80	X		X	
O'HARE	ORD	FAA	WTR	TAKEOFF	80	X	X	X	
ATLANTIC CITY	ACY	FAA	WTR	ROTORCRAFT	85-86			X	
IDAHO FALLS		FAA	WTR	727,757,767	90		X	X	
DALLAS FORT WORTH	DFW	FAA	WTR	LANDING	91		X	X	
KENNEDY	JFK	VAR	WTR, RASS and Sensor Testing	LANDING	94-03	X			
MEMPHIS	MEM	NASA	AVOSS	LANDING	95	X			
DALLAS/FORT WORTH	DFW	NASA	AVOSS	LANDING	97-00	X			
KENNEDY	JFK	PANYNJ	JET BLAS	TAKEOFF	99	X			
SAN FRANCISCO	SFO	FAA	SOIA	LANDING	00-03	X			X
ST. LOUIS	STL	FAA	CSPR	LANDING	03-06	X	X		X
DENVER	DEN	NASA	WAKE ACOUSTICS & WTR	LANDING	03 & 05-06			X	X
ST. LOUIS	STL	FAA	CSPR	DEPARTURE	06-09				X
FRANKFURT	FRA	FAA	CREDOS & WTMD	DEPARTURE	07-08				X
HOUSTON	IAH	FAA & NASA	WTMD	DEPARTURE	07-09				X
SAN FRANCISCO	SFO	FAA	CSPR, WTMD & WTMA	LAND & DEP	06-09				X
ATLANTA HARTSFIELD	ATL	FAA	WTMA	LANDING	09-11				X
KENNEDY	JFK	FAA	WTMA	LANDING	09-11				X

Aircraft Wake Turbulence

- Fundamental Measurement Challenge
  - Unsteady Flow Measurements
  - Very Large for Traditional Fluid Mechanics Diagnostics Tools
  - Very Small for Traditional Meteorological Sensors
  - Wake Measurements Require Sensors to Take "Snapshots" of the Vortices Whereas Wind Measurements Can Afford More Time Averaging:
    - Wake Measurements Require More SNR

Some General Overall Updates on Measurements

General Hardware Progress Since the 1990s

- 24-7 Unattended, Automated Data Collection – Statistically Including Seasonal and Diurnal Effects.
- Raw or Semi-Raw Data Saved to Better Support Future Reprocessing.
- Measuring Wakes from Higher Aircraft Altitudes than 1990s – Wake Measurements Over 1000 Feet AGL is Routine Currently.
- Better Departure Vortex Measurements for the Single Runway Studies.
- Increasing Usage of Remote Sensing, Particularly Pulsed Lidar.
- Simultaneous Multiple Test Sites Data Collection – Better Quantify Similarities and Differences of Site Specific Characteristics.
- Automated Aircraft ID and Trajectory Infrastructure Available.
- Processing and Storage Capacity and Cost Significantly Improved.

Wake Turbulence Data Collection - Survey

Relatively Matured Flight Techniques

- Flow Visualization (Smoke Injection, Smoke Screen)
- In Flight Probes on Penetrating Aircraft (Multi-Hole Probes or Hot Films)
- And Recently, Airborne Pulsed Lidar (Example: Airbus / DLR)

Relatively Matured Ground Based Techniques

- Instrumented Tower Flyby Technique (Sensors Typically Propeller Anemometers or Hot Films)
- Propeller and Sonic Anemometer Arrays (Windline)
- Acoustic Radars (Mono-Static and Bi-Static Sodars)
- Lidars (Continuous Wave / LDV and Pulsed)

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Some Exploratory / Onging Research Efforts

- Pressure Transducer Array
- Radio Acoustic (RASS)
- Infrared Imaging
- Microwave Radiometry
- Radar (FMCW, VHF, UHF, L-, S-, and C-bands X, K, mm-Wave)
- Pulsed Ultrasonic Acoustic
- Phased Microphone Array (Conventional Microphones and Lasers)

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Remaining Brief Will Highlight Experience With

- Windline
- Vortex Sodar
- CW Lidar
- Pulsed Lidar
- Vortex RASS
- Phased Microphone Arrays

Windline Anemometer Arrays

Operating Principle: Measures Vortex Induced Crosswind Flow Field Near Ground Using Single or Multiple-Axis Anemometers. Anemometer Array Perpendicular to Flight Path Permits Tracking Wake Lateral Position.

Typical Deployment is Under a Flight Path Near Threshold

Manufacturer: No Commercial Vendor; Integrated and Fielded by Volpe with Key Components from Campbell Scientific (A/D) and R. M. Young (Anemometers)

Sampling Rate: 2 Hz.

Threshold: 0.3 m/sec.

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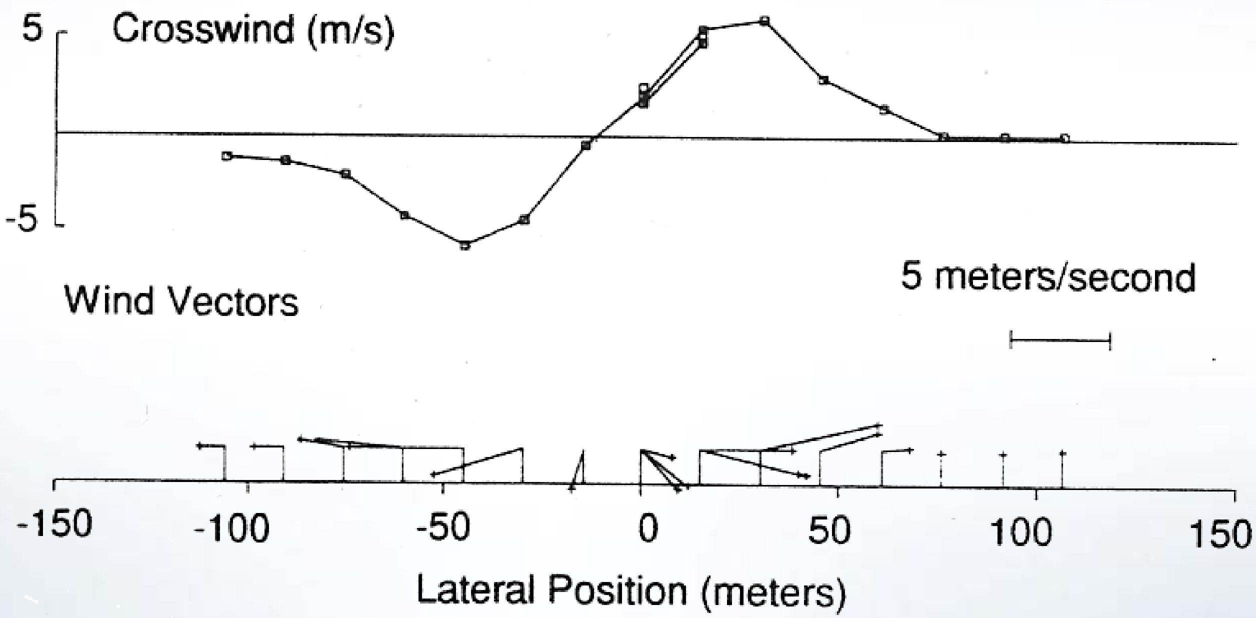
Windline Anemometer Arrays

STL Windline

Sample Windline Data



From JFK Windline ; 18 Seconds After Flyby ; B747

Windline Milestones

- First Deployed in 1970s
- Windline Measurements at JFK in 1970s Were the Only Dataset Sensor Measurements Till Recently Relevant to 2500-Ft Rule for Closely-Spaced Parallel Runways
- JFK 1994
  - Reference Sensor for Evaluating Other Sensors (RASS)
  - First Automatic Wake Data Collection (No On-Site Personnel)
- SFO 2000-2002
  - Supported Development of SOIA Procedure
  - Largest Wake Turbulence Dataset Ever Collected from One Site (Quarter a Million Landings).
  - Real Time Processing Developed for Education Purpose
- SFO 2001: Benchmark Pulsed Lidar IGE Vortex Data
- SFO WL Data Still Used by NASA for Modeling and by FAA for ReCat
- Internationally Windline Has Also Been Used at Frankfurt for Developing CSPR Wake Mitigation Concepts

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Vortex Sodar – "Acoustic Radar"

Principle of Operation: Narrow, Vertical Acoustic Beam Backscatters from Thermal Fluctuations in the Atmosphere. Good SNR in Wake Vortices Because of Vortex Mixing of Engine Exhaust. Vertical Profile of Vertical Flow Field Derived from Range Gating and Doppler Shifts. Multiple Sodars Can Form a Sodar Array to Cover Large Lateral Distances

Bi-Static Mode Operation Also Explored in the 70s (Based on Ray Refraction of Sodar Acoustic Signal)

Typical Deployment is Under or Near Flight Path Scanning Upward

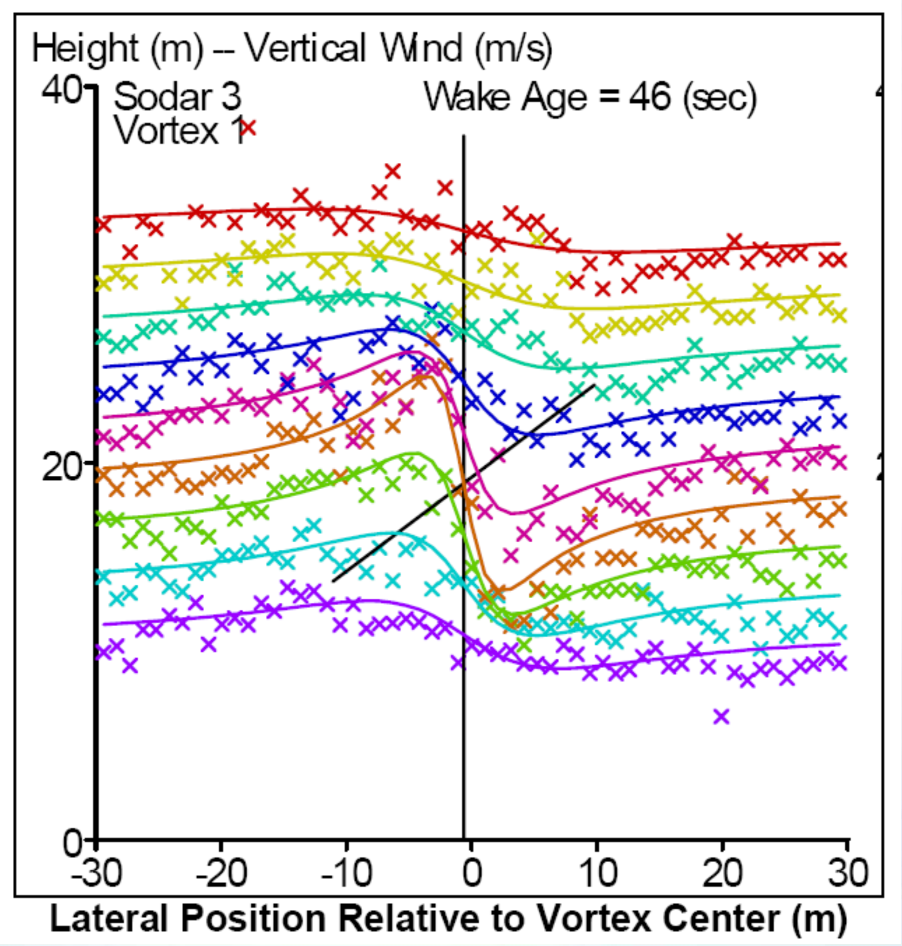
Manufacturer: Volpe Center Built the First Systems (Used in 1970s -1991). Recent Tests (2000+) Used Commercial Wind Sodar from AeroVironment, Monrovia, CA (Currently Atmospheric Systems Corp.)

Transmitting Frequency: 3000 - 4500 Hz

Recent Revival of Sodar Hardware as a Wake Sensor by Groups in Australia and New Zealand

Sample Vortex Sodar Data

From STL 2005



Vortex Sodar Milestones

- ORD Landing Dataset (1976-1977):
  - 7011 Arrivals
  - Lateral Transport Coverage = 1000 ft
- ORD Departure Dataset (1980):
  - 8760 Departures
  - Lateral Transport Coverage = 1300 ft
- Examined Initial SR Departure and B707 and DC8 Specific Classification Topics
- Baseline Circulation Decay Curve for ReCat Efforts in the 80-90s within DOT.
- Best Long Transport Sensor (e.g. at 1990 Idaho Falls Test) Until Pulsed Lidar
- Used at STL to Evaluate Detection Sensitivity of Pulsed Lidar and Characterization of Ambient / Environmental Vortices

CW Lidar

Principle of Operation: (Sometimes Called Laser Doppler Velocimetry) Signal Depends Upon Backscatter from Aerosols. Range Resolution Achieved by Focusing Down the Beam. Beam Scanned in plane Perpendicular to Aircraft Flight Path. Line-of-Sight Velocity Obtained from Doppler Processing.

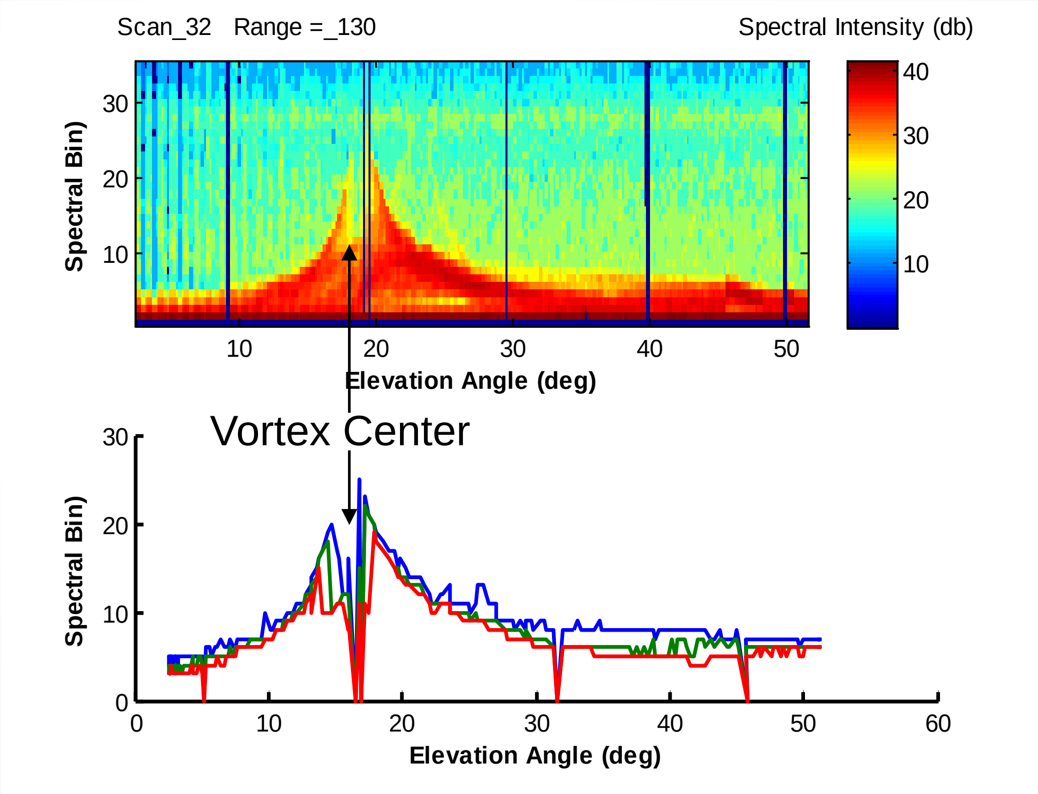
Typical Scan Geometry is Scanning Upward Under Aircraft.

Manufacturer: Initially Developed by NASA Marshall with Support from Lockheed. Volpe Bought a Unit from Lockheed in 1977, Developed Improved Software and Used Until 1991. MITLL Develop New Unit in 1996, which Could Sense Sign of Doppler Shift.

Operating Wavelength: 10 microns (CO_2 Laser), 12-Inch Mirror

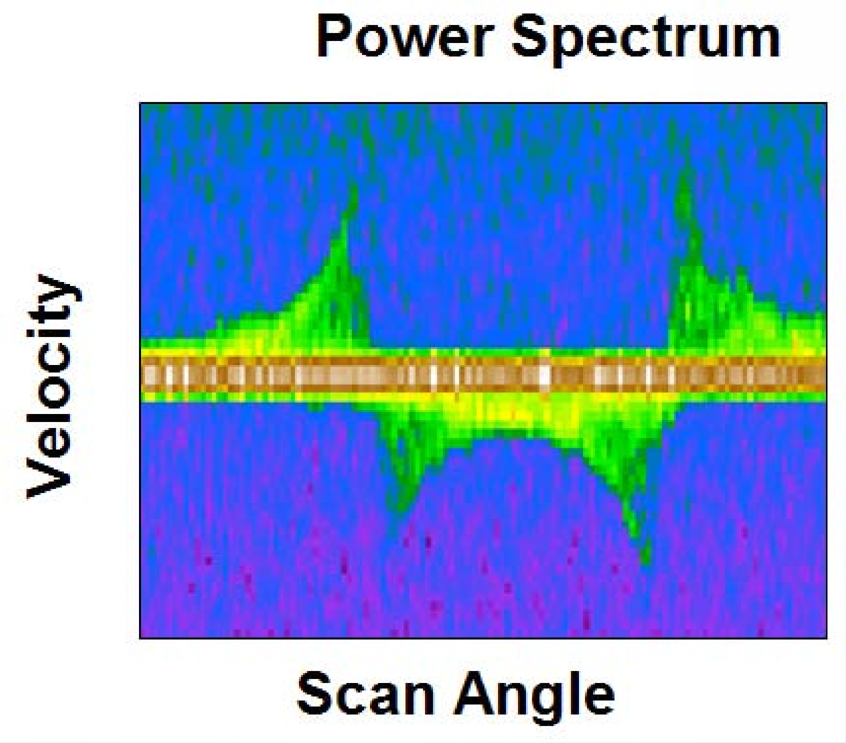
CW Lidar Example - NGE

From Idaho Falls, B767, 1990 – Side Scan of One Vortex



Another CW Lidar Example - OGE

From DEN 2003, MITLL – Below GS Scan



CW Lidar Milestones

- B747 Wake Alleviation Test (1970s – NASA Test)
  - Measured Impact of Alleviation on Vortex Flow Field
- Separation Standards for Rotorcraft Wake Vortices (1980s - FAA)
- Aircraft VOrtex Spacing System (AVOSS) Demonstration at DFW
- Measurements from MEM and DFW Used to Develop APA Wake Model (1990s – NASA and FAA)
- Benchmarking Pulsed Lidar Data in EU (2000s – DLR, ONERA, DERA/QinitiQ)

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Pulsed Lidar – "Optical Radar"

Principle of Operation: Same as CW Lidar Except that Range is Determined by Range Gates, Not Focusing. Line-of-Sight Velocity Obtained from Doppler Processing.

Maturity: Spinoff from NASA Pulsed Lidar (Developed by NASA-CTI-RTI). Increasingly Becoming the Primary Sensor for Wake Research ; Can Scan into Ground

Typical Deployment is Scan from Side of Runway, But Other Scan Types Possible.

Manufacturer: Lockheed Martin Coherent Technologies (Louisville, CO)

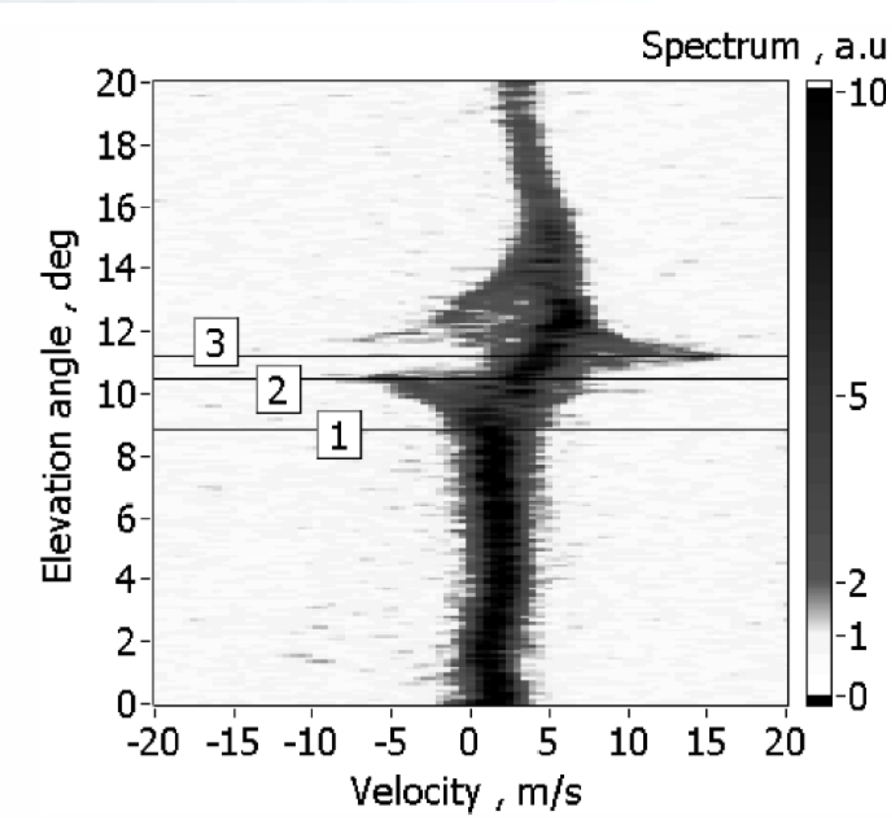
2 Micron Wavelength (Eye Safe)

Pulse Rate: 500 Hz

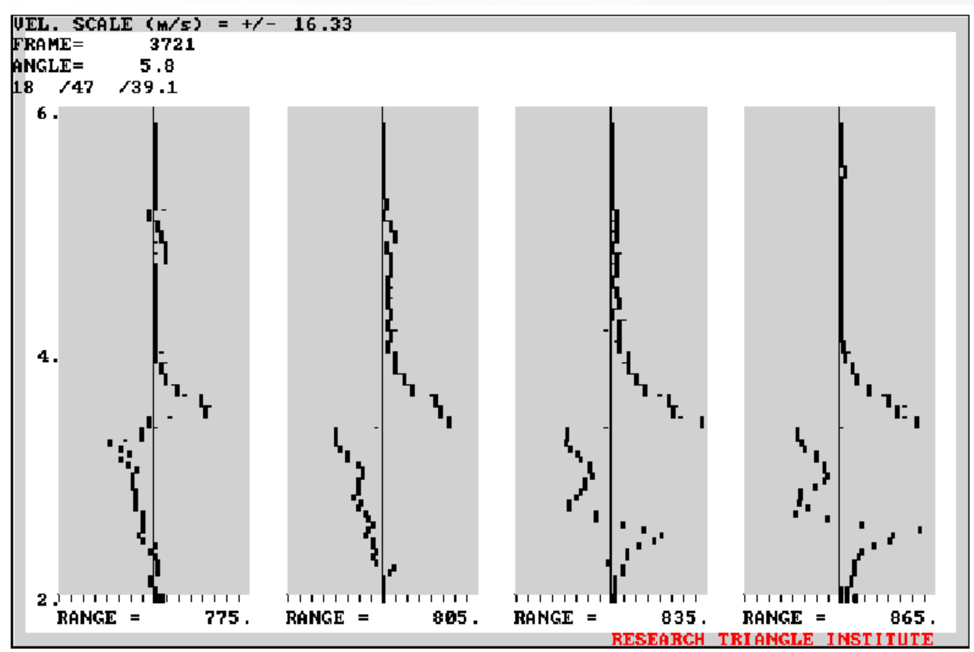
Pulse Energy: 2mJ

Pulse Length: 400±40 ns

Pulsed Lidar Example



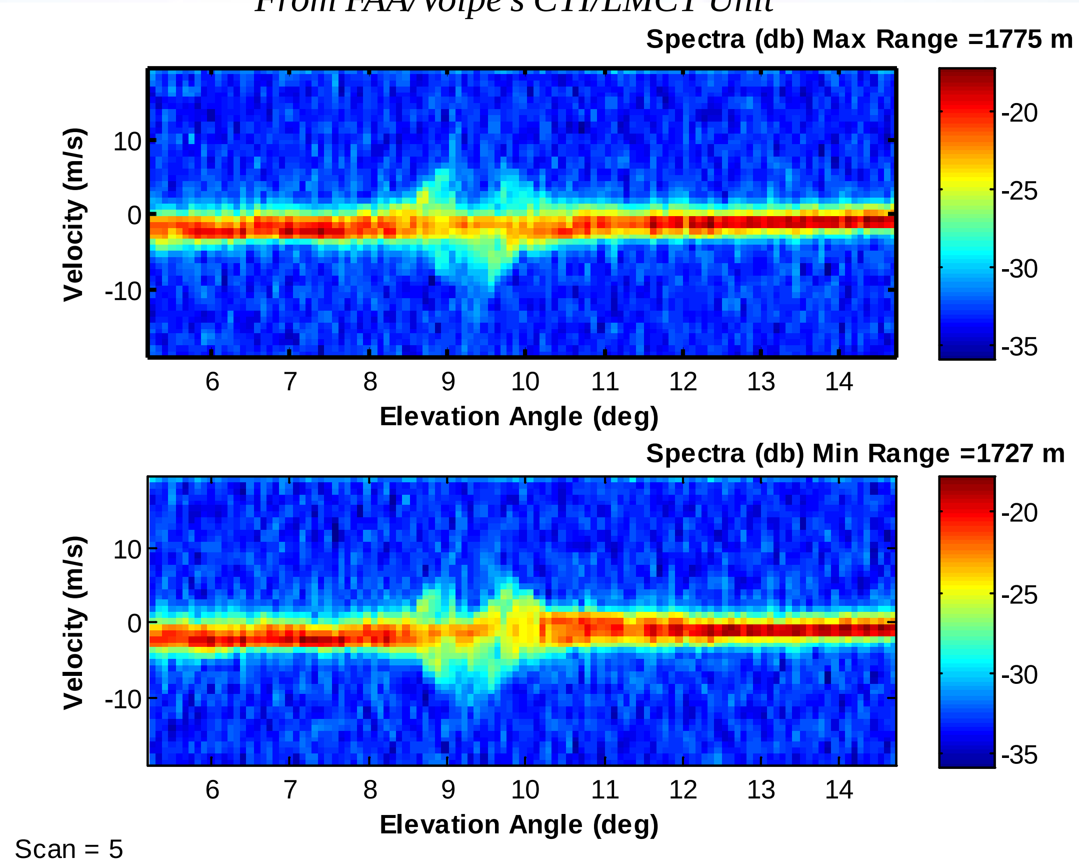
From DLR's CTI Unit



From NASA's CTI Unit

Another Pulsed Lidar Example

From FAA/Volpe's CTI/LMCT Unit



Pulsed Lidar Milestones

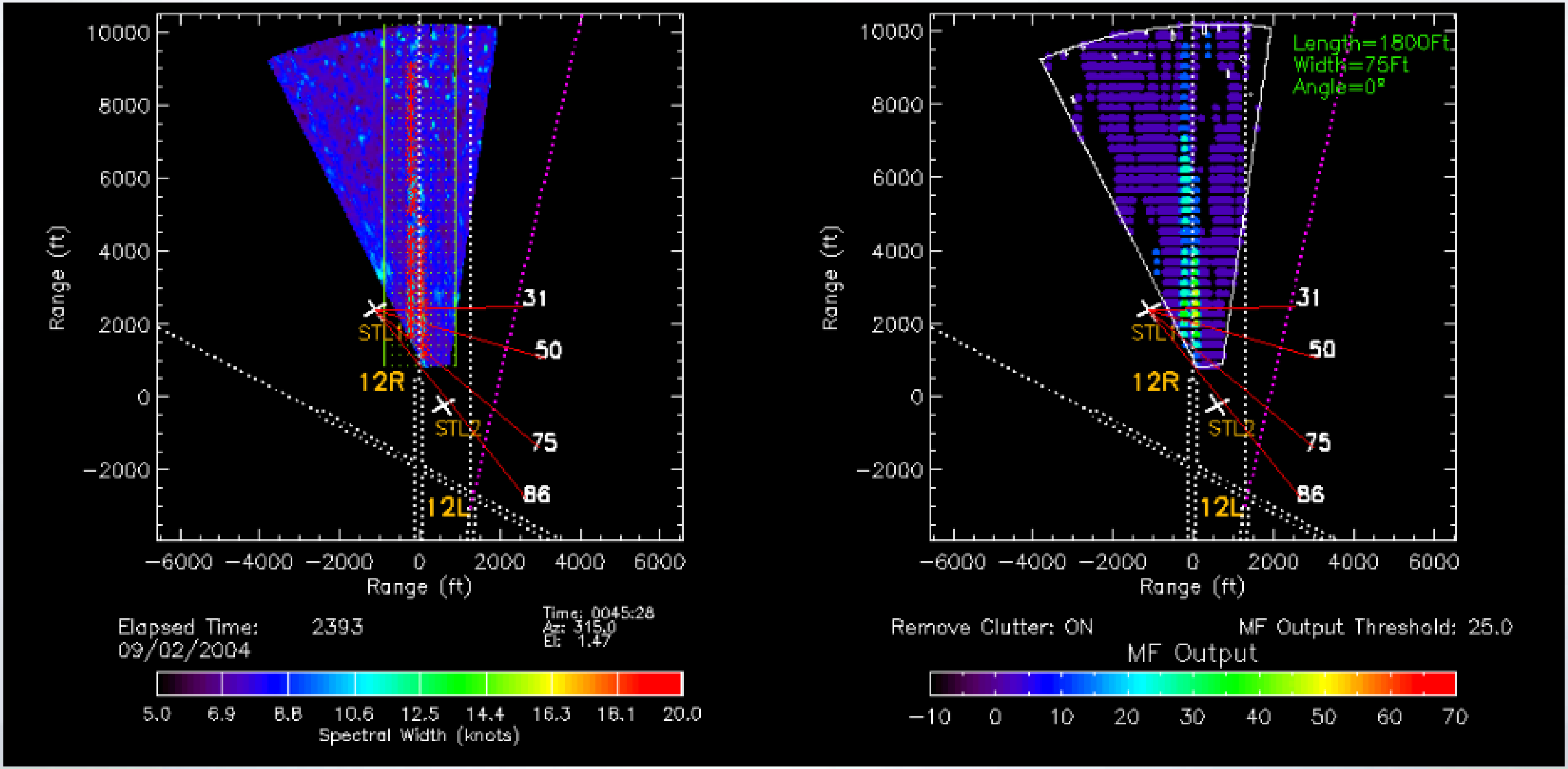
- SFO SOIA OGE Wake Transport Study (2001 - FAA)
- Various Assessments Associated with the A380 Wake Separation Standards (Circa 2000s – Airbus/DLR)
- CSPR Waiver / Rule Change for Large and Small Aircraft (FAA: 2003 – Present)
- Ground Truth Sensor for Wake Acoustics Investigations at Denver (NASA: 2003-2005)
- Departure Wake Vortex Measurements in STL (FAA: 2006 – Present)
- Departure Wake Vortex Measurements
  - Frankfurt (CREDOS: FAA/Eurocontrol: 2007)
  - IAH, SFO and IAH (WTMD: FAA / NASA)
- CSPR / WIDAO Arrival Study at CDG (Eurocontrol, 2007)
- Time Based Separation Study at LHR (Eurocontrol / NATS, 2008)

Other Possible Pulsed Lidar Scans

- Spectra is Broaden when Lidar Interacts with a Chunk of Turbulence.
- Spectral Width Can Then be Plotted as Color Contours to Visualize Vortices. This Can be Done with Either Lidar Scanning in RHI (Range-Height-Indicator) or PPI (Planned Position Indicator) Mode.
- EU's MFLAME Program Demonstrated Feasibility Using the Axial Flow Feature in Wake Vortices to Produce the Spectral Broadening Based Wake Visualization by Having a "Zig-Zag" PPI Scan.
- FAA-Volpe-CTI Also Experimented a PPI Based Wake Visualization Technique by Scanning Towards Arrival Aircraft and Below the Glide Slope

Other Possible Pulsed Lidar Scans

PPI Spectral Width Experiment from STL



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Radio Acoustic Sensing System (RASS)

Principle of Operation: Whereas Conventional Atmospheric Radars Rely on Density Fluctuations to Provide a Backscatter Signal (Same as Sodars), a RASS Generates its Own Density Fluctuations in the Vortex in the form a Strong Acoustic Signal. The Radar Scattering is Greatly Enhanced by the Proper Wavelength Matching Between the Expanding Acoustic Wave and the Radar Wavelength. The Wake Flow Field Adds to the Doppler Shift from the Moving Acoustic Wave.

Manufacturer: Developed by WLR Research (Bill Rubin) with Components from Vaisala.

Radio frequency: 915 MHz, Acoustic frequency: 2 KHz

Maturity: A Test at JFK Showed that RASS Doppler Signals are Observed When Wake Vortices are Located Inside the Radar Range Gate. Position and Strength Data Can be Obtained.

Possible Vortex RASS Status / Future

- Further Development is Needed to Make RASS a Useful Wake Sensor.
- Renewed Interest at Penn State: In-House R&D Continues Towards a Field Deployable Demonstration Unit.
- Because It Can Penetrate Clouds, a Matured RASS Wake Sensor Could Potentially Study OGE Wake Descent Under All Weather Conditions. This is Ideal for Studying Single Runway Operation Under Light or No Winds).

Phased Microphone Array

Principle of Operation: Multiple Conventional Microphones Situated on the Ground and Passively Record the Sound Vortices Naturally Emit. If a Coherent Sound Source Exists, Each Microphone then Hears the Same Version of the Signal with Various Time Delays. Phased Array Processing Used with Assumptions on the Location and Source Nature to Adjust Artificially the Time Delay Needed Between Microphones to Focus / Constructive Interface on the Source.

Manufacturer: No Commercial Vendor When First Deployed; Integrated and Fielded by OptiNav and Microstar Laboratories. Currently B&K, Qinetiq and OptiNav Offer Microphone Array Systems for Traditional Airframe and Jet Noise Work that Can be Modified for Wake Acoustics.

Frequency Range Experimented: From 50 to 1000 Hz.

252 Microphone Elements ; Array Pattern Design is Critical

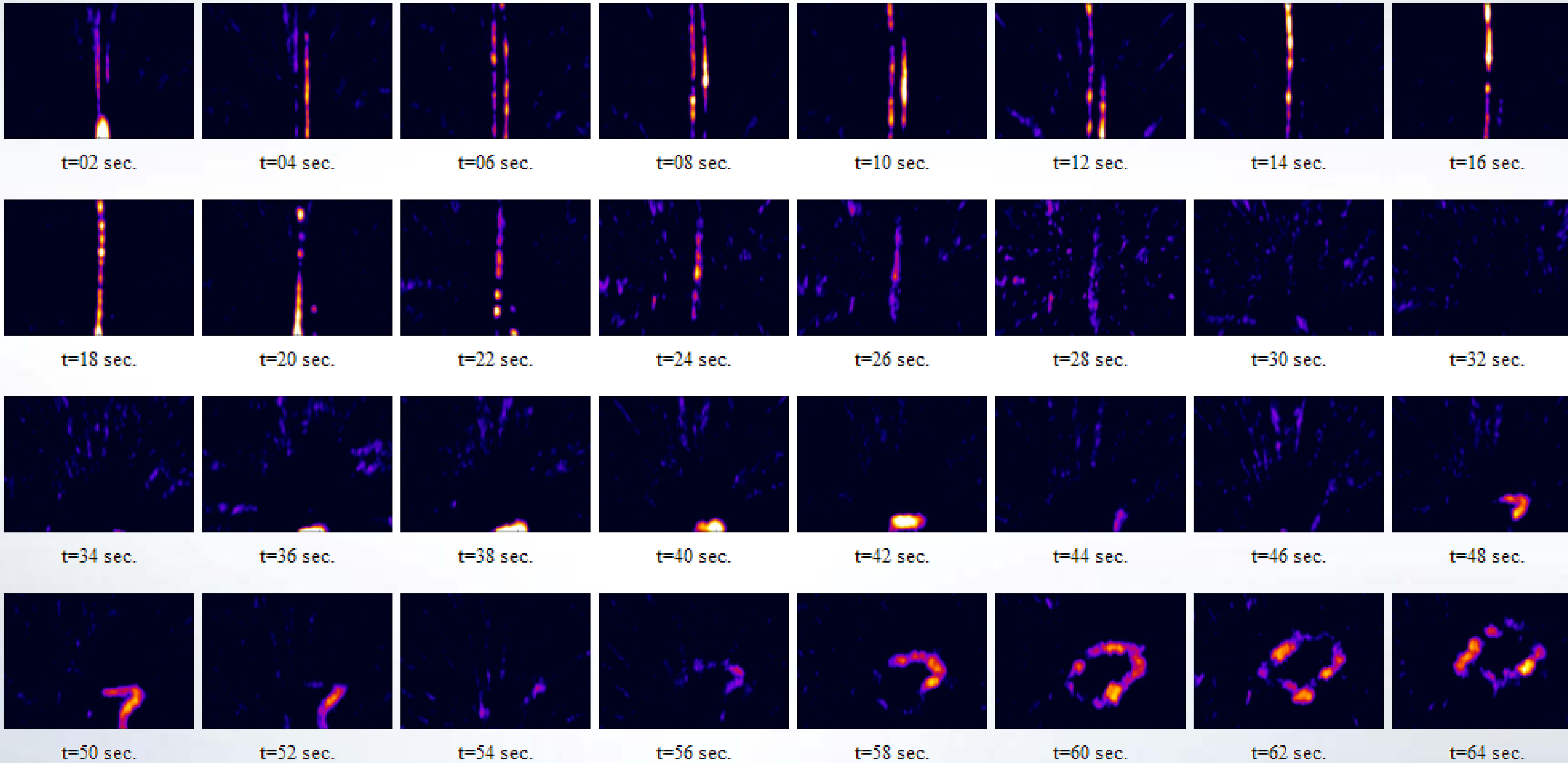
DLR-Berlin Has Conducted Similar Experiments (Some in Denver)

Maturity: Useful in Visualizing Wake Dynamics Without Smoke, Contribute to Better Understanding of Other Wake Sensors. Has a Definitive Research Role.

Phased Microphone Array

Photograph of the Microphone Array in Denver, 2003

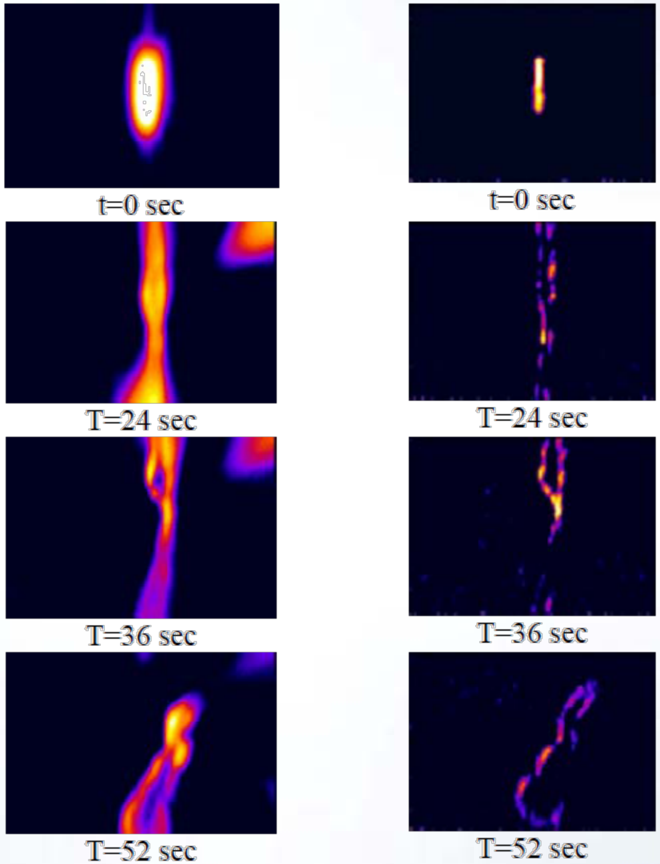
Sample Microphone Array Data



200-400 Hz Band, 10 ft by 10 ft Beamforming Grid at 500 Feet AGL

1500 ft by 1000 ft Space ; B735 on September 16, 2003

Another Sample Microphone Array Result



(a) 0-200 Hz Band, 10 dB Dynamic Range (b) 200-400 Hz Band, 6 dB Dynamic Range

Figure 3-3 Horizontal Beamforming Batch Processing for a B-737-300

Phased Microphone Array Milestones

- Deployed in Denver 2003 to Better Understand Passive Wake Acoustics Phenomenology at OGE Altitude
- Can Reveal Crow Linking, Crow Instability and Other Contorted, Axially Incoherent Shape in Wake Vortices.
- Flow Visualization Like Data Presentation Enhanced Understanding of Lidar Data Scanning Through Contorted Vortices
- Surface EDR Correlated with Time-to-Link (Enlarged the “Sarpkaya Curve” Data Set)
- Has Good Spatial Resolution to Obtain Vortex Spacing – High Quality bo Distribution Statistics
- Has a Research Role Especially When Flow Visualization Like Qualitative Data Are Desired as Part of the Wake Sensor Measurements. The Combination May Assist Further Development of Fast-Time Engineering Models and Benchmark CFD Wake Simulations.

Summary of Sensors from Volpe Perspective

Sensor	Range	Weather Limits	Use
Windline	Vertical: Low Lateral: Adjustable	Essentially None	Airport Datasets
Vortex Sodar	Vertical: Medium Lateral: Adjustable	Heavy Rain and Snow	Airport Datasets
CW Lidar	Medium	Heavy Fog and Rain, Clouds	Special Tests, Airport Datasets
Pulsed Lidar	Long	Heavy Fog and Rain, Clouds	Special Tests, Airport Datasets
Vortex RASS	Medium	Essentially None	Research
Phased Microphone Array	Medium	Rain, High Winds	Research

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Something for Wake Sensor Developers to Think About

Research vs. Operational Sensors – One Version

Parameter	Research	Operational System
Spatial Coverage	Yes	Yes
Location Accuracy	Yes	Maybe
Vortex Strength Capability	Yes	Maybe
Unmanned Operation	No	Yes
Real-Time Processing	No	Yes
All Weather	No	Yes
Low Cost	No	Maybe

Research vs Operation

- Available Sensors Require Tradeoff Between Data Quality and Data Quantity
- Some Questions can be Answered by a Few High Quality Research Measurements
- Cost Per Vortex Track Becomes Important in Operational Sensors
- Automatic, Unmanned Operation Desirable

Meaning of “No Data”

- Seen from the Past Two Days Ample Examples of Successful Wake Tracking and Characterizations, But We are Interested Sometimes in No Data Cases
- Why Was Vortex Track Terminated?
- Why No Vortex Data from Aircraft Passage Through Sensing Volume?

Some Planned and Ongoing Activities

- Additional W-Band Radar Wake Turbulence Analysis (Initial Results Shown in Tom Seliga's Brief)
- Interested in Evaluating Wind Energy Market Pulsed Lidars for Wake Turbulence Program – Primarily for Wind Measurements
- Interested in Evaluating Radar Wind Profilers
- Pulsed Lidar Wake Algorithm Developments
- Enhancement in Turbulence and Stratification Characterizations

Some Summary Remarks

- Experience with Some of the Current Wake Sensors Highlighted
- Wake Sensing Has Benefited from Advances in Electronics and Sensing Technology
- Wake Sensing Capabilities Have Greatly Advanced Since the 1970s, or Even the Early 1990s
- Recent Data Collection and Processing in an Offline Research Mode Has Started to Generate Capacity Gains Safely.
- Acknowledge the Contributions Made to date from Sensor Community
- Further R&D Should Have the Application in Mind
- As a User, We Still Want More Overall Improvements:
  - Research Mode: Better, Cheaper and Faster