

Passive Wake Acoustics Measurements at Denver International Airport

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Abstract

From August to September 2003, NASA conducted an extensive measurement campaign to characterize the acoustic signal of wake vortices. A large, both spatially as well as in number of elements, phased microphone array was deployed at Denver International Airport for this effort. This paper will briefly describe the program background, the microphone array, as well as the supporting ground-truth and meteorological sensor suite. Sample results to date are then presented and discussed. It is seen that, in the frequency range processed so far, wake noise is generated predominantly from a very confined area around the cores.

Background and Introduction

Wake vortex is a subject of continual interest in aviation since the 1970s from the perspectives of both safety and capacity. Currently the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) are conducting a joint Wake Turbulence Research Program. The overall research effort distinguishes between near-term, mid-term, and long-term activities. Long-term efforts, conducted primarily by NASA, will investigate a solution involving active prediction and monitoring of wake behaviors to mitigate the adverse effect of wake turbulence on airport operations.

As a part of the long-term research, NASA has been working towards a real-time wake vortex advisory system. It is envisioned that such a system could provide pilots and controllers advance warning of the location and nature of hazardous wake turbulence. An integral part of such a wake vortex advisory system is a suite of meteorological and wake monitoring sensors. Amongst the many wake sensor concepts, there is currently an effort in

examining the fundamental phenomenology as well as the associated operational implications of acoustic emission from wake vortices as the basis for passively detecting, tracking and characterizing wake vortices.

The technical literature on acoustic emission by wake vortices is rather sparse¹⁻⁴. Consequently, as a first necessary step in achieving fundamental understanding of the phenomenon, a large microphone test was conducted at Denver International Airport (DIA) from August 28th to September 19th of 2003. Under the sponsorship and overall supervision of NASA Langley Research Center, the DOT Volpe Center and supporting contractors (Titan, OptiNav and Microstar Laboratories) fielded a 252-element phased microphone array to characterize the acoustic signature of wake vortices as a function of aircraft type, meteorological conditions, as well as wake positions and strengths measured by two Lidars⁵. In addition, the Denver microphone test provided an opportunity to conduct field evaluation of recent modifications to a laser-based wake acoustic sensor named

SOCRATES (*Sensor for Optically Characterizing Ring-Eddy Atmospheric Turbulence Emanating Sound*), which is being developed by Flight Safety Technologies (FST) and Lockheed-Martin (LM). A four-beam SOCRATES sub-system was also fielded by FST-LM at the Denver test site. In addition, under the FST funding, the German Aerospace Center in Berlin (DLR - Berlin) deployed its phased microphone array to further characterize the acoustic properties of aircraft wake vortices. The complete list of the test participants and supporting organizations is found in the Appendix.

Although the Denver experiment presents ample opportunities for cross validation of sensors and processing techniques, the present paper will only focus on the NASA-DOT phased microphone array related efforts, as well as the exploratory results to date. Additional preliminary results from the microphone test are also found in Ref. 6.

Test Site

Due to the interest to first characterize the acoustic signature of wake vortices in the out-of-ground-effect (OGE) regime (defined as altitude over half of the initial lateral separation distance of vortices first generated), measurements were conducted at a location under the flight path of runway 16L, at a location two nautical miles from the runway threshold where the nominal arriving aircraft altitude is approximately 700 feet. Arrivals are the focus at this time in part because of the competing jet noise is greatly reduced in such a flight profile. The selection of the Denver International Airport is motivated both by its diverse aircraft mix, as well as the relative pristine acoustic environment. Finally, it may be of interest to note that the microphone measurements were manned, and 99 percent of the measurements were made under Visual Meteorological Conditions (VMC).

Sensor Locations

Fig. 1 shows an aerial photograph of the array test site. The magnetic-north direction in Fig. 1 is approximately pointing at the 11 o'clock direction. The various sensor locations are marked by numbers and they are as follows. 1: NASA-DOT Volpe Microphone Array; 2: Meteorological Tower, 3: AeroVironment Sodar, 4: NASA-DOT Volpe Instrumentation Trailer (which also housed a Metek Sonic Anemometer and a Kipp & Zonen Microwave Radioameter); 5: MIT Lincoln Laboratory Continuous Wave Lidar; 6: SOCRATES Laser Array; 7: DLR - Berlin Microphone Array; 8: FST-LM-DLR Instrumentation Trailers. Due to a required minimum standoff distance and topography considerations, the CTI Pulsed Lidar was located 0.75 mile west of the NASA-DOT Volpe microphone array. The Pulse Lidar is therefore not shown in the aerial photograph taken right over the array area in Fig. 1.



Figure 1 Aerial Photograph of the Test Area.

The CTI Pulsed Lidar and MIT Lincoln Laboratory's Continuous Wave Lidar were fielded so that they both scanned over the microphone array. As such, they complemented each other in providing the ground-truth tracks and aerodynamic characterization of the wakes. They include positions of the vortex cores, strengths of the vortices, as well as the velocity distribution as a function of time. Additional information on the two Lidars can be found in Refs. 7 - 9.

Dynamics of wake vortices is recognized to be strongly influenced by meteorological conditions. Likewise, meteorology has an important impact on sound propagation and

attenuation. A suite of weather sensors was therefore fielded to support both wake aerodynamics and acoustics studies. The meteorological sensors included a 107 feet tower instrumented with three-axis R. M. Young Gill propeller anemometers at three heights and a Vaisala temperature and relative humidity point measurement sensor at mid-height of the tower. The tower was of mobile nature and was used later to hang a noise source close to the microphone array center for acoustic calibration. An AeroVironment Sodar was used to measure three components of the wind field above the height of the meteorological tower. A Metek sonic anemometer was used to provide a point measurement of the atmospheric turbulence as well as temperature. Lastly, a Kipp & Zonen microwave radiometer was used to provide temperature profiles over the array area. Additional weather information such as barometric pressure, ceiling, and RVR are obtained from airport ASOS data.

Microphone Array System Description

The system was designed and integrated by Microstar Laboratories and OptiNav. It is capable of supporting up to 256 microphone channels. For the Denver measurements, 252 channels were used for microphones, and the remaining four channels were allocated for auxiliary input such as that from a GPS receiver. The system's main components are: 252 Panasonic electric capsules WM-61A microphones, 8 32-channels' preamplifiers with software configurable gain (made by ACB Engineering), 32 8-channels Σ - Δ 16-bit A/D cards with on-board analog fourth-order Bessel anti-aliasing filters as well as on-board DSP's (made by Microstar Laboratories), and a data collection workstation. Both the microphones and the preamplifiers can operate in a frequency range from 20Hz to 20kHz. The non-uniform spacing / sparse microphone array pattern was designed by OptiNav, with the array center being on the extended centerline of runway 16L. A photograph of the array area is shown in Fig. 2.

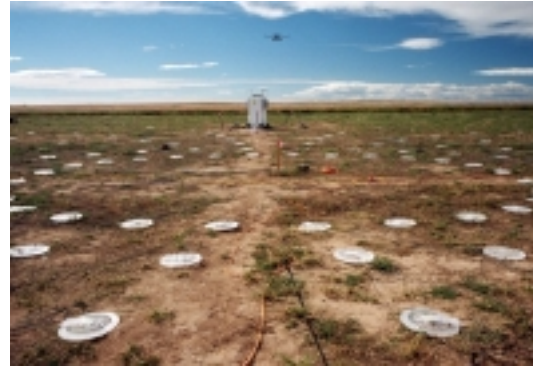


Figure 2 Array Center Area with a Vintage Point of Looking Towards Runway 16L (i.e., South). The Rectangular Object is an Environmental Enclosure Housing the Data Acquisition Equipment for one of the Four Sub-Arrays.

The pattern was designed to allow array processing over a broad frequency range of 20 to 1000 Hz. The dimensions of the array were approximately 100 feet longitudinally (along the flight path), and 400 feet laterally (normal to the flight path) as shown in Fig. 3. The acoustic signal collected by each of the microphones was first amplified, then passed through the anti-aliasing filter before it is sampled at 153600 samples/sec., and digitized by the A/D card. The digital signal undergoes 2 stages of filtering using 2 symmetric linear phase FIR filters implemented by the on-board DSP before down-sampling the data to a rate of 25600 samples/sec. Finally, it is important to note that all the A/D channels were synchronously sampled. This is critical to allow for the implementation of the array processing algorithms performed in the post processing stage.

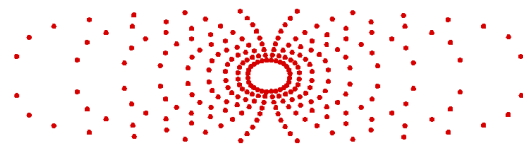


Figure 3 The Microphone Array Pattern Used in the Government Wake Acoustics Study.

Acoustic Data Processing Description

The first stage of the data processing aims at providing a quick-look and baseline description of the data from September 3rd to September 19th - a period during which the measurement equipment became fully online. The frequency band of 20 to 200Hz is the focus in this first stage data processing.

The raw data are first passed forward and backward through an 8th order IIR Butterworth filter resulting in phaseless filtering. The cutoff frequency of the filter was approximately 200 Hz. It is then decimated twice, by a factor of 5 each time, for a combined factor of 25. This reduced the sampling rate from 25,600 samples per sec. to 1024 samples per sec. to enable faster processing. A time domain delay-and-sum beamforming^{1, 10} algorithm is used to focus at an altitude of 500 feet. A grid of 76 x 51 points with a uniform spacing of 20 feet in both directions was used. This represents a 1500 feet x 1000 feet patch of the sky at 500 feet with the larger dimension being normal (i.e., E-W) to the flight path. The choice of the grid spacing was in part assisted by simulating the array response at the same altitude. The simulation results showed that the resolution of the array at an altitude of 500 feet above the center of the array is approximately: 25 feet (E-W), 60 feet (N-S), and 200 feet (Upward), at 100 Hz (i.e., the middle of the 200 Hz analysis band based on 3 dB bandwidth). The beamforming algorithm focuses the array at each point of the grid, and performs 2 seconds integration of the acoustic power in the selected frequency band. At the end of each two-second integration period, a color contour map revealing the noise source locations is generated. A 10 dB color scale is used where black is 0 or less, and the brightest color is 10 dB or more. For each flyby, the frames are assembled into a movie file. This presentation scheme allows visualization of the wake evolution in manners similar to observing smoke release in dedicated flight tests or from vortex-induced condensation marking the vortex cores in very moist days.

Sample Results and Discussion

As indicated before, only data from September 3rd to September 19th are examined at this time. During this time frame, 897 arrival measurement attempts were made, and the associated aircraft distribution is shown in Fig. 4.

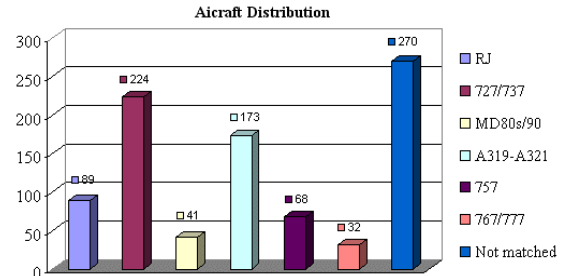


Figure 4 Aircraft Distribution in the Data from September 3rd to September 19th.

It should be noted that Fig. 4 represents the result of cross-referencing the field logbook (i.e., visual identification of aircraft by various array operators) with the ARTS database from DIA noise abatement office. The category “not matched” refers to aircraft that could not be uniquely cross-referenced with the ARTS database. This is mostly related to the ambiguous definition of arrival time in the ARTS data, as well as DIA controllers re-routing arrival traffic initially bound for other runways to land on 16L to accommodate the measurement campaign. It is expected that a very significant portion of the aircraft in the “not matched” class can be identified by cross-referencing with field logbooks from other sensors.

For facilitating subsequent discussion, the concept of non-dimensional wake age is introduced^{11, 12}. First, zero time is taken as when the aircraft flew over the array, which in the two second averaged frames, is when the bright aircraft noise spot is approximately in the middle of the field of view. Time is then normalized by the theoretical time it takes for a vortex pair to sink by 79 (more specifically, $\pi/4$) percent of the wingspan.

Fig. 5 shows a B767 flyby on September 3rd, at 7:43 pm local Denver time. Only every other images from the beamforming movies are shown for brevity. The bright oval noise source shown in $T = 0$ sec. is the aircraft itself. Although wake vortices are continuously being generated for as long as lift is produced, it usually takes anywhere between 5 to 10 seconds to complete the roll-up process and form the two salient counter-rotating features behind aircraft. This is a likely reason why vortex-like features do not appear immediately in these frames. Fig. 5 suggests that for this arrival, vortices are fully formed in the beam pattern at around 8 seconds after flyby. Also from previous wake research, it is expected that wakes would remain in their columnar form in a uniform wind field and relatively insensitive to external atmospheric influence. One non-dimensional time for 767 is approximately 24 seconds, and the sequence of frames from Fig. 5 appears to be consistent with the earlier finding.

The lateral separation distance in the vortex pair as revealed by the noise source maps is next investigated. This distance is theoretically 79 percent of the wingspan. Such a comparison is best carried out when the wake reaches the beamforming altitude of 500 feet. In the absence of Lidar data at the time of this writing, the following estimate is made. For B767, the vortex pair is theoretically estimated to descend with a velocity of 5.11 feet/sec. after rolled-up. At this speed, the wake will reach 500 feet altitude at $T = 39$ sec. The average of lateral spacing taken from $T = 38$ (not shown in Fig. 5) to $T = 40$ is 110 feet. This represents 70 percent of the B767 wingspan, which compares quite favorable with the theory by assuming the wing being elliptically loaded. It should be emphasized that measurements on the initial separation distance of the vortex pair is not a trivial task, and this quantity is often obtained from wind tunnels and tow tanks. It may be of interest to compare the phased array results with the recent finding from a controlled, high Reynolds number A340-300 tow tank test¹³ simulating cruise –

a condition that would better approximate elliptical wing loading. A spacing of 64 percent of the wingspan was found to be a more representative percentage based on this particular tow tank test. It is interesting to note that the phased microphone array and tow tank results both suggest that the theoretical value of 79 percent of wingspan often quoted may be too large. As for the remaining of the run, data collection was unfortunately terminated prematurely for this flyby. Information beyond 56 seconds was therefore unavailable.

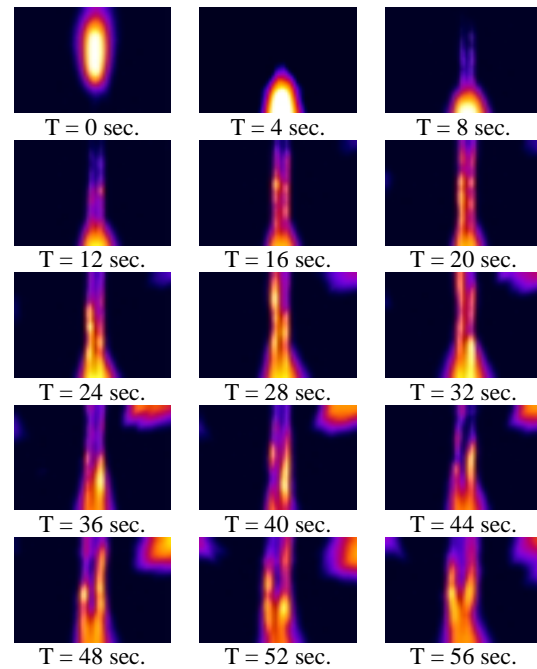


Figure 5 Event 030903_194324

As another example, results are shown from a B737 flying over the array on September 16, at 11:25am local Denver time. From the source localization map, the vortex pair appeared as a line of noise source. Further investigation is necessary to understand this particular type of appearance. However, an interim candidate explanation is offered as follows. The theoretical initial lateral distance between the vortex pair for B737 is estimated to be 74.5 feet. Such a distance is spanned across less than four grid points in the beamforming process. If the same scaling factor of 0.7 from the previous sample result

were applied, the initial lateral separation of the vortices from a B737 would then have been 66 feet. Such a distance is about three grid points in the beamforming process. The physical distance that needs to be resolved therefore borders the resolution limits of both the beamforming grid and array resolution.

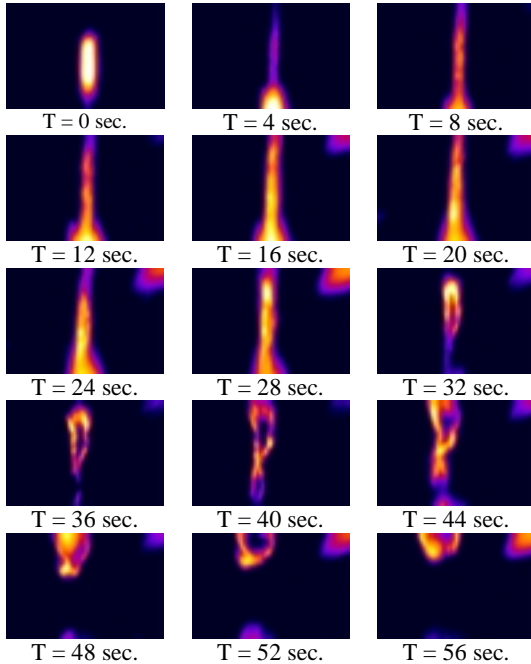


Figure 6 Event 030916_112527

The non-dimensional time for B737 is 12 seconds, and it is again seen that the wake remained straight within this time frame. At about 28 seconds after flyby, the wake is seen to start developing a Crow instability¹⁴ ring-like feature. At 32 seconds after flyby, the ring feature is very distinctive. Following the ring motion in the subsequent frames, it can be seen that the wind field is such that a headwind and a crosswind from east existed during this landing. At 60 seconds and beyond (not shown here), the wake appeared to have been demised.

Although the size of the entire wake oval is of the order of twice that of the wingspan in the lateral direction, the beamforming results suggest that sound generation in the frequency band of 200 Hz and below is basically confined to regions close to or within the cores.

Closing Remarks and Future Work

Currently the Denver data are being examined by team members from NASA LaRC (POC: Earl Booth), DOT-Volpe (POC: Frank Wang) and Florida Atlantic University (FAU; POC: Nurgun Erdol), as well as OptiNav (which produced the results given here; POC: Robert Dougherty) and Titan (POC: Robert D'Errico). The data processing and analysis activities shown here represent only a small fraction of the overall ongoing Government effort in understanding the acoustics of wake vortices. Additional signal processing techniques are being applied to the same dataset in order to quantify the overall performance relative to the baseline processing results. These activities are expected to expand the state-of-the-art understanding of wake acoustics. Ultimately, the following list of technical issues would need to be properly addressed in various stages of the DIA data analysis.

- Do wake vortices generate a unique acoustic signature?
- How consistently do wake vortices generate these signature?
- What are the characteristics of these signatures and circumstances under which they are generated?
- What is the frequency range of these acoustic signals?
- Can wake strength be reliably inferred from wake acoustic signature? What is the fundamental scientific principle?
- If the answers to all of the questions are positive, then assess the feasibility of an acoustic-based sensor system in detecting, identifying, tracking wake vortices and quantifying the circulation in a high ambient noise environment typically found in major airports.

Results of these studies will be disseminated to the community when available.

References

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- ⁸Heinrichs, R. M., *Wake Vortex Measurements with a CW 10.6 μm Coherent Laser Radar*, NASA First Wake Vortex Dynamic Spacing Workshop - NASA CP-97-206235, May 13-15, 1997.
- ⁹Heinrichs, R. M. and Dasey, T. J., *Analysis of Circulation Data from a Wake Vortex Lidar*, AIAA Paper 97-0059, Reno, NV, January 1997.
- ¹⁰Johnson, D. H. and Dugeon, D. E., *Array Signal Processing: Concepts and Techniques*, Prentice Hall, NJ, 1993.
- ¹¹Greene, G. C., *An Approximate Model of Vortex Decay in the Atmosphere*, Journal of Aircraft, Vol. 23, No. 7, July 1986, pp. 566-573.
- ¹²Robins, R. E., Delisi, D. P. and Greene, G. C., *Algorithm for Prediction of Trailing Vortex Evolution*, Journal of Aircraft, Vol. 38, No. 5, September-October 2001.
- ¹³Scarano, F., van Wijk, C. and Veldhuis, L. L. M., *Traversing Field of View and AR-PIV for Mid-Field Wake Vortex Investigation in a Towing Tank*, Experiments in Fluids, Vol. 33, No. 6, December 2002, pp. 950-961.
- ¹⁴Crow, S. C., *Stability theory for a Pair of Trailing Vortices*, AIAA Journal, Vol. 8, No. 12, December 1970, pp. 2172-2179.

Appendix: Test Participants and Supporting Organizations

- NASA LaRC
- DOT Volpe Center
- Titan
- OptiNav
- Microstar Laboratories
- CTI
- MIT LL
- AeroVironment
- WLR Research
- SCENSI
- FST
- Lockheed Martin
- Anteon
- DLR – Berlin
- FAU
- United Airlines
- DIA International Airport
- Local Denver FAA

NASA's Wake Acoustics Research

Presentation by NASA and DOT-Volpe Center

***4th NASA Integrated CNS Conference and Workshop
Fairfax, VA, April 26-30, 2004***

Denver Wake Acoustics Test – Introduction

- **NASA Conducted an Extensive Measurement Campaign at DIA on the Phenomenon of Acoustic Emission of Wake Vortices.**
- **August 18 to September 26, 2003.**
- **Recorded About 1200 Flybys (Mostly for Aircraft in Landing Configuration).**

NASA's Interest in Wake Sensors

- **NASA Developed an Active Wake Vortex Predictor for the Terminal Area (AVOSS - Aircraft Vortex System) which was Demonstrated at DFW in July 2000.**
- **Under the Joint NASA-FAA Wake Turbulence Research Management Plan (RMP), NASA Will Focus on Developing Mid- and Long-Term Products to Improve NAS Capacity without Compromising Safety.**

NASA's Interest in Wake Sensors

- **NASA, as Part of Its Long-Term RMP Efforts, Continues to Mature the Predictor and Wake Sensor Components.**
- **NASA Has Been Exploring a Number of Technologies for the Wake Sensor Component of a Wake Vortex Advisory System.**
- **Examples Are Lidar, Windline, Sodar, Radar, RASS and More Recently...**

NASA's Interest in Passive Wake Acoustics

- **Congress Directed NASA to Examine the Concept Behind SOCRATES (Sensor for Optically Characterizing Remote Atmospheric Turbulence Emanating Sound) - A Laser Based Passive Wake Acoustics Sensor Under Development.**

Objectives of the Denver Wake Acoustics Test

- ✓ **1: Scientific Investigation of the Acoustic Properties of Aircraft Wake Vortices and Ambient Noise Characterization Using a NASA-DOT Phased Microphone Array.**
- ✓ **2: Assess Improvements in SOCRATES Instrumentation.**
- ✓ **3: Benchmark NASA-DOT Microphone Array Using DLR Array.**

Denver International Airport

- ✓ **Desirable Acoustic Environment**
- ✓ **Diverse Traffic Mix, Abundance of *Large* and *Heavy* Aircraft**

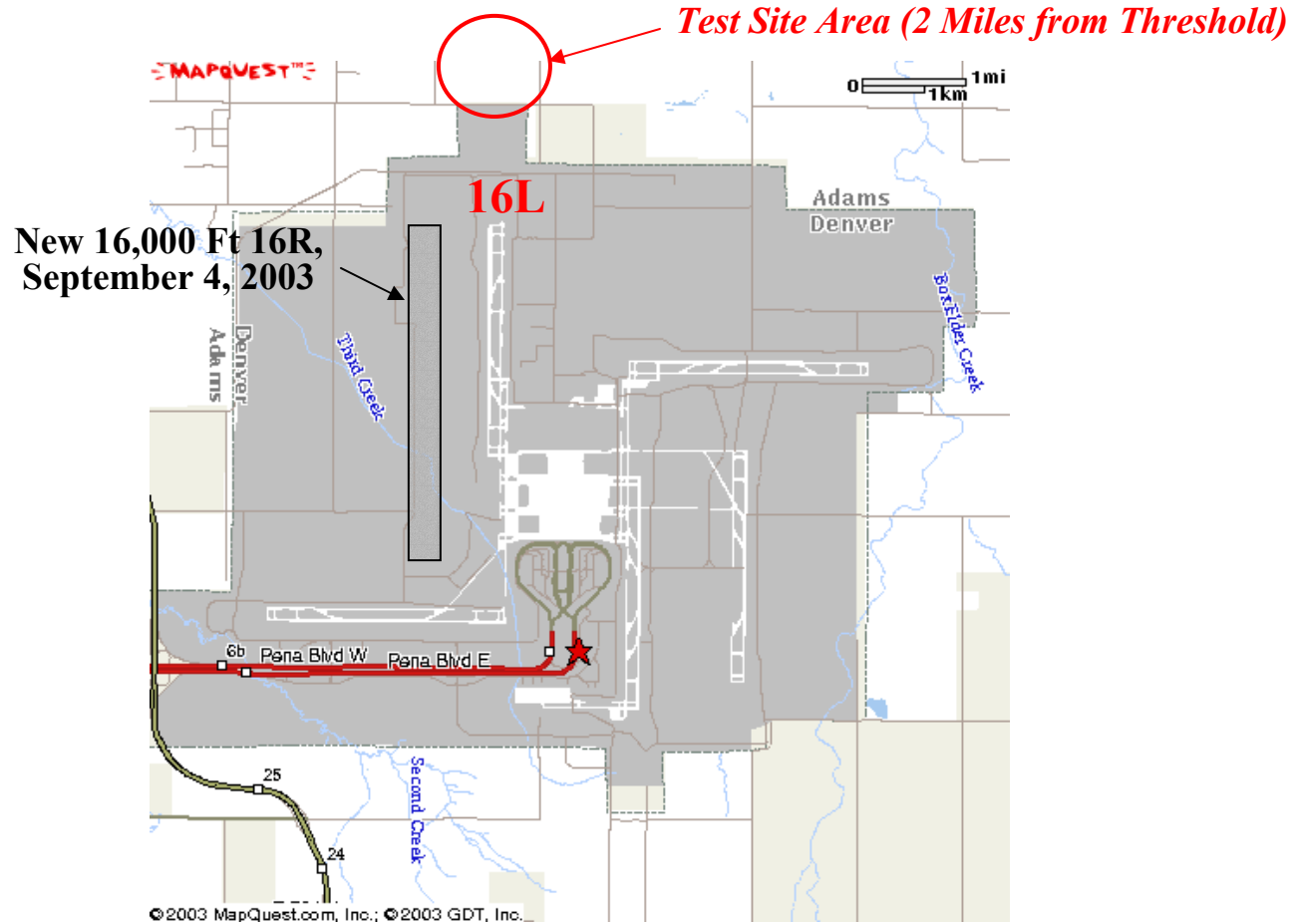
Participating and Supporting Organizations

- ② **NASA LaRC**
- ② **DOT Volpe Center**
- ② **Titan**
- ② **OptiNav**
- ② **Microstar Laboratories**
- ② **CTI**
- ② **MIT LL**
- ② **AeroVironment**
- ② **WLR Research**
- ② **FST**
- ② **Lockheed Martin**
- ② **DLR - Berlin**
- ② **Anteon**
- ② **FAU**
- ② **United Airlines**
- ② **DIA Airport**
- ② **Local Denver FAA**

General Test Configurations

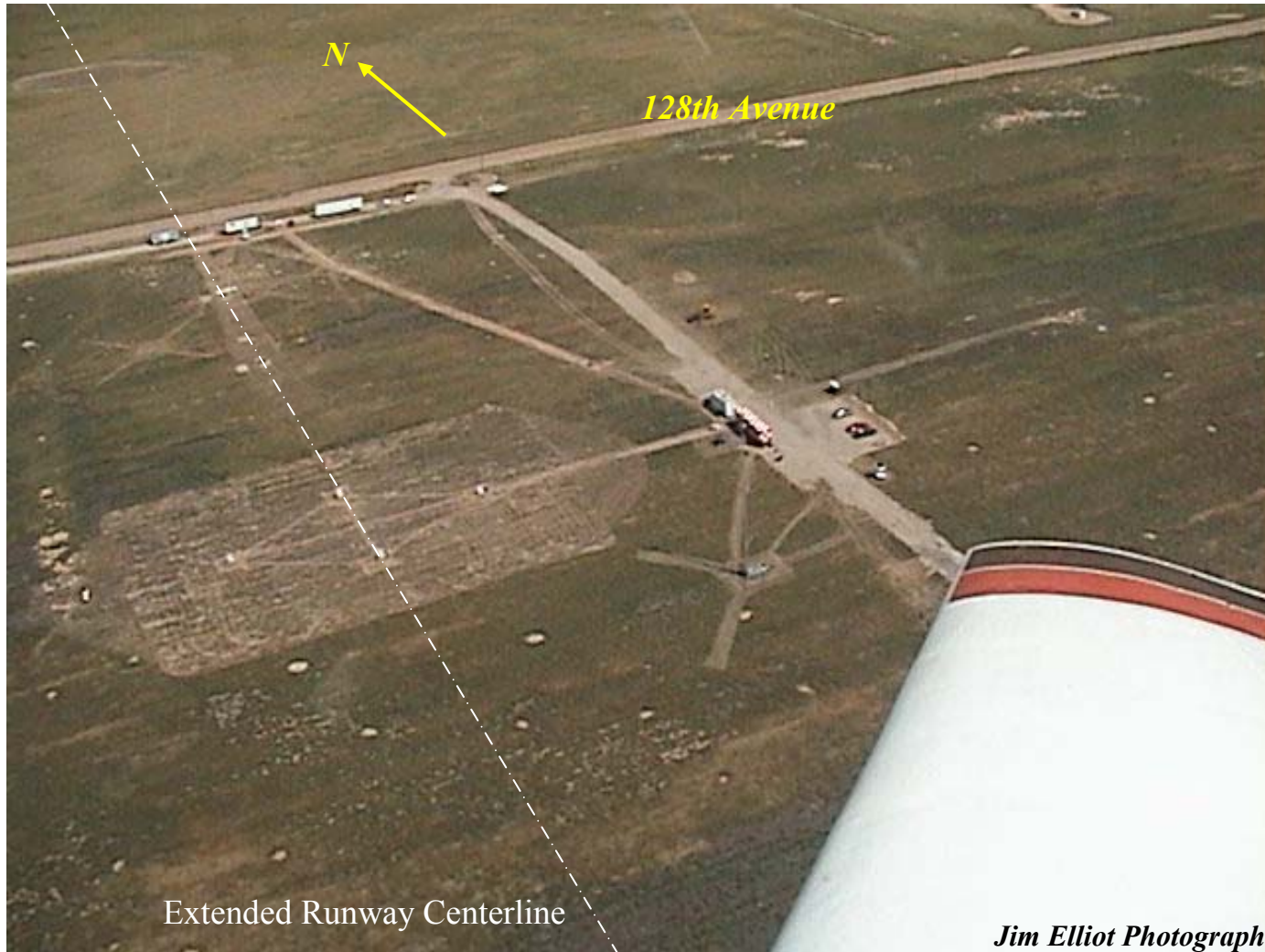
- **Landing Configuration.**
- **Vortices Generated from Nominally 700 Feet Altitude.**
- **Acoustic Data from Government Microphone Array.**
- **Lidars Providing Ground-Truth Wake Track and Strength Data.**
- **Metrological Sensors Characterizing State of the Atmosphere.**
- **Aircraft Identification and Flight Tracks from ARTS.**

DIA Test Site



The first operation on 16R/34L was a United Airlines 777 departure, flight 244 to Chicago at 10:38AM local time.

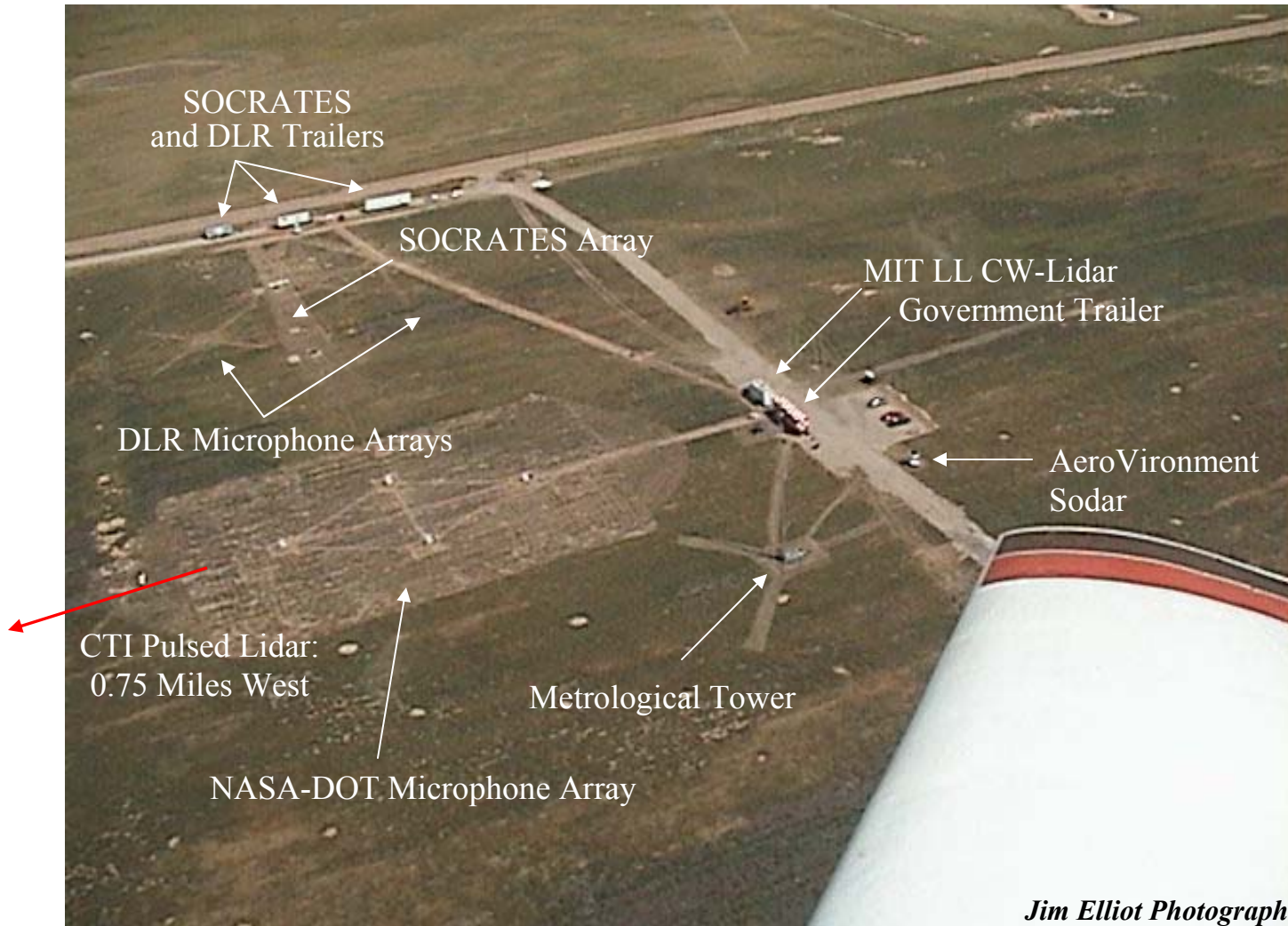
Test Site Aerial Photograph



Extended Runway Centerline

Jim Elliot Photograph

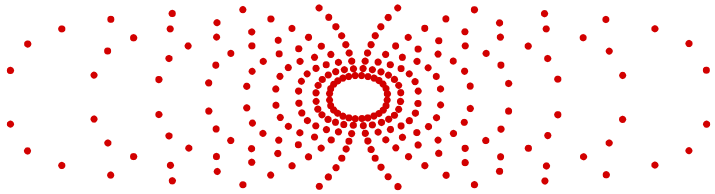
Test Site Aerial Photograph



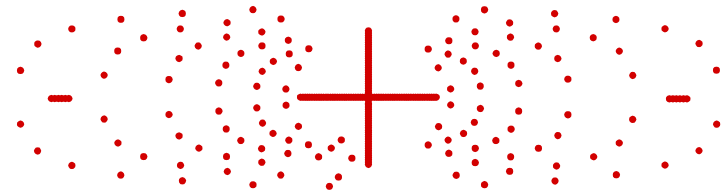
Primary Acoustic Sensor - NASA-DOT Array

- **Two Configurations Deployed.**
- **Configuration 1 – 8/28 to 9/19 (20 – 1000 Hz).**
- **Configuration 2 – 9/22 to 9/23 (10 – 2000 Hz).**

Array Layout



Configuration 1



Configuration 2

Aerodynamic Sensors

■ **CTI Pulsed Lidar**

■ **MIT LL CW Lidar**

Metrological Sensors

- **AeroVironment Wind Sodar**
- **107 Ft Tower with R. M. Young Propeller Anemometers at Three Heights**
- **Vaisala Temperature and Relative Humidity Sensor at Mid-Height of Tower**
- **Kipp & Zonen Microwave Radiometer Temperature Profiler**
- **METEK Ultrasonic Anemometer**

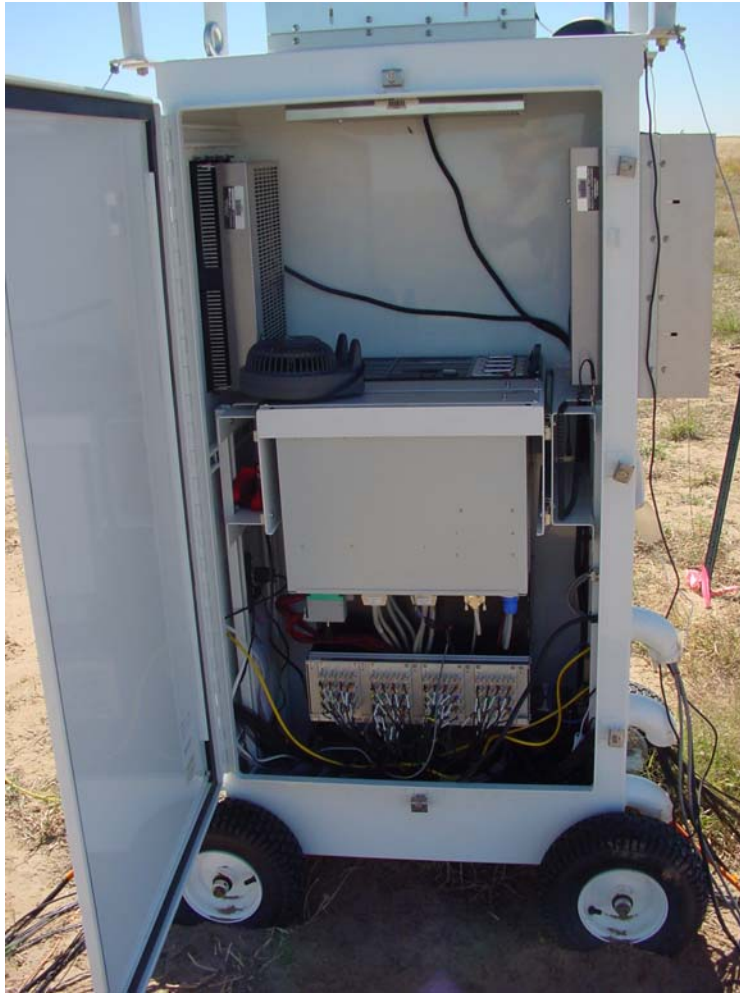
Additional Measurements

- **SOCRATES Laser Array**
- **DLR Phased Microphone Arrays**

Looking South from the Government Array



Close-Up of the Array Components



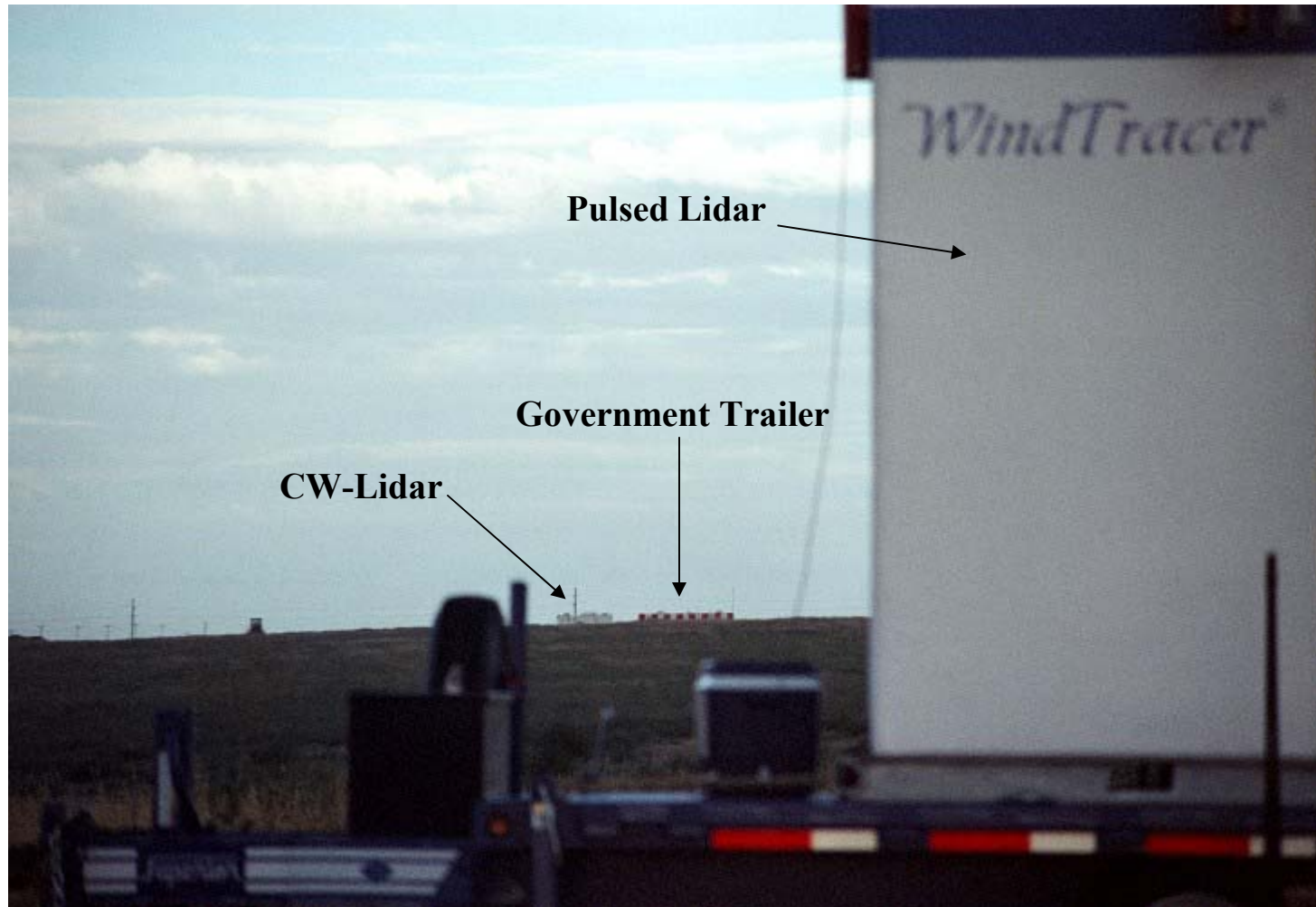
Looking West

Government Trailer

MIT LL CW Lidar



Looking East from CTI Pulsed Lidar



Looking South from SOCRATES

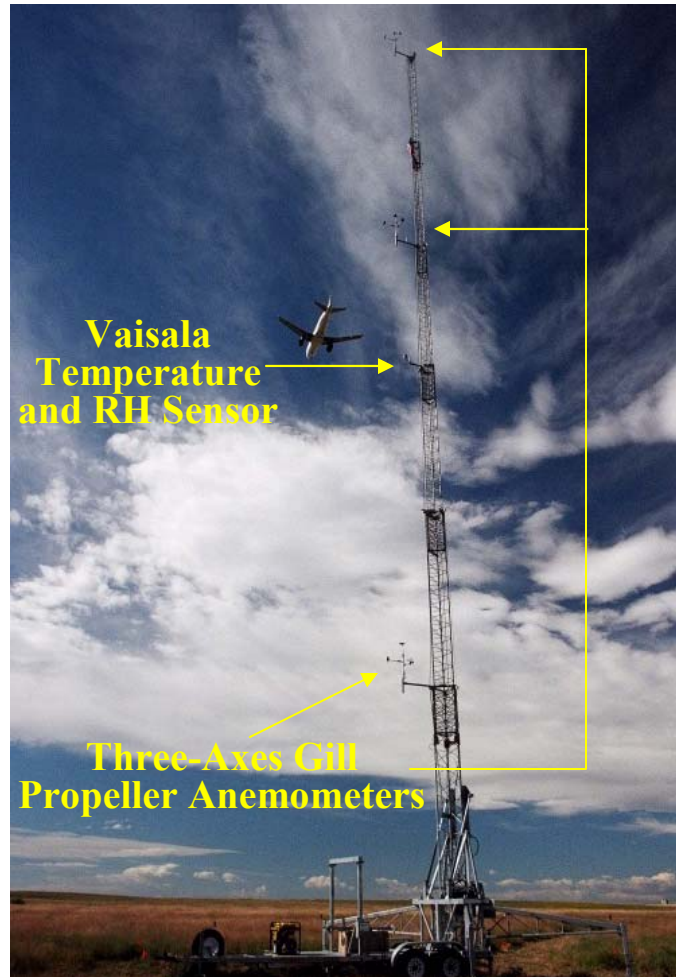


Lockheed-Martin Photograph

Meteorological Sensors



Tower – Metrological and Array Calibration



OptiNav Photograph

Meteorological Sensors



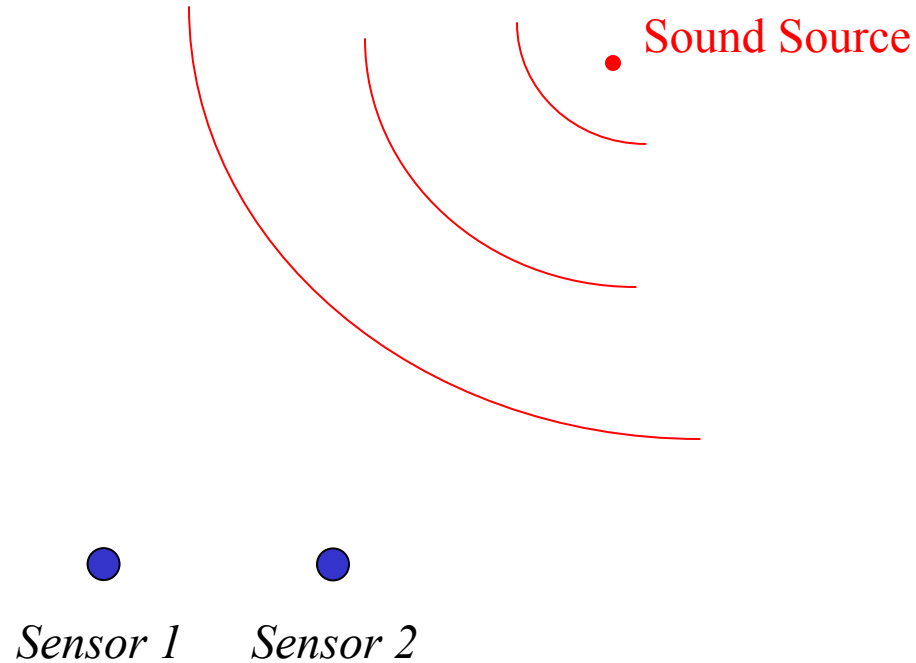
METEK Ultrasonic Anemometer



Kipp & Zonen Microwave Radiometer

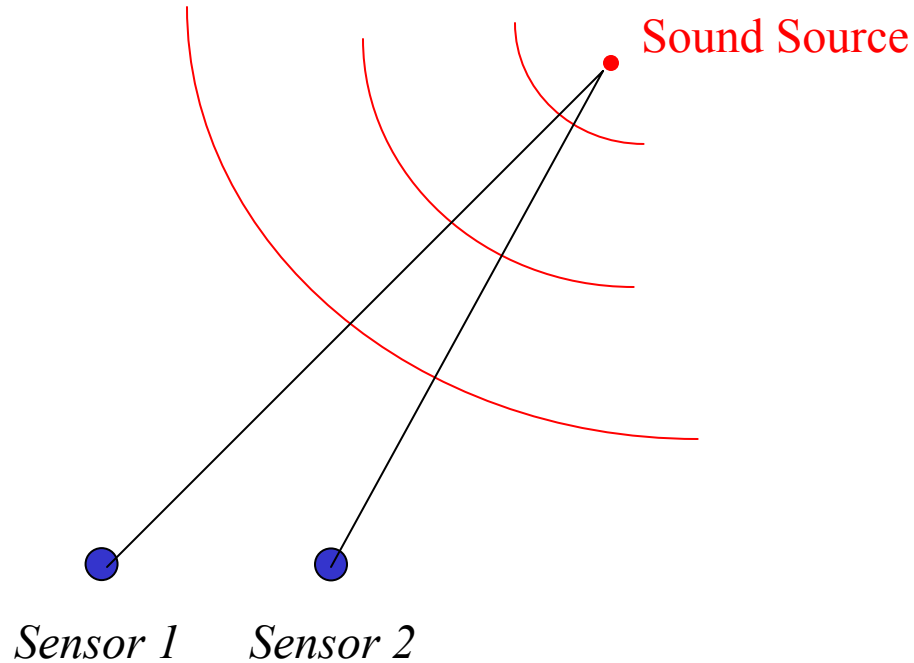


Array Signal Processing



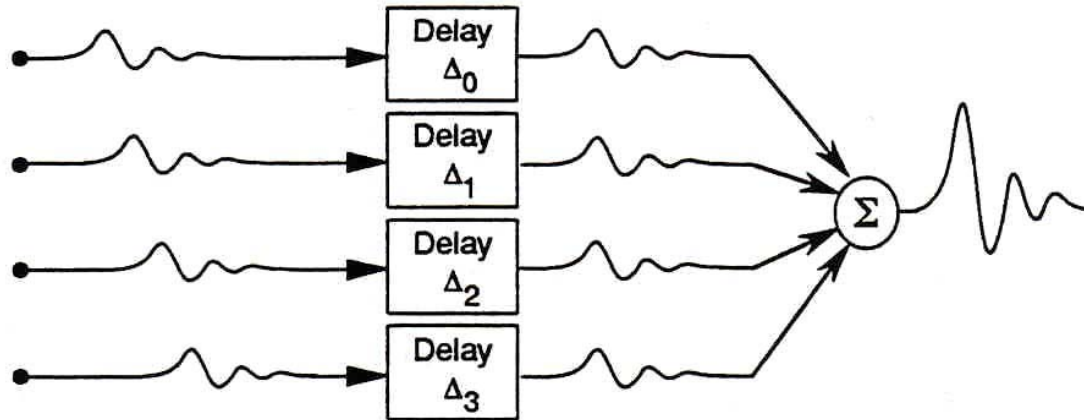
Sensor 2 Hears an Earlier Version of Sensor 1

Array Signal Processing



The Time Delay Sensor 1 Hears is Proportional to the Additional Distance the Same Sound Needs to Travel in Getting to Sensor 1

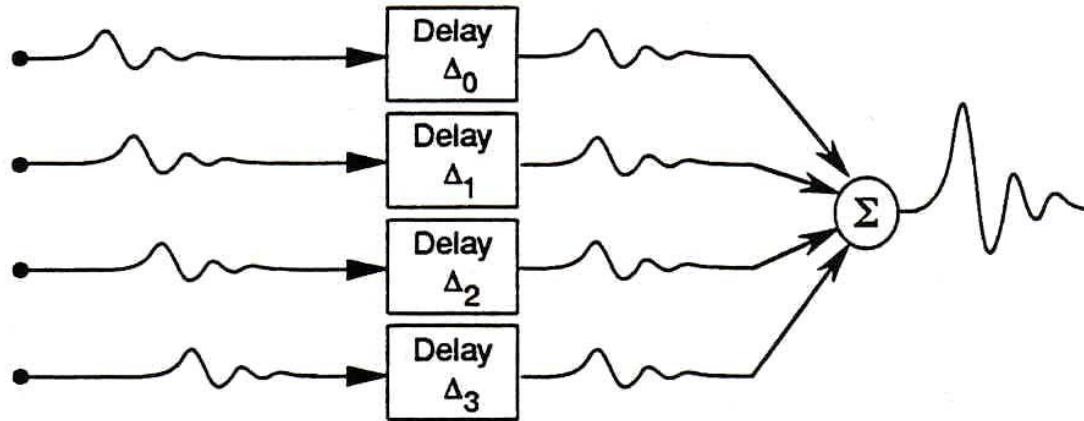
Delay and Sum Beamforming



- **If the Location of Sound Source Were Known, Appropriate Time Shifts in the Recorded Signals from Different Sensor Elements in the Array can be Applied in Software.**
- **Acoustic Signature from the Source of Interest is then added Constructively; Signal is Amplified from the Investigated Location.**

Figure Taken from Johnson, P. and Dudgeon, 1993

Delay and Sum Beamforming



- **Meanwhile, Sound From Other Locations Add Up Incoherently. The Result of Incoherent Summation Could be Shown as a Lower-Amplitude Wave ; Unwanted Noise is, in Effective, Rejected.**
- **Entire Array Acts as a Directional Acoustic Sensor (Hence, “Beamforming”).**

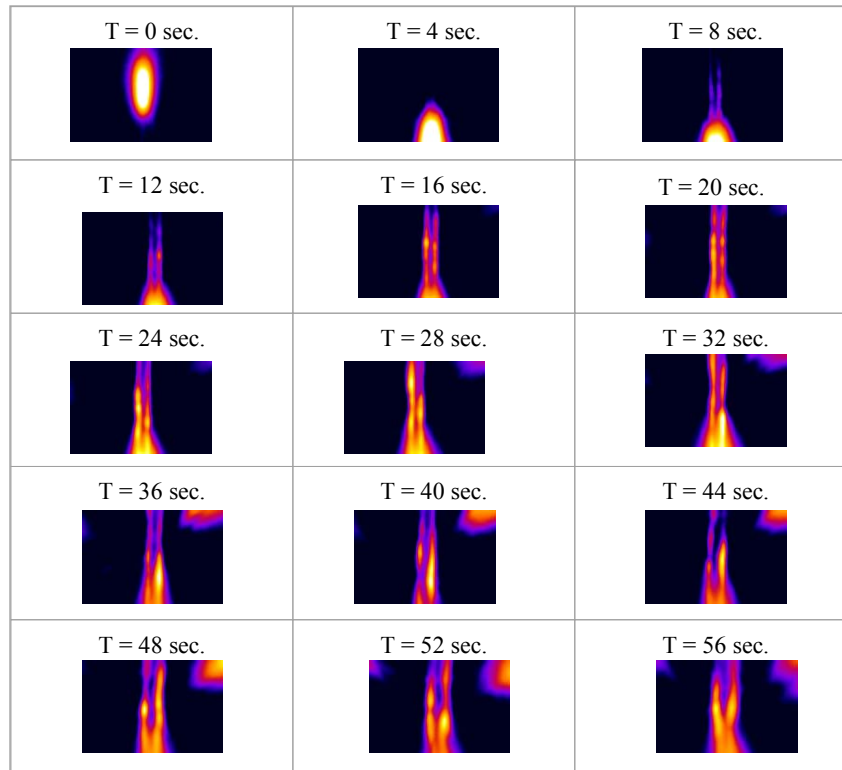
Figure Taken from Johnson, P. and Dudgeon, 1993

Delay and Sum Beamforming

- **Noise Source Location is Usually not Known - Need to Find it.**
- **Systematically Vary/Search Assumed Noise Source Locations.**
- **Apply the Appropriate Delays and then Sum Signals Based on Assumed Locations.**
- **Acoustic Pressure Level Computed at Each Searched Location (i.e., Grid Points).**
- **Results Can be Visualized as Contour Plots - Noise Source Localization Map (“Acoustic Imaging”; “Acoustic Camera”).**

Sample Results - Microphone Array

- Run 030903_194324 : September 3 at 7:43PM Local Time (B767).
- Beamforming at 500 Feet Altitude, 1000 Feet x 1500 Feet Coverage Area for a Horizontal Beamforming Planes (“Snapshots”).
- The Analysis Band is 200 Hz and Below.



Data Analysis Needs to Address

- **Do Wake Vortices Generate a Unique Acoustic Signature?**
- **How Consistently do Wake Vortices Generate These Signature?**
- **What Are the Characteristics of these Signatures and Circumstances Under which they are Generated?**
- **What is the Frequency Range of these Acoustic Signals?**

Data Analysis Needs to Address

- **Can Vortex Strength be Reliably Inferred from Wake Acoustic Signatures? What is the Fundamental Scientific Principle?**
- **If the Answers to All of the Questions are Positive, Then Assess the Feasibility of an Acoustic-Based Sensor System Detecting, Identifying, Tracking Wake Vortices and Quantifying the Circulation in a High Ambient Noise Environment Typically Found in Major Airports.**

Questions?



OptiNav Photograph