Sensors and Instrumentation for Aeroacoustic Noise Characterization and Assessment

Microphone Phased Arrays

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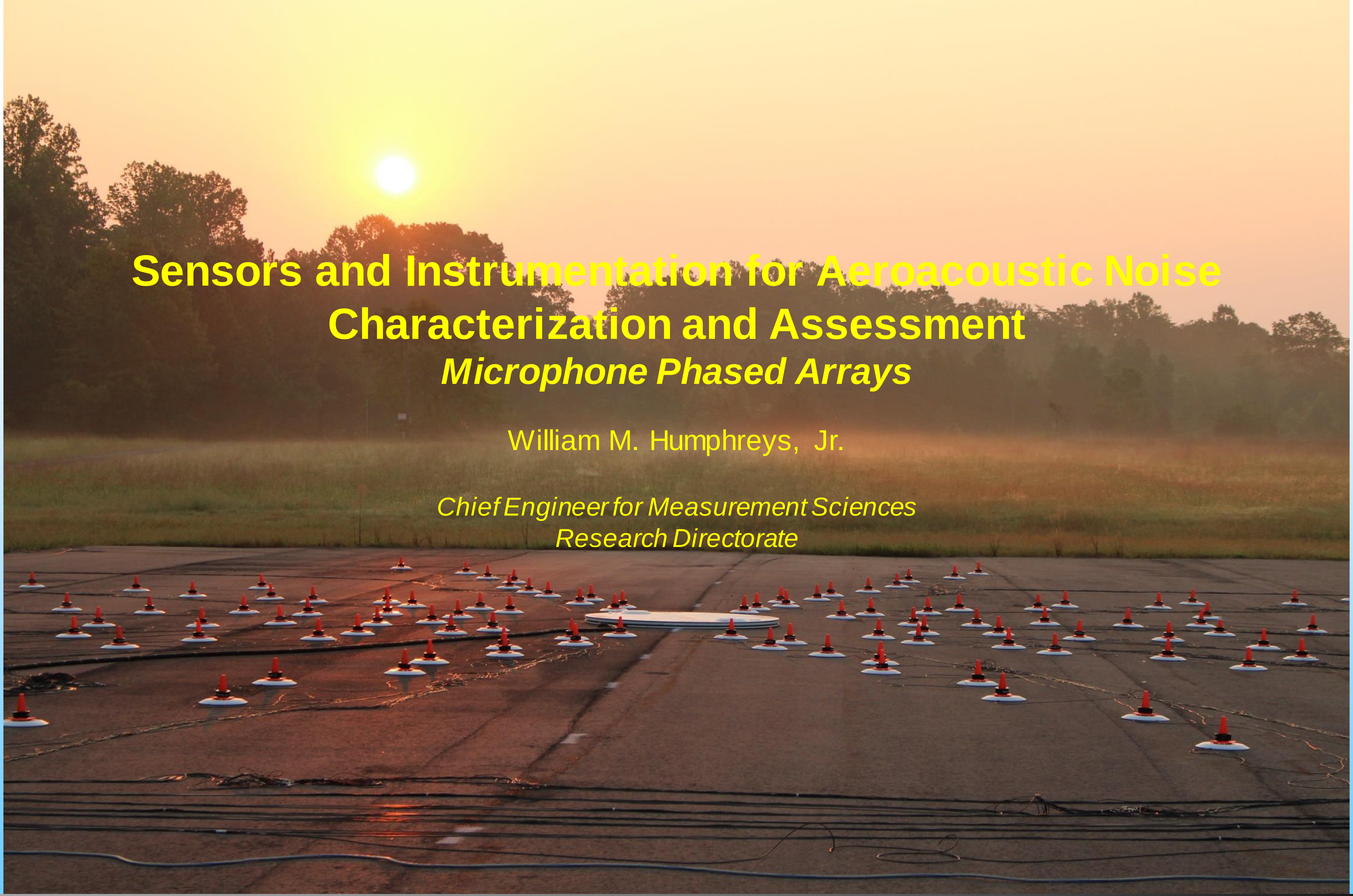
Chief Engineer for Measurement Sciences
Research Directorate



Outline

- Motivation
- Aeroacoustic Measurement Fundamentals
- Ground Facility Array Systems
- Flyover Testing Array Systems
- Array Health Monitoring
- Summary

Motivation

ARMD Strategic Implementation Plan – Strategic Thrust 3 (Ultra-Efficient Subsonic Transport)

- "Sustainable growth to meet the demand for air transportation during these decades calls for safe, economical, energy-efficient, and *quiet* community-friendly transport aircraft with the payload, speed, and range performance demanded by the market."
- "…. These goals also support meeting and exceeding projected noise and NOx standards recommended by ICAO (the International Civil Aviation Organization)."

Noise & Flight Demonstrators

- Advanced technology demonstrators may introduce novel sources of aircraft noise
- Preparatory wind tunnel testing addresses component and integration noise
- Acoustic flight testing provides best means of understanding full vehicle acoustics of novel configurations

Acoustic Measurements

- Single microphones give overall noise, but are unable to assess source contributions without vehicle configuration changes
- Microphone phased arrays can assess source contributions for various subsonic civil transport concepts as well as supersonic / high speed transport category aircraft during takeoff, approach and landing
- Arrays commonly used in wind tunnel aeroacoustic testing, but are also utilized for flyover flight testing

Aeroacoustic Measurement Fundamentals

Fundamentals – Brief History of Experimental Aeroacoustics

1878 – Strouhal relates sound generation to fluid motion

1915 – Rayleigh studies sound radiation from periodic vortex shedding

1950s – First commercial jet engines developed; significant community noise generated

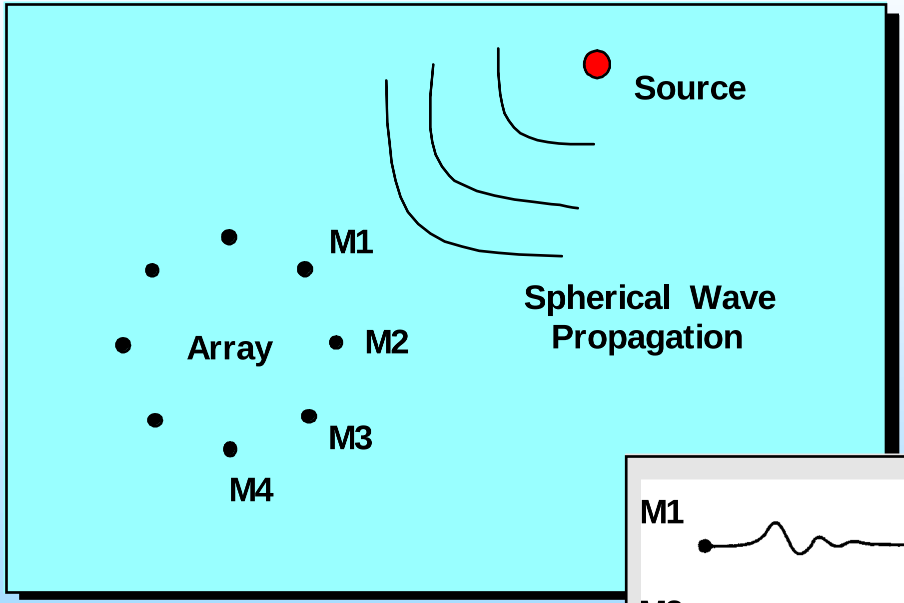
1952 – Lighthill studies physics of jet noise, leading to analogy on sound propagation in 1954

1969 – Ffowcs Williams and Hawkings develop propagation models for sound

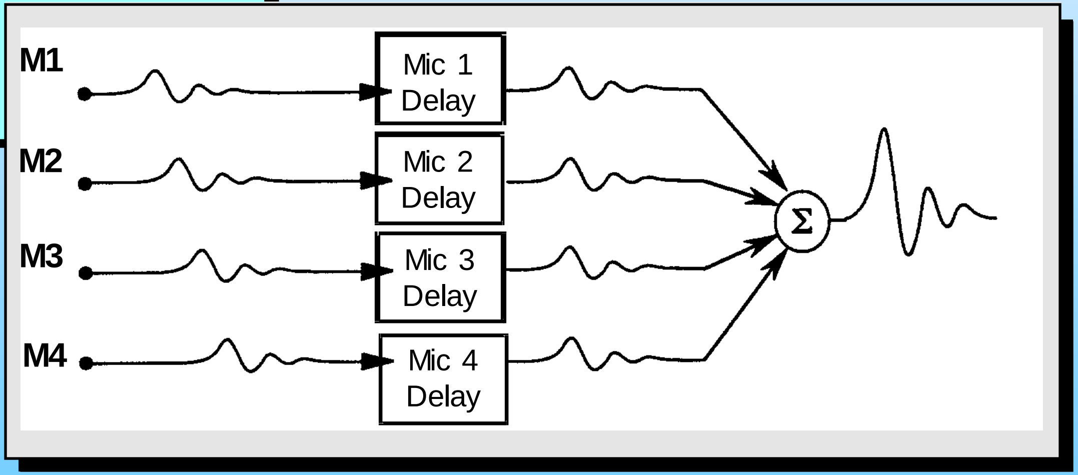
1970s – Acoustic mirrors used in wind tunnels to identify noise sources on models

1990s – Extensive use of microphone phased arrays begins for noise source characterization, especially for measuring airframe and undercarriage noise on models and in flight

Fundamentals – How do Microphone Arrays Work?



- Geometric pattern of microphones chosen (can be 2D or 3D), simultaneously sampling the acoustic field
- Microphone delays chosen based on a particular steering direction (measurement region)
- For a nonuniform array and a single noise source, only one set of delays will sum constructively



Delay and Sum Beamforming

Fundamentals – How do Microphone Arrays Work?

$$Y_n = \frac{\mathbf{e}_n^T \mathbf{G} \mathbf{e}_n}{m_0^2}$$ → Frequency-domain beamformer

$$\mathbf{G} = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1m_0} \\ \vdots & G_{22} & & \vdots \\ \vdots & & \ddots & \vdots \\ G_{m_0 1} & & & G_{m_0 m_0} \end{bmatrix}$$ → Cross spectral matrix containing microphone auto/cross spectral terms

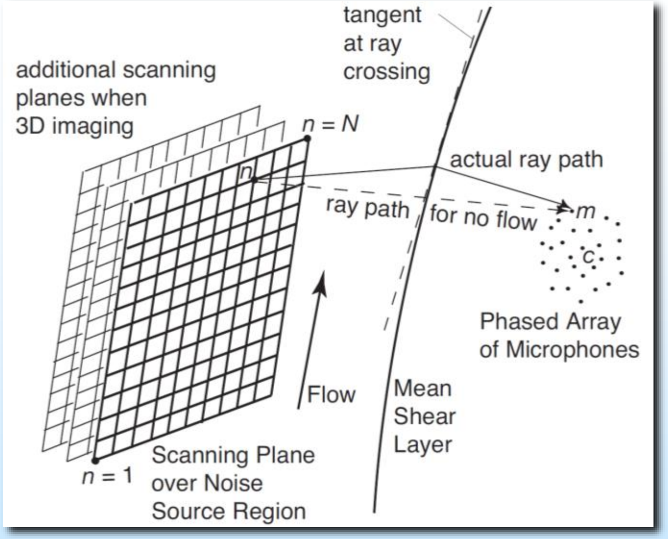
$$\mathbf{e}_n = \mathrm{col}\begin{bmatrix} e_1 & e_2 & \cdots & e_{m_0} \end{bmatrix}$$ → Steering vector (*n* refers to grid location)

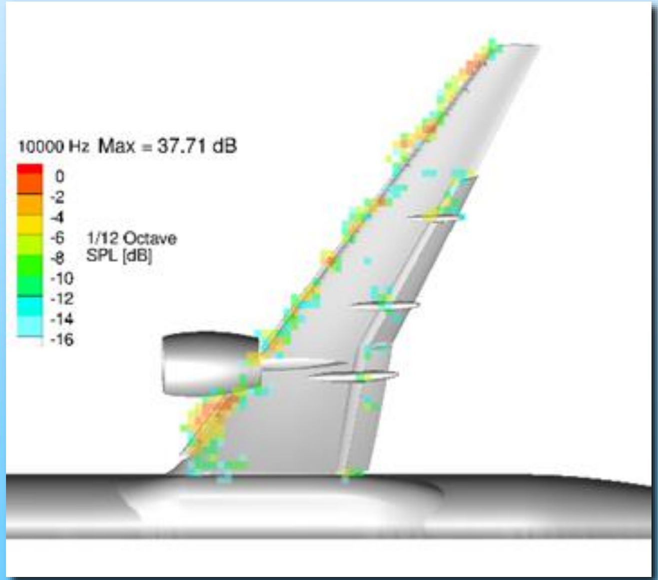
$$e_m = a_m \frac{r_m}{r_c} \exp(j 2 \pi f \tau_m)$$ → Steering vector element (*m* refers to microphone #)

Time delay from grid location to microphone

Fundamentals – How do Microphone Arrays Work?

- To improve resolution, delay and sum beamforming is performed in the frequency domain, with a cross spectral matrix (auto spectra, cross spectra) formed from the microphone time history measurements
- A measurement grid is defined over the test article, with beamforming performed individually at each grid point yielding a noise measure at that point
- For measurements in open-jet tunnels, the refraction of sound through the shear layer is corrected (amplitude and path time) prior to beamforming
- The result is an ensemble of contour maps showing noise regions on a model as a function of spatial location and beamform frequency





Fundamentals – Advanced Array Processing

- Enhanced resolution techniques have been developed to improve the spatial resolution of phased arrays.
- One of the first of these to come into widespread use is the Deconvolution Approach to the Mapping of Acoustic Sources (DAMAS), introduced by Brooks and Humphreys at NASA Langley Research Center in 2004.

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- The technique relies on the generation of an influence matrix that models the response of the array over the measurement grid. This array response is then deconvolved from the observed beamformer source distribution using an iterative solver to produce a realistic source distribution where array geometry effects are removed.

Desired Source Distribution

BF Source Distribution

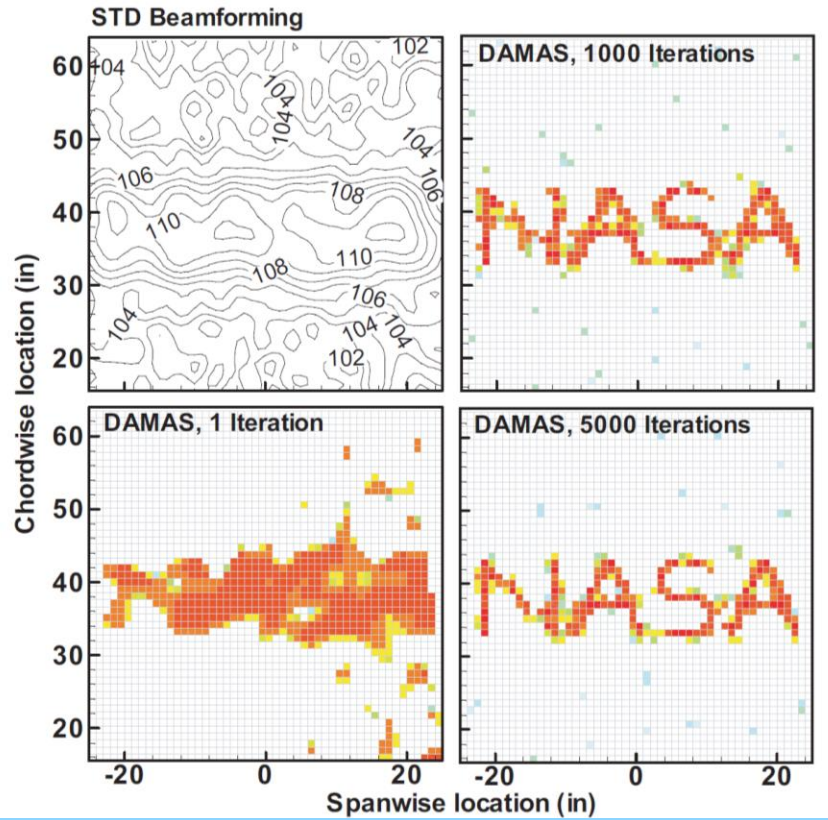
$$\hat{X} = \hat{A}^{-1}\hat{Y}$$

Influence Matrix

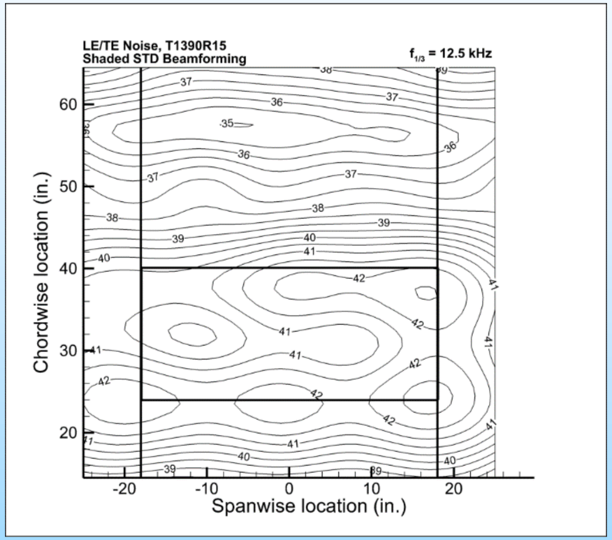
$$X_n^{(i)} = Y_n - \left[\sum_{n'=1}^{n-1} A_{nn'} X_{n'}^{(i)} + \sum_{n'=n+1}^{N} A_{nn'} X_{n'}^{(i-1)}\right]$$

Gauss-Seidel Solver

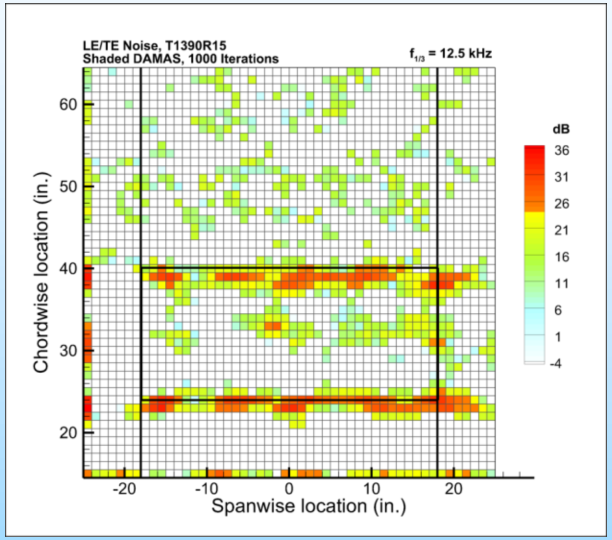
Fundamentals – Advanced Array Processing



DAMAS Example – Synthetic Data



STD Beamforming



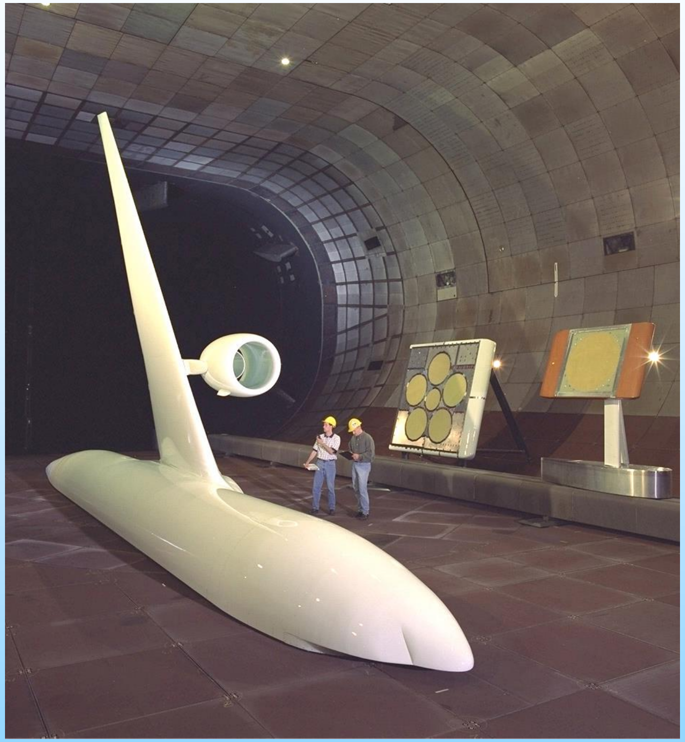
DAMAS Output

DAMAS Example – Wing Leading Edge / Trailing Edge Noise

Brooks and Humphreys, “A Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS) Determined from Phased Microphone Arrays”, Journal of Sound and Vibration, Vol. 294 (2006)

Ground Facility
Aeroacoustic Measurements

NASA Ground Facility Aeroacoustics



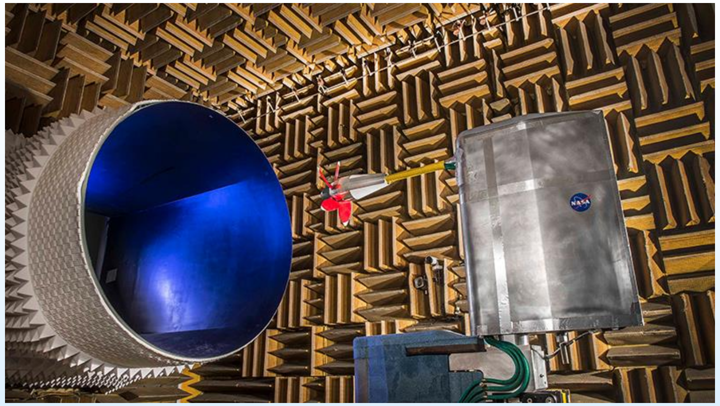
40- by 80-foot Wind Tunnel

NASA Ames

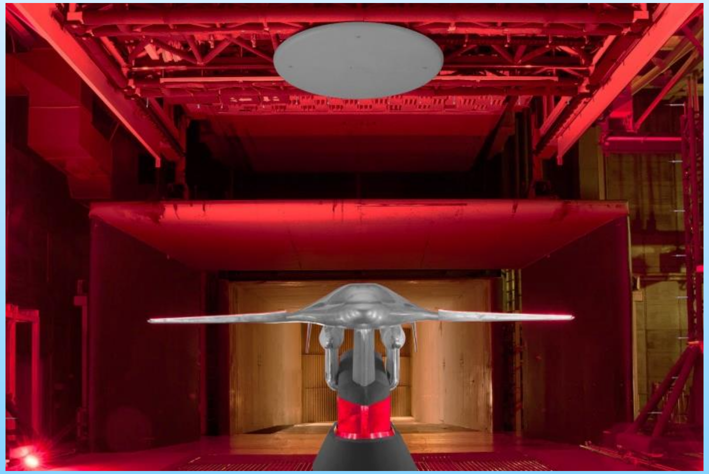
9- by 15-foot Wind Tunnel

Aeroacoustic Propulsion Laboratory

NASA Glenn



Low Speed Aeroacoustic Wind Tunnel



14- by 22-foot Subsonic Tunnel

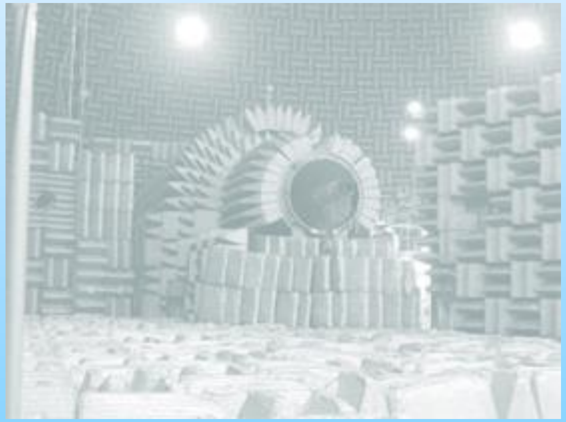
NASA Langley

NASA Ground Facility Aeroacoustics

40- by 80-foot Wind Tunnel

NASA Ames

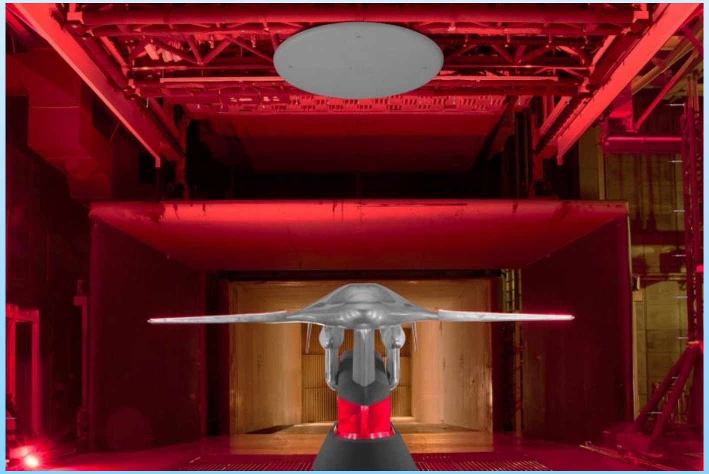
9- by 15-foot Wind Tunnel



Aeroacoustic Propulsion Laboratory

NASA Glenn

Low Speed Aeroacoustic Wind Tunnel

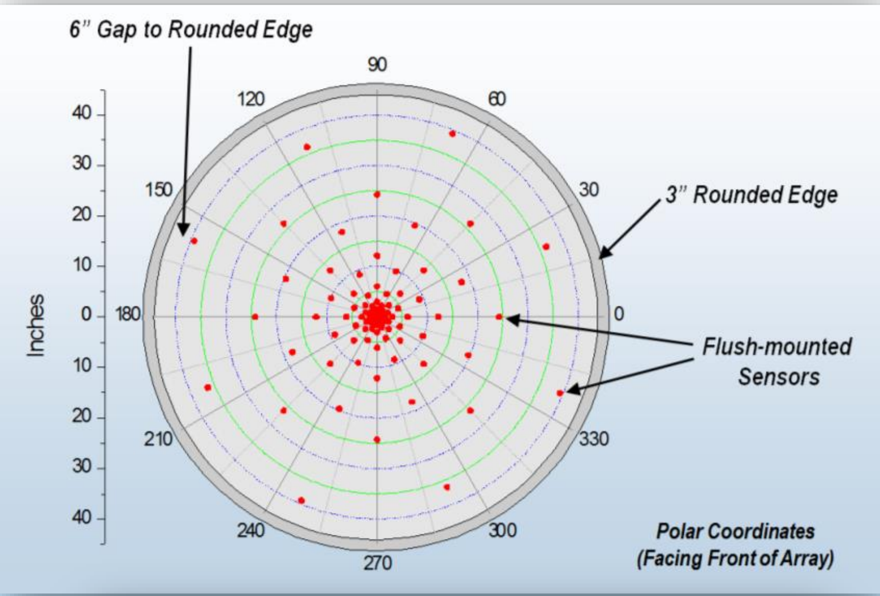


14- by 22-foot Subsonic Tunnel

NASA Langley

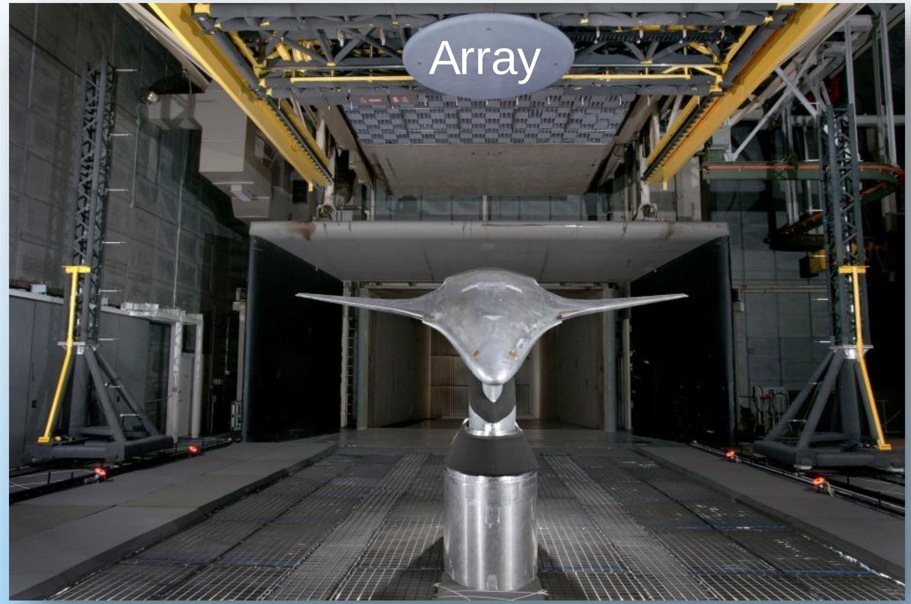
14- by 22-foot Subsonic Tunnel Array

- 97 pressure microphones and preamplifiers
- Arrangement of 16 spiral arms each containing six microphones with one microphone at center
- Sensors flush-mounted on an 8.05-ft double layer fiberglass honeycomb panel
- Frequency range: 1.5 – 80 kHz
- Array incorporates integral inclinometers, accelerometers, and temperature sensors to provide real-time health monitoring of panel



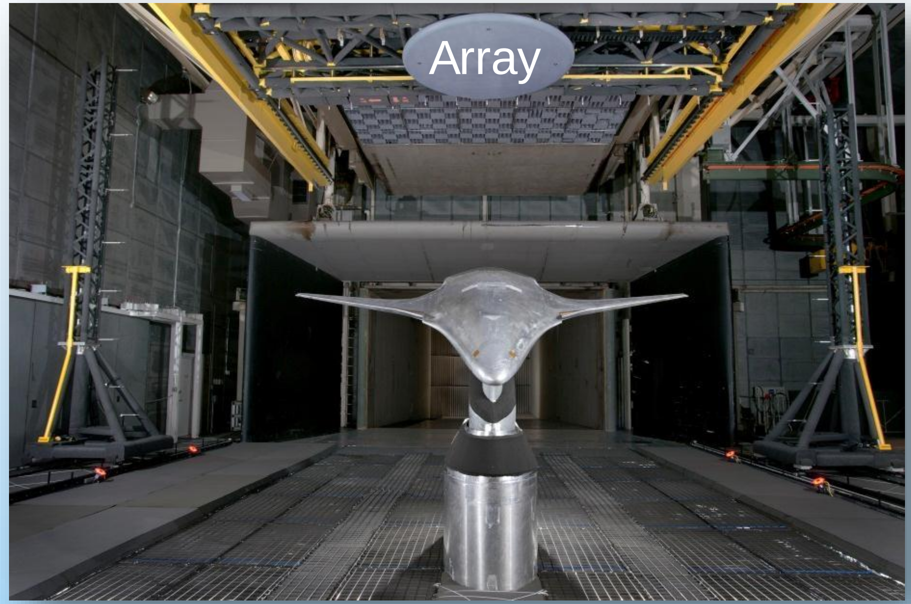
Humphreys, et al., "Development of a Microphone Phased Array Capability for the Langley 14- by 22-Foot Subsonic Tunnel", AIAA 2014-2343

14- by 22-foot Subsonic Tunnel Array



Overhead configuration for full-span model testing (e.g., HWB entry)

14- by 22-foot Subsonic Tunnel Array



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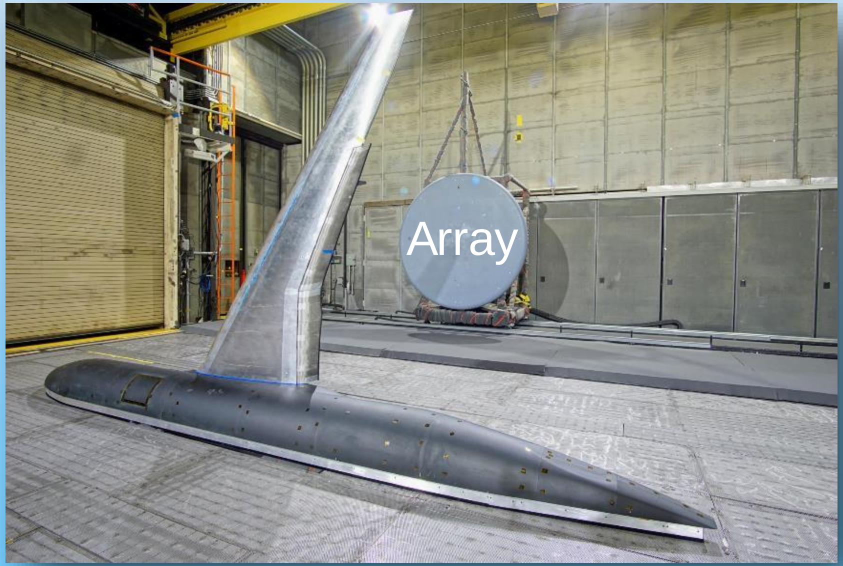
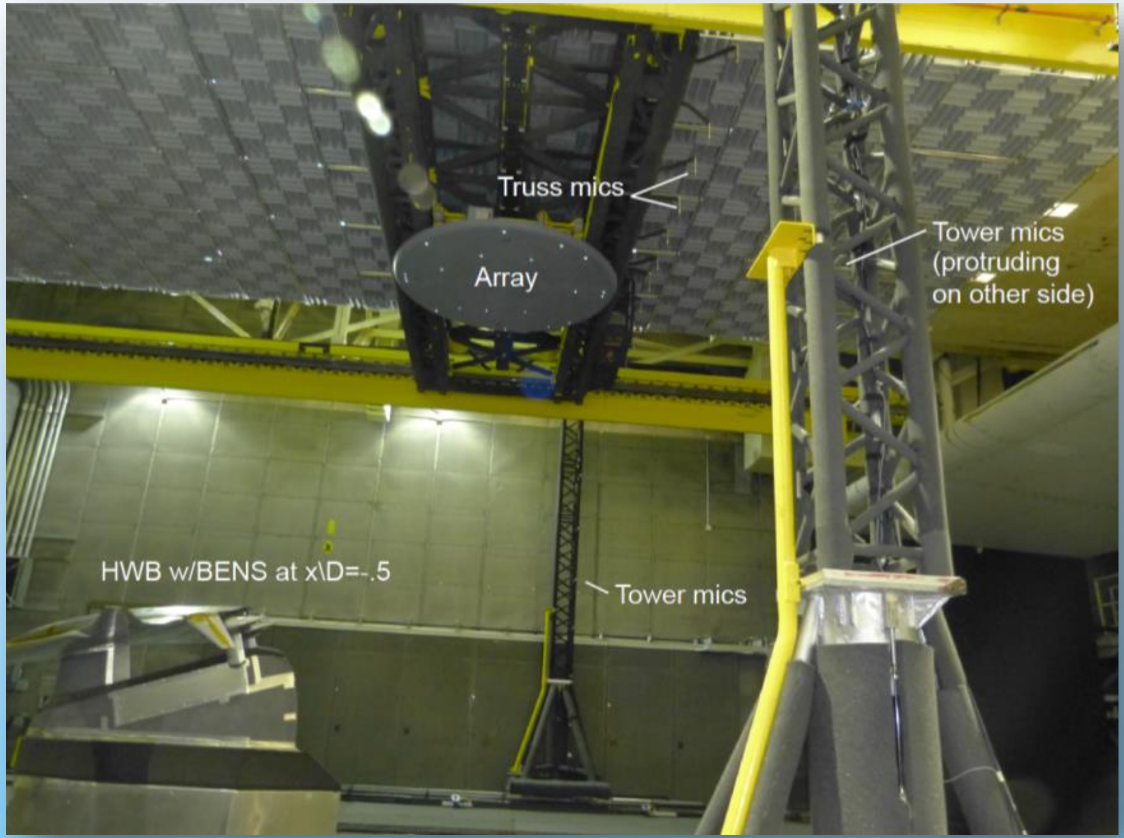


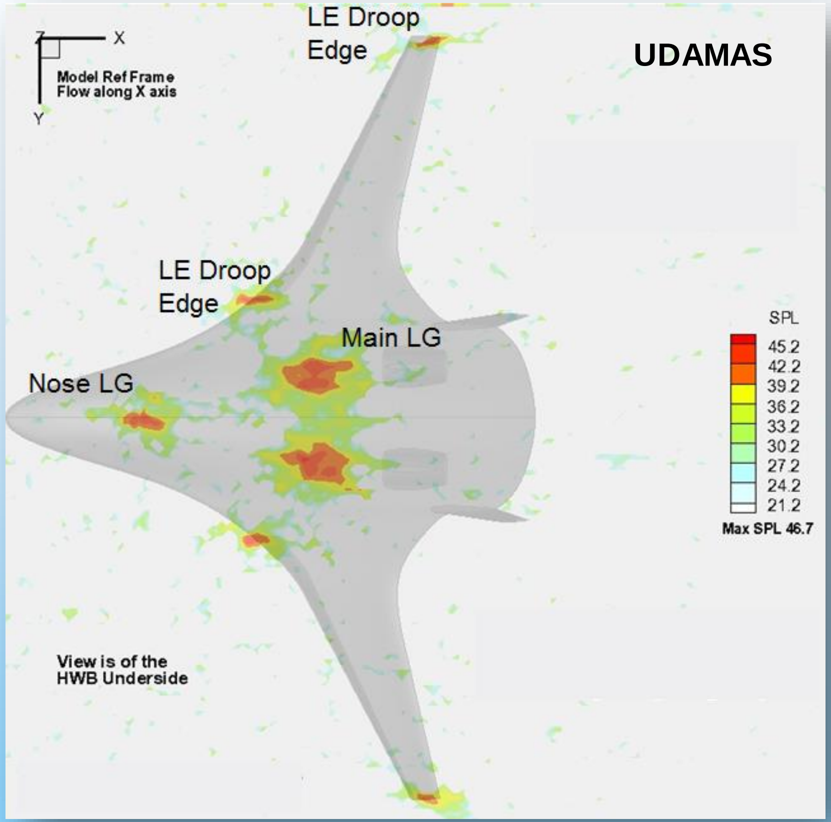
Sideline configuration for semispan model testing (e.g., Common Research Model entry)

14- by 22-foot Subsonic Tunnel – Directivity Microphones

- Microphones mounted on pair of towers on either side of the test section and on the facility overhead traverse
- Towers supported by 40-ft linear traversing rails synchronized with overhead traverse
- Populated with 29 microphones and preamplifiers
- Microphones spaced at nominal 7.5-deg increments around test section for hemispherical measurements

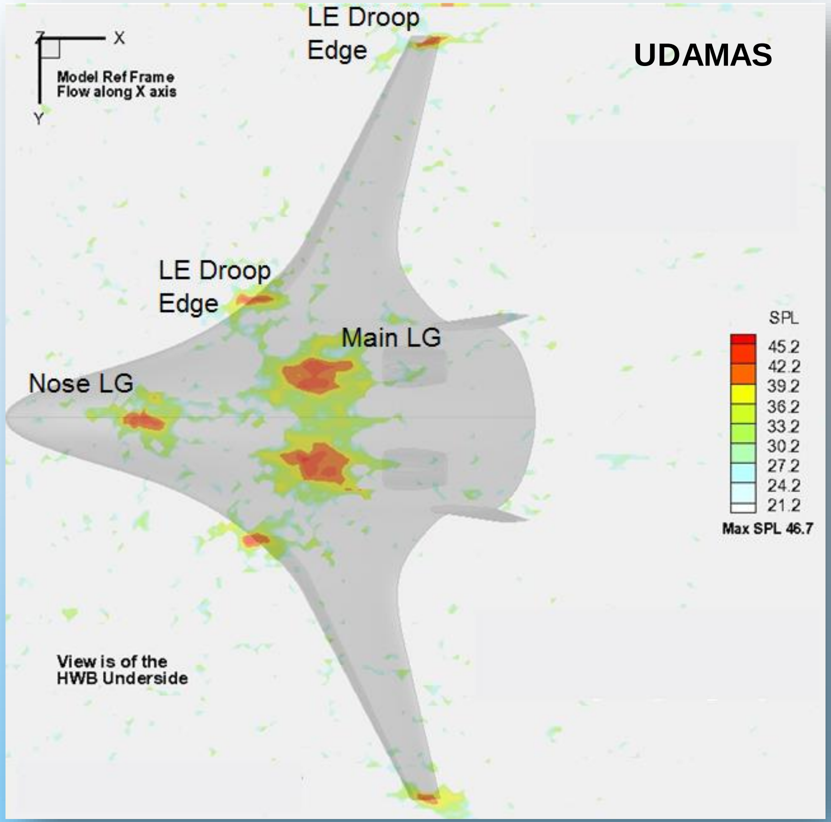


Data Product Examples
Beamforming / Deconvolution



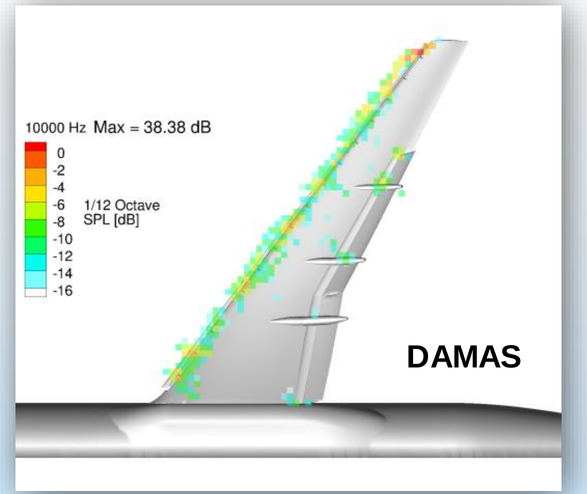
HWB Airframe Noise Example
(Array in Overhead Configuration)

Data Product Examples
Beamforming / Deconvolution



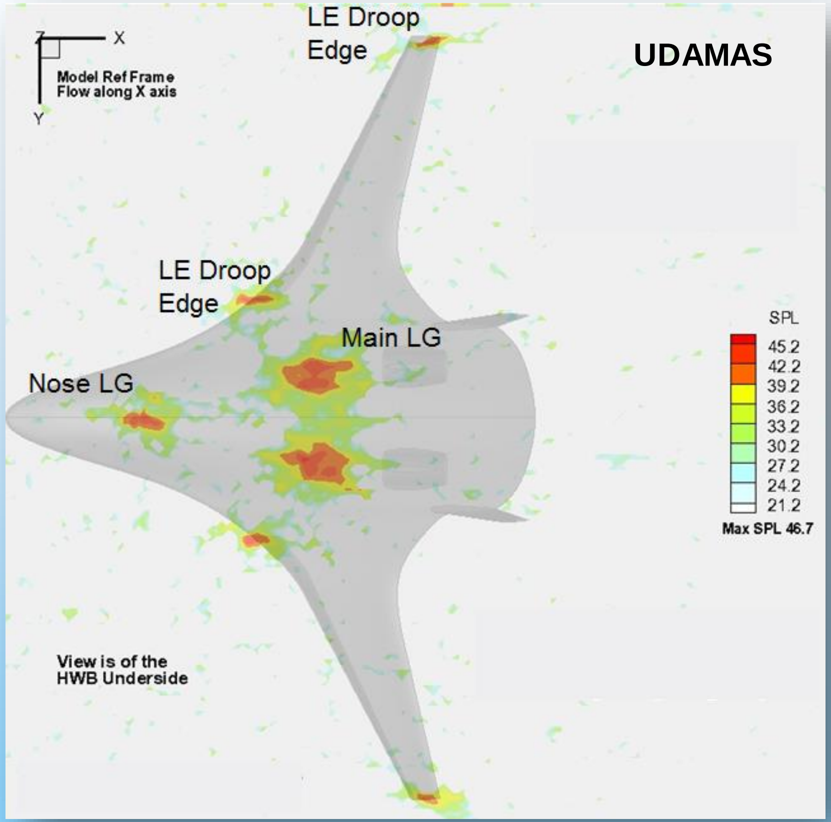
HWB Airframe Noise Example (Array in Overhead Configuration)

Full-span Slat Noise



CRM-HL Slat Noise Example (Array in Sideline Configuration)

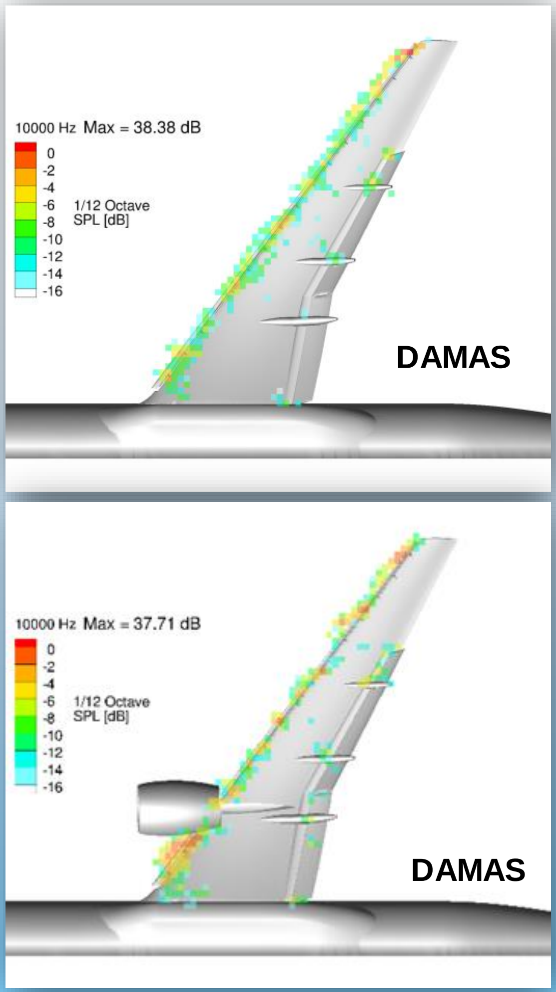
Data Product Examples
Beamforming / Deconvolution



HWB Airframe Noise Example (Array in Overhead Configuration)

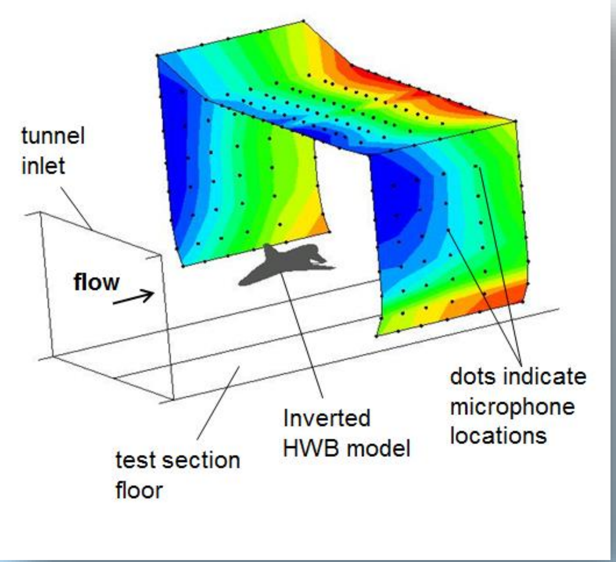
Full-span Slat Noise

Part-span Slat Noise

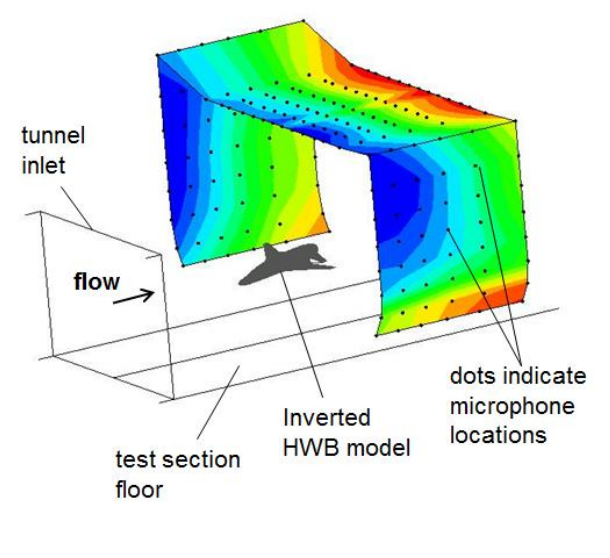


CRM-HL Slat Noise Example (Array in Sideline Configuration)

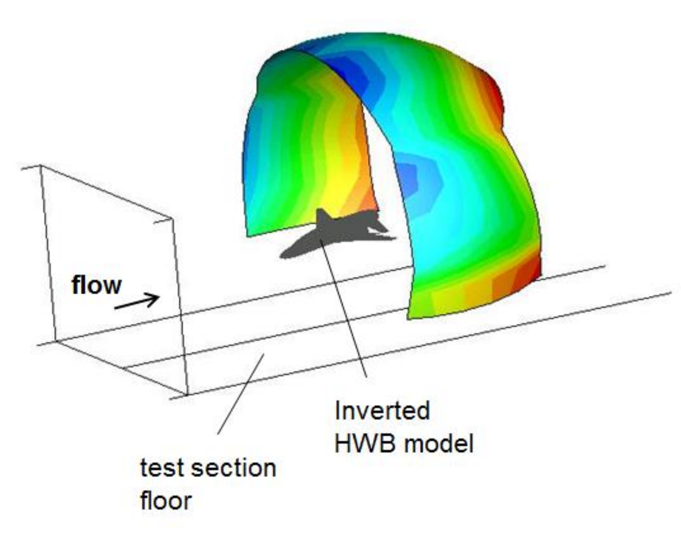
Data Product Examples
Hemispherical Directivity



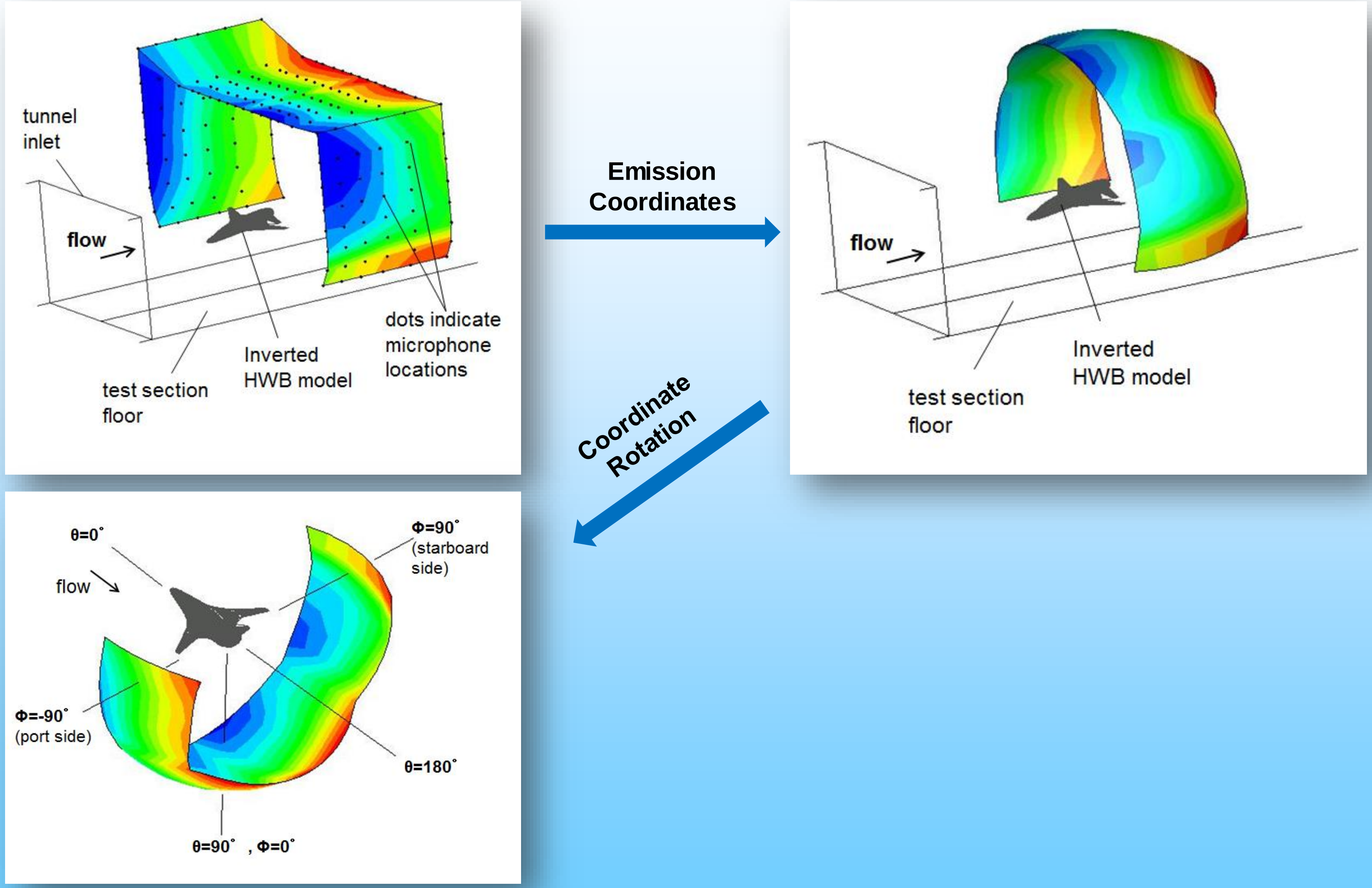
Data Product Examples
Hemispherical Directivity



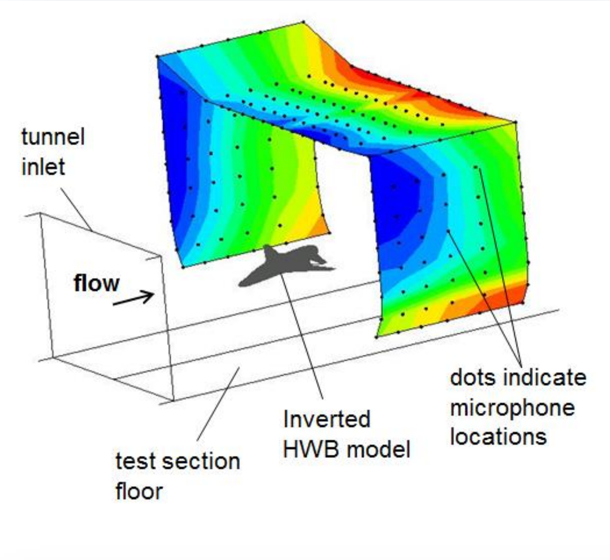
Emission Coordinates



Data Product Examples
Hemispherical Directivity



Data Product Examples
Hemispherical Directivity



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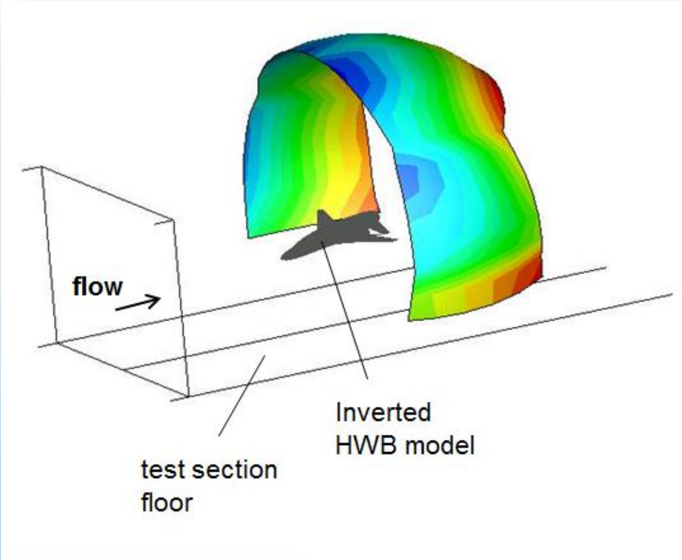
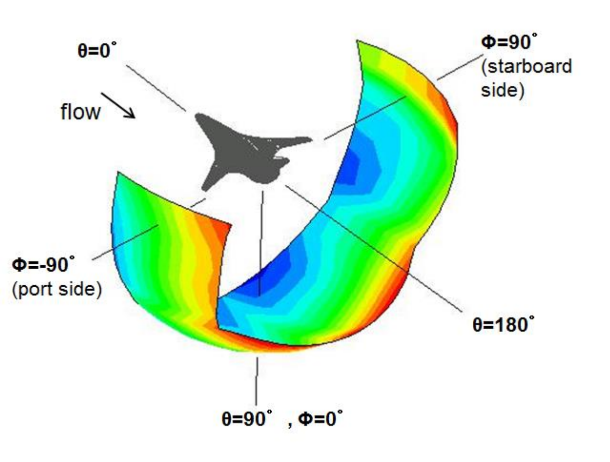
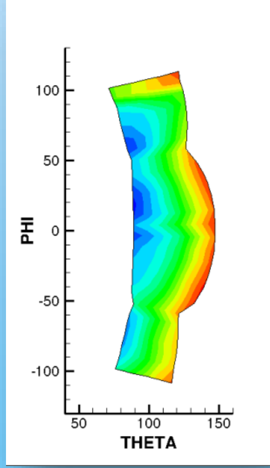


Coordinate Rotation



Unfold

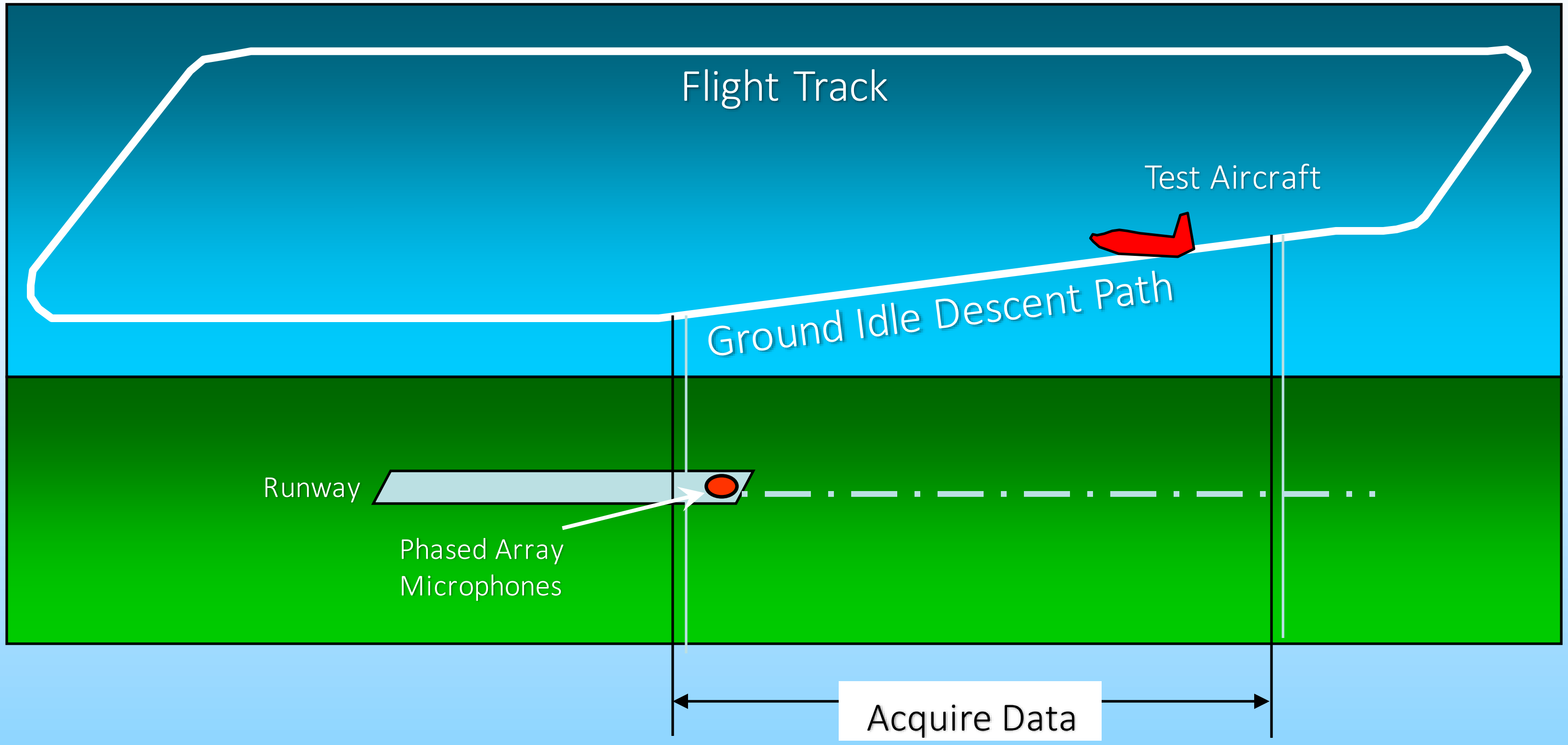


Final Data Product

Hutcheson et al., "Airframe Noise from a Hybrid Wing Body Aircraft Configuration", AIAA 2016-2708

Flight Test
Aeroacoustic Measurements

Flyover Array Testing

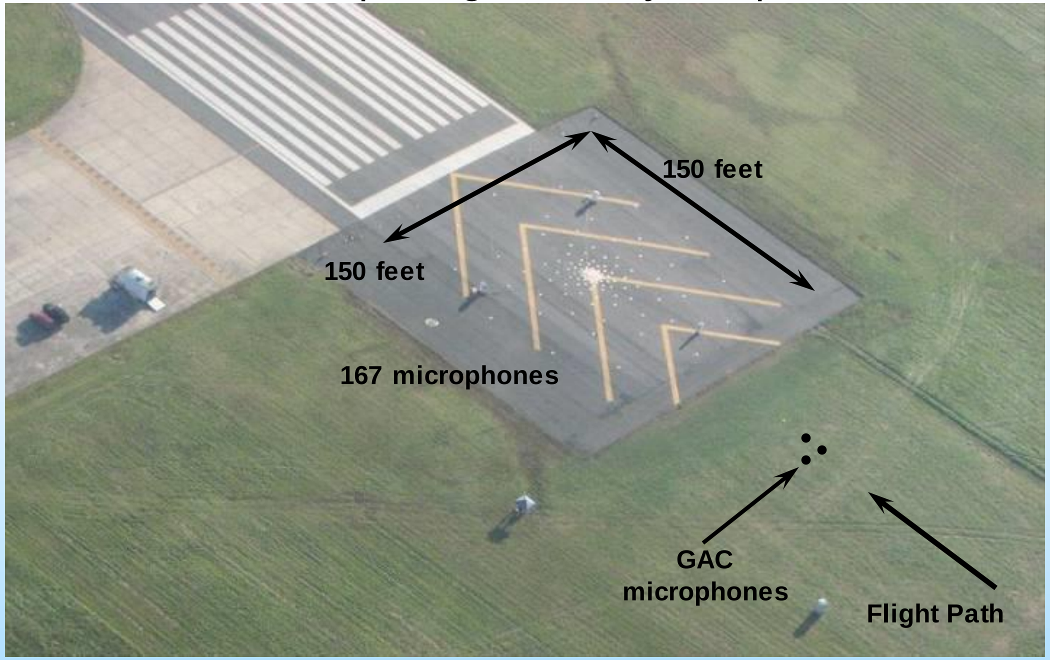


1st Generation Flyover Array System

Gulfstream aircraft (S/N 501)

Runway 4 at WFF

Wallops Flight Facility - September 2006



NASA phased array specifications:

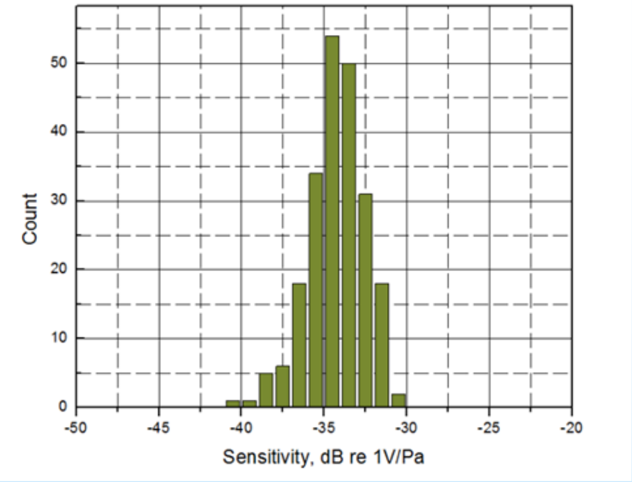
- Nonuniform spiral clustering of 167 microphones
- COTS electret microphones
- Frequency range: 500 Hz - 8 kHz
- Moisture contamination an issue, unwanted microphone sensitivity drift
- No method for performing in-situ calibrations or tracking of sensitivities

Khorrami, et al., "Preliminary Analysis of Acoustic Measurements from the NASA-Gulfstream Airframe Noise Flight Test", AIAA 2008-2814

Improved Array Microphones

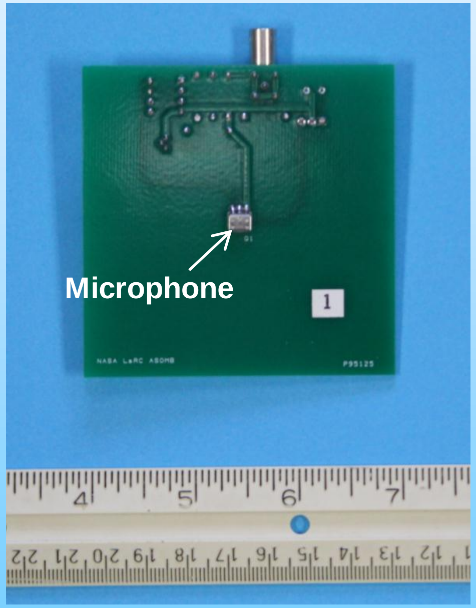
Lessons Learned from 1st Generation Array Testing

- Knowles Acoustic WP-23849 waterproof microphone used as the sensing element
- Two wire, low noise, 4-mA constant current excitation of sensor (LEMO connector)
- Temperature compensated using simple voltage regulator and op amp
- Mounted on 3- by 3-inch printed circuit boards manufactured by Advanced Circuits, Inc.
- Total of 270 completed microphones in stock (185 for array + spares)

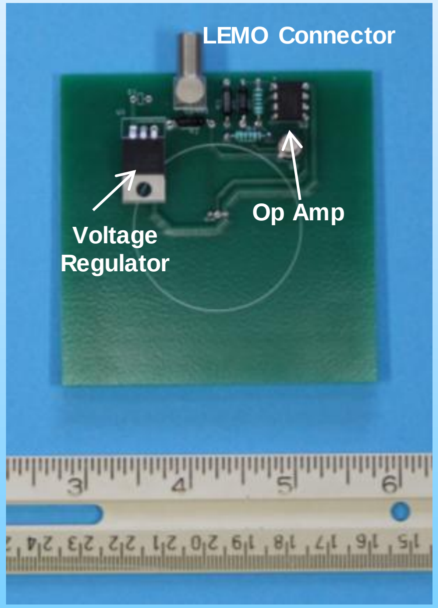


Sensitivity Histogram for Ensemble of Fabricated Units

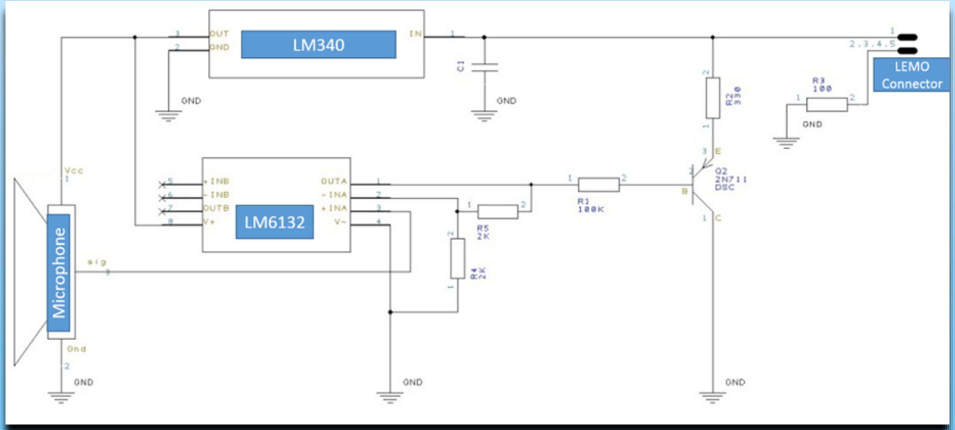
WP-23849 Microphone
Width = 5.54 mm



PCB Front Side



PCB Back Side



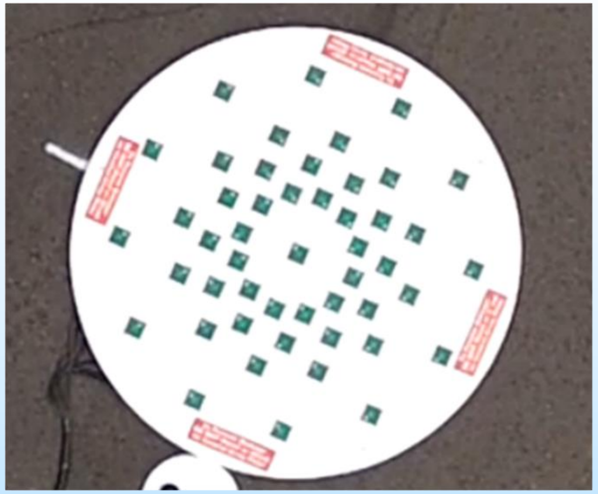
Microphone 4mA Constant Current Receiver Circuit

Humphreys, et al., "Development and Calibration of a Field-Deployable Microphone Phased Array for Propulsion and Airframe Noise Flyover Measurements", AIAA 2016-2898

Improved Microphone Mounts

Central Plate

Aluminum Cutout and Holder



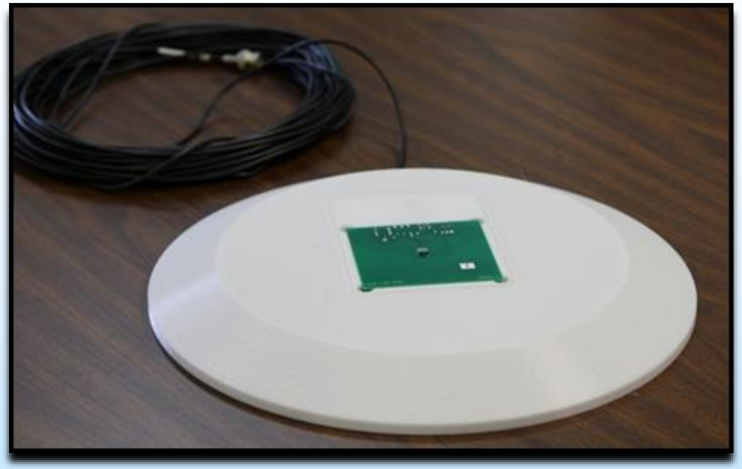
Completed Assembly
(Photo from Field Deployment)

- 72-inch diameter central plate
- Supports inner 49 microphones of array
- Manufactured from machined aluminum honeycomb
- Flush mounted microphones held in place using Velcro
- Cover plate used for moisture / overnight dew protection
- Outer edge treated with foam to minimize scattering

Improved Microphone Mounts
Ground Plates

- Flush mounted microphones held in place using Velcro
- Weighted 6-inch traffic cone used for moisture / overnight dew protection
- Separate 400-foot coaxial cables used to power microphones and route signals to data acquisition system

Central Plate and Ground Plates on Runway at Fort A.P. Hill



2nd Generation Flyover Array System

- Proof of concept test for array
- Multiple fixed-wing sUAS aircraft tested
- Lessons learned were incorporated into the array design

Fort A.P. Hill - August 2015

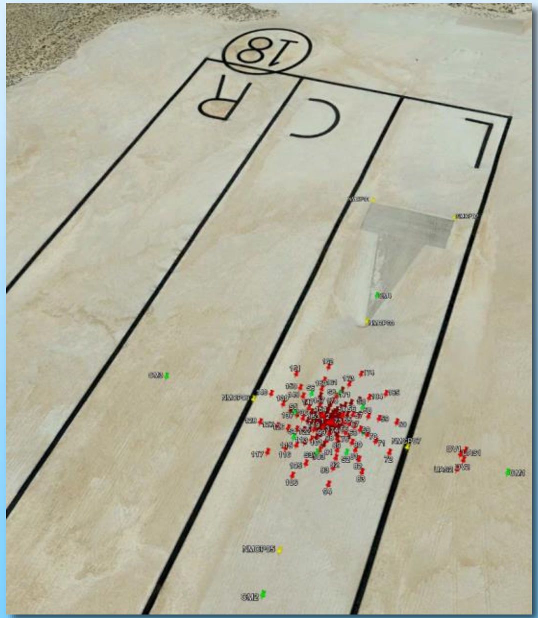
Langley JFLiC sUAS aircraft

NASA phased array specs:

- Starburst pattern of 185 microphones
- Frequency range: 500 Hz - 8 kHz
- Hardened, waterproof microphone packaged in-house

Current Generation Flyover Array System

NASA 804 aircraft - ACTE Flaps



Runway 18L at Edwards

NASA Armstrong (Edwards AFB) – 2016, 2017, 2018

Aerial View of Array on Runway 18L

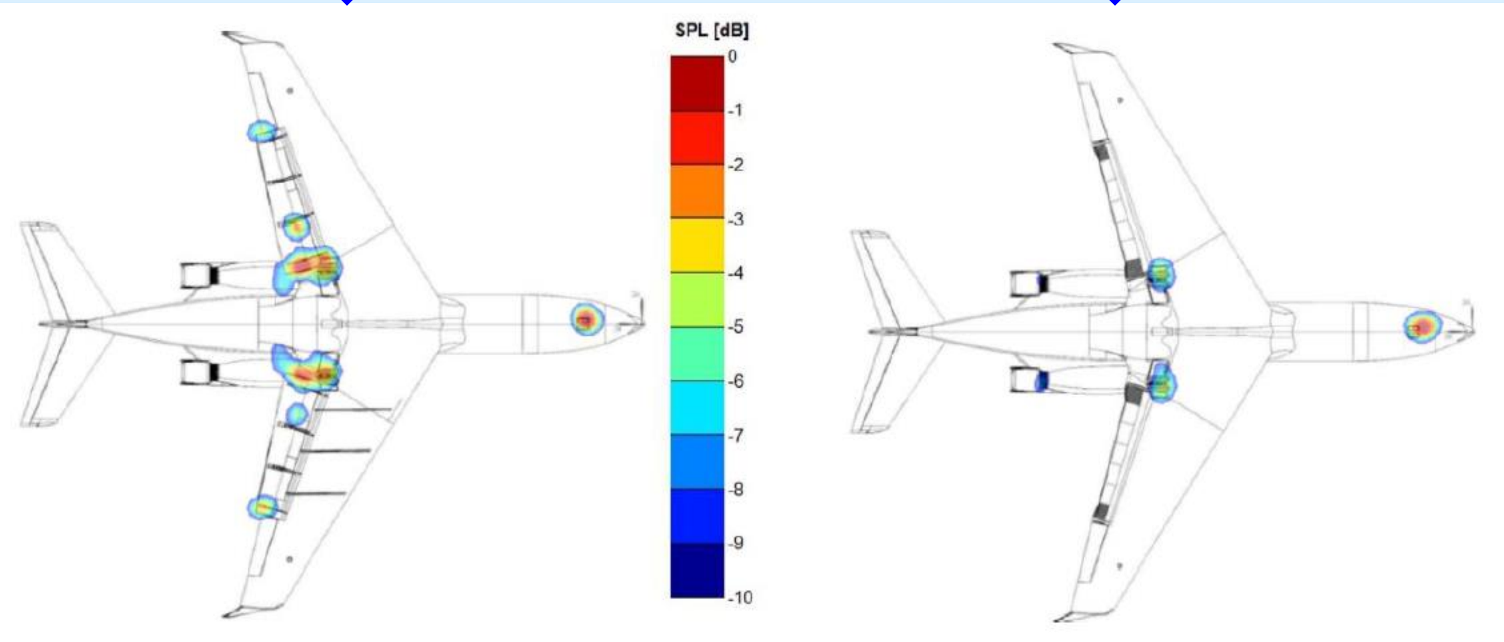
NASA phased array specs:

- Spiral clustering of 185 microphones
- Frequency range: 200 Hz - 8 kHz
- Hardened, waterproof microphone packaged in-house

Data Product Example from Flyover Array System

NASA Armstrong (Edwards AFB) – 2016, 2017, 2018

Gulfstream G3 Aircraft



Baseline Measurements

With Noise Treatments Added

Khorrami, et al., "Flight Test Evaluation of Airframe Noise Mitigation Technologies", AIAA 2018-2972

Flyover Array Health Monitoring

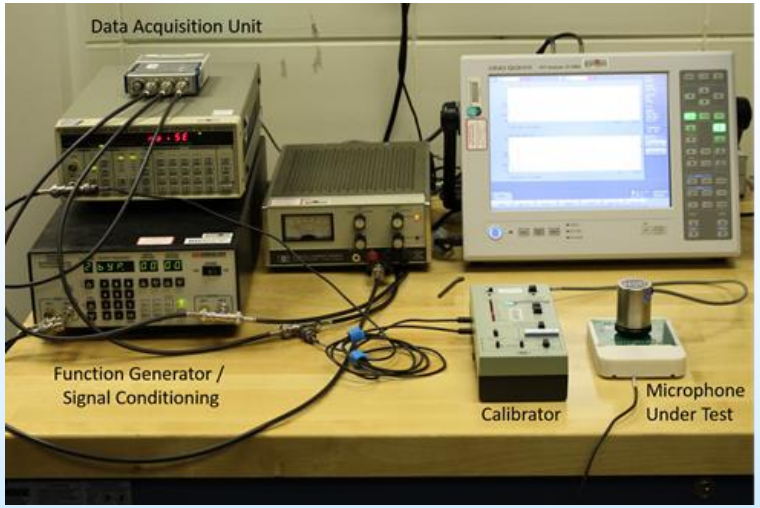
Array Health Monitoring
Why Needed

- Extreme environment on lakebed at Edwards
- Large temperature swings in August (60 – 110 deg F)
- Very low humidity (< 10% at times)
- Dusty environment
- High solar flux during day

With multiweek deployments of array, it is necessary to monitor changes in array performance and sensor health at regular intervals

Calibration Methods and Array Health Monitoring

- Benchtop calibrations
  - Before and after deployments
- Aerial sound sources for health monitoring
  - A.P. Hill and Edwards AFB
- Ground sources for health monitoring
  - Edwards AFB



Aerial Sound Source

Ground Source

Aerial Sound Sources for Array Health Monitoring

	Mark I ACV	Mark II ACV
sUAS Type	Multi-Rotor, 6 Brushless Motors	Multi-Rotor, 8 Brushless Motors
Manufacturer	Prioria Robotics	DJI
Diagonal Length	31 inches	41.1 inches
Maximum Weight	16.6 lbs	24.3 lbs
Landing Rails	Fixed	Retractable
Speed	0 – 23 knots	0 – 42.5 knots
Endurance	25 minutes	15 minutes
Command and Control	Remote Control Ground Station	Remote Control Ground Station
Sound Source Payload	Anchor MiniVox Lite PA Speaker	Anchor MiniVox Lite PA Speaker

Mark I ACV at Fort A.P. Hill

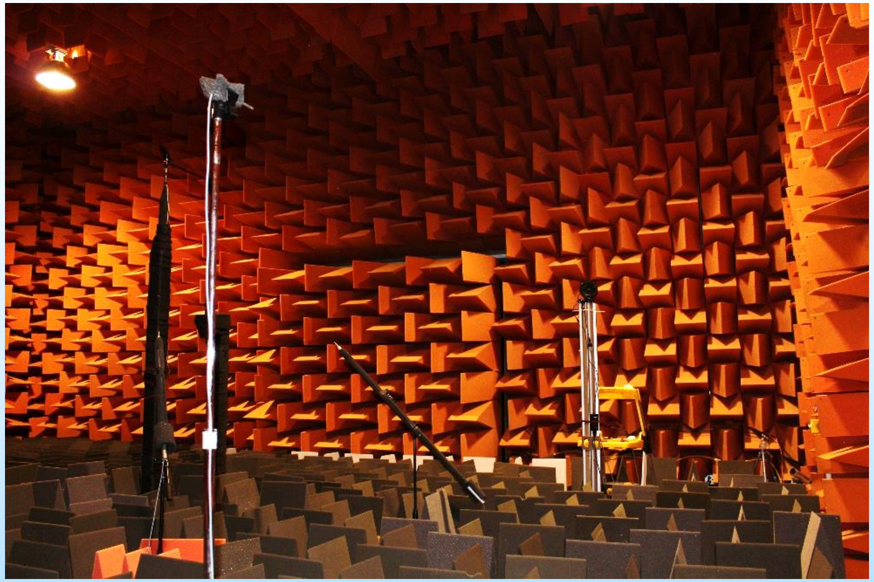
Mark II ACV at Edwards AFB

Array Health Monitoring Procedure

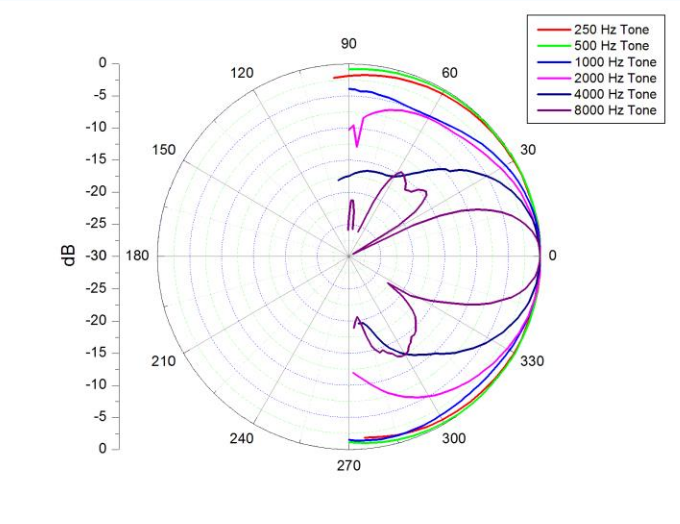
- Wave files developed to excite the speaker with white noise and tones spanning 1 – 8 kHz
- Calibrations performed with vehicle at altitudes spanning 50 – 400 feet
- Goal is to monitor microphone sensitivities on a daily basis by recording signal levels as a function of speaker excitation and vehicle altitude
- Challenge is to account for effects of speaker directivity, vehicle movement, atmospheric propagation, wind, and variable rotor noise

Array Health Monitoring

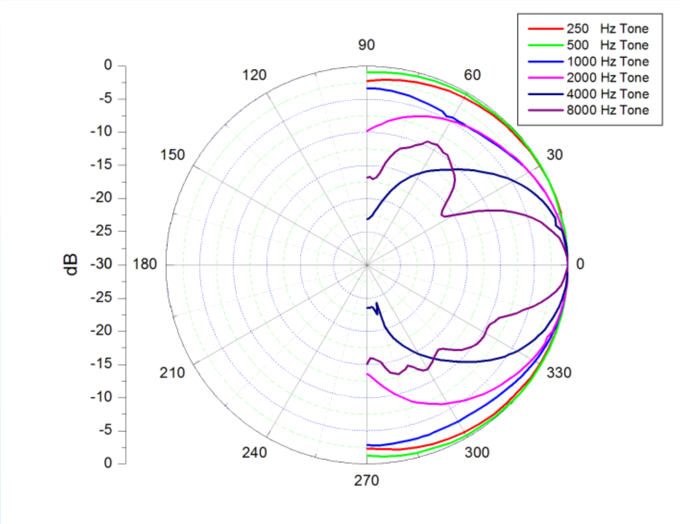
Aerial Sound Source Characteristics



Directivity Testing in Langley SALT Facility



Polar Directivity versus Frequency



Azimuthal Directivity versus Frequency

Directivity Correction:

$$\Delta dB_i = \frac{P_\theta(\alpha_i) + P_\varphi(\alpha_i)}{2}$$

$$\alpha_i = sin^{-1}\left(\frac{r}{d}\right)$$

Predicted dB Loss at Edge of Array Due to Sound Source Directivity

	Altitude = 100 feet		Altitude = 200 feet		Altitude = 400 feet	
Frequency (Hz)	Polar dB Loss	Azimuthal dB Loss	Polar dB Loss	Azimuthal dB Loss	Polar dB Loss	Azimuthal dB Loss
250	0.1	0.05	0.04	0.01	0.01	0.004
500	0.1	0.07	0.05	0.04	0.04	0.03
1000	0.8	1.1	0.2	0.4	0.1	0.2
2000	1.3	1.0	0.6	0.3	0.2	0.2
4000	2.2	2.1	0.6	0.5	0.3	0.1
8000	8.6	6.8	1.8	1.8	0.6	0.6

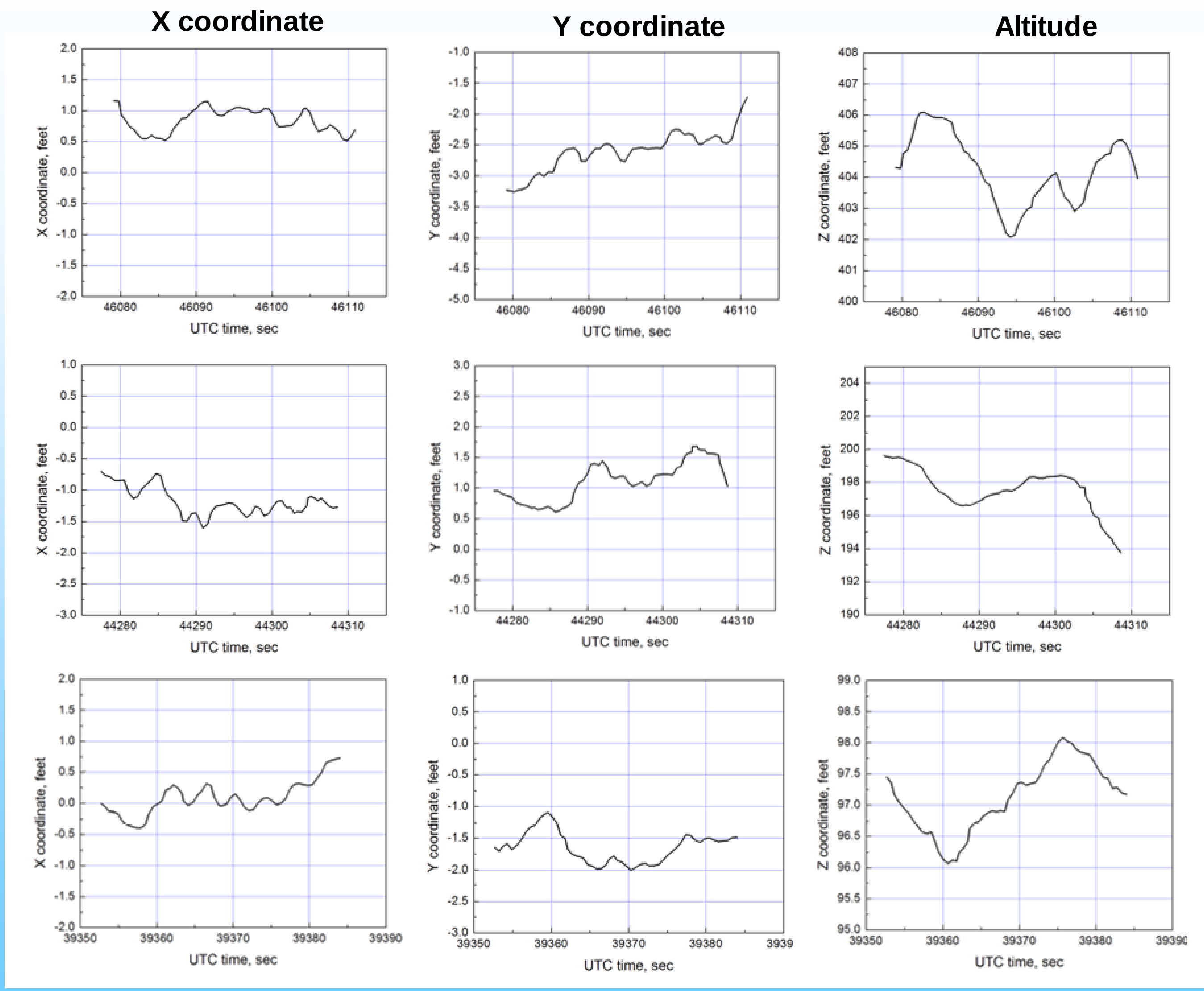
Array Health Monitoring

Representative Vehicle GPS Tracking Data

Altitude = 400 feet

Altitude = 200 feet

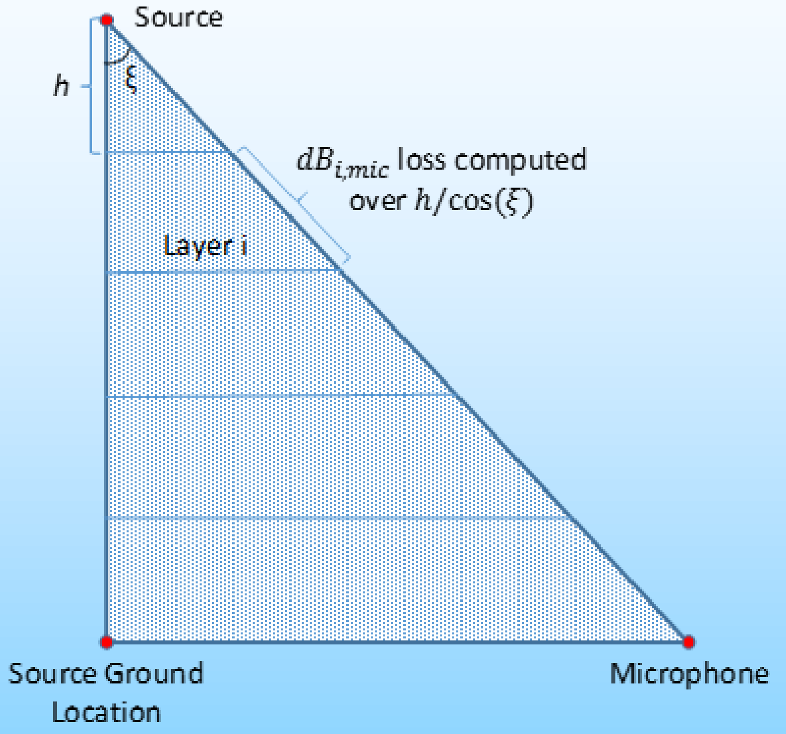
Altitude = 100 feet



Data Corrections

Atmospheric Attenuation

- Layered correction approach to account for inversions and other atmospheric effects
- Atmosphere stratified into levels each with height *h*
- Local attenuation computed across each level using weather profiling data from radiosonde balloon
- Losses summed to achieve total correction



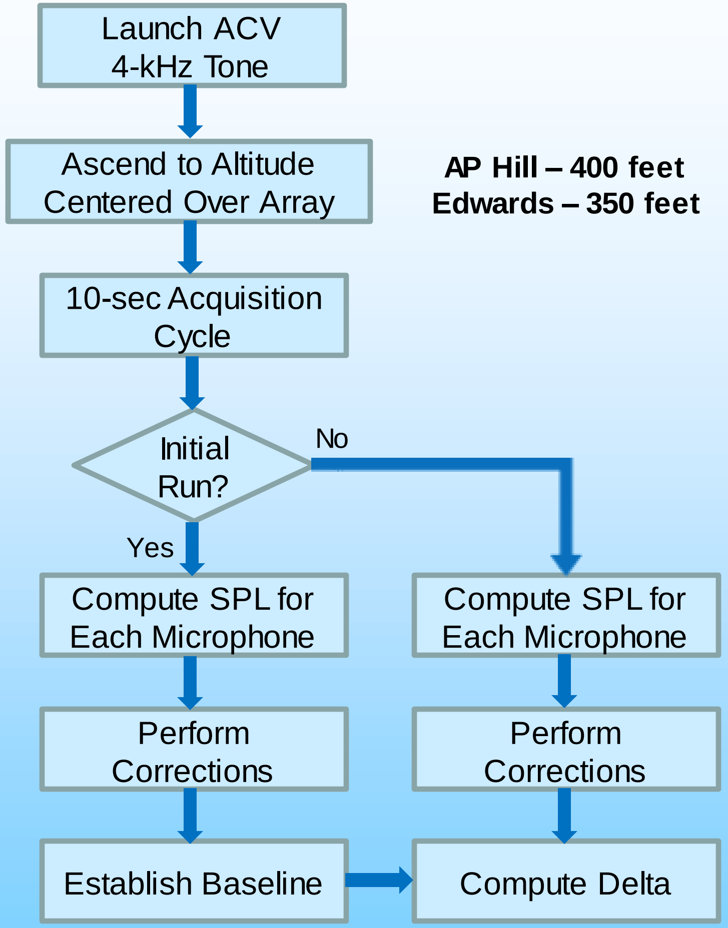
$$dB_{total,mic}(f) = \sum_{i=1}^{n} dB_{i,mic}(f, T_i, H_i, d_i)$$

True, H.C., "The Layered Weather Correction for Flyover Noise Testing", AIAA 1976-0895

Aerial Sound Sources - Mark II ACV at Edwards

Health Monitoring Strategy

Aerial Sources

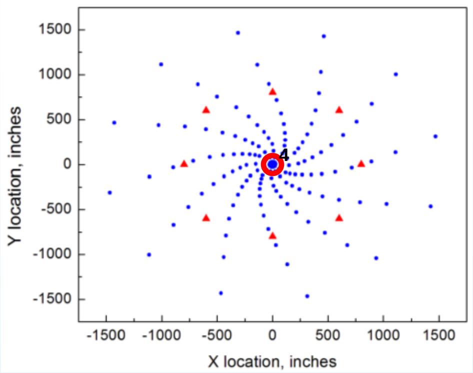


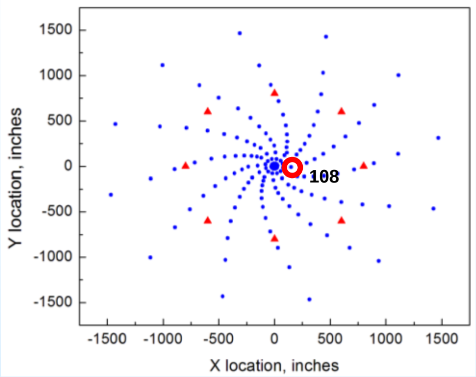
AP Hill – 400 feet
Edwards – 350 feet

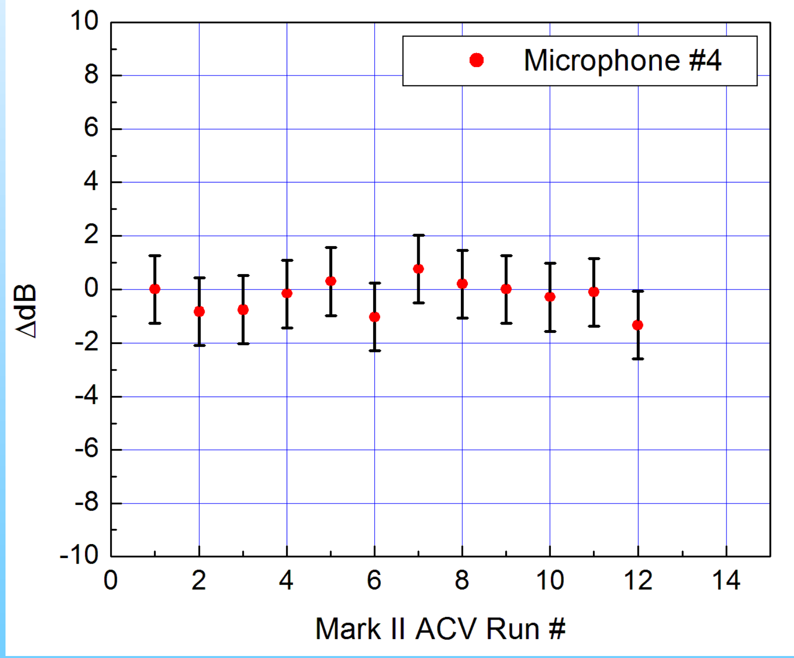
$$\Delta dB_{mic} = \left(dB_{mic} - dB_{ref}\right)_{calibration} - \left(dB_{mic} - dB_{ref}\right)_{baseline}$$

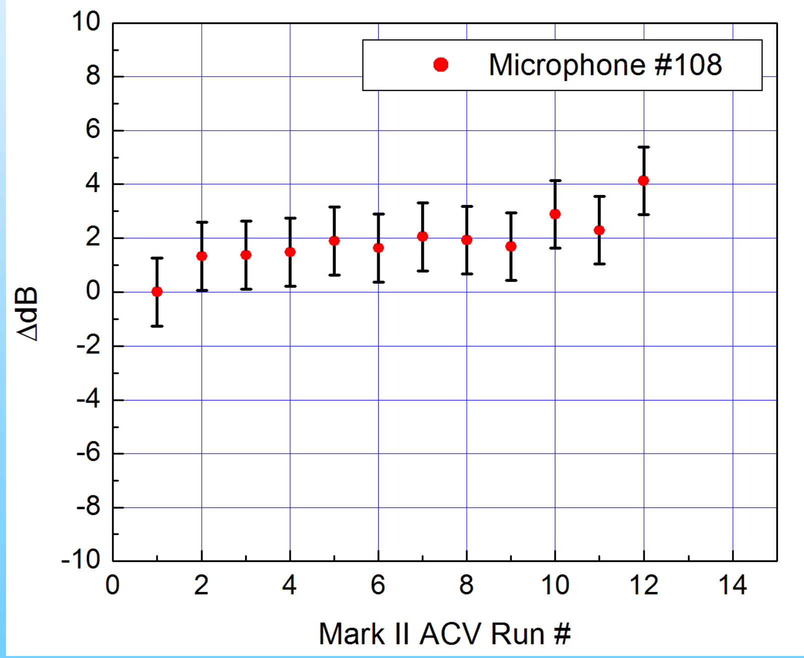
Health Monitoring Examples – Edwards AFB

Mark II ACV







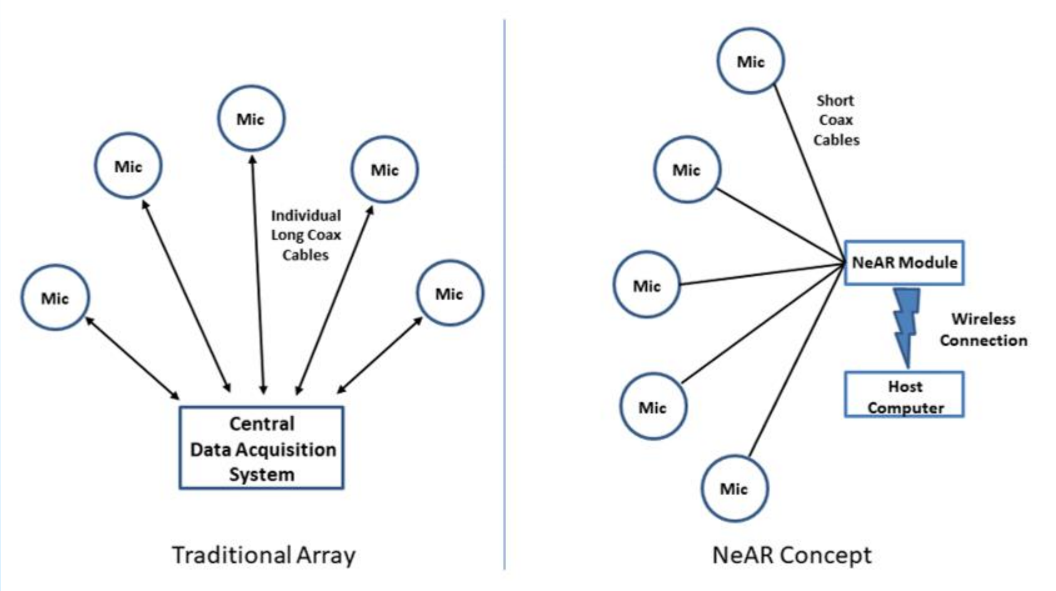


Humphreys, et al., "Evaluation of Methods for In-Situ Calibration of Field-Deployable Microphone Phased Arrays", AIAA 2017-4176

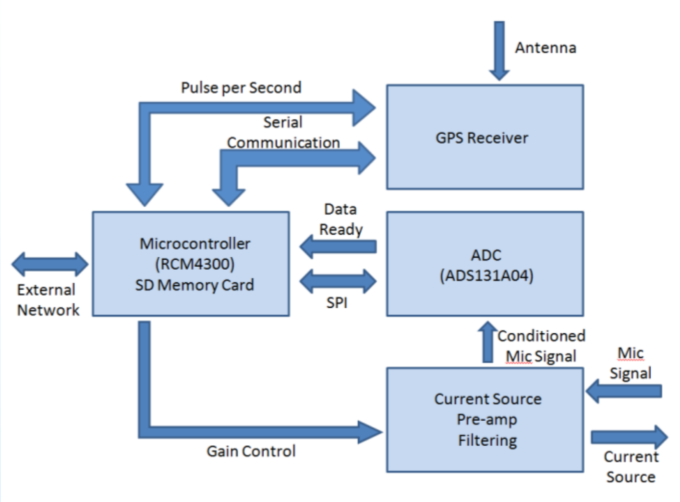
Current Research Areas

Current Research Areas

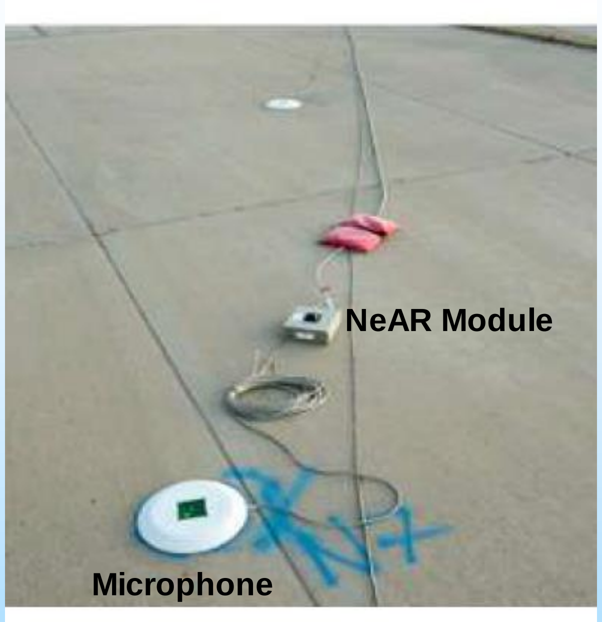
- Development of wireless sensor and edge computing technologies for outdoor arrays



Networked Array Recorder (NeAR) System



NeAR Module



Proof of Concept
Test at Edwards AFB

Goal → Reduce array setup complexity by eliminating miles of interconnect cabling (74,000 feet of cabling required for Edwards array)

Culliton et al., "Networked Array Recorder (NeAR) Microphones for Field-Deployed Phased Arrays", AIAA 2019-3290

Summary

- Microphone phased arrays are now the primary sensor system for obtaining noise source location and strength data on various wind tunnel models
- Advanced array processing has enabled the development of high-resolution techniques (e.g., DAMAS) for pinpointing noise radiation sources on models
- Multiple NASA facilities at Ames, Glenn, and Langley routinely use microphone array technology for aeroacoustic ground testing
- Use of phased array systems is increasing for flyover noise testing of aircraft
- Long-duration outdoor deployments requires the development of health monitoring strategies for the sensors – two techniques have been developed
- Current research areas:
  - Development of wireless sensor technologies for outdoor arrays

Acknowledgments

LaRC 14x22 HWB Testing

Small Army of Folks
Required For Array Testing

Fort A.P. Hill Testing

NASA Armstrong (Edwards) Testing