

# **Airframe Noise Flight Test Measurements Using an Electret Condenser Microphone Array**

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# Outline

- **Flight Test Overview**
- **Test Matrix**
- **Array Instrumentation**
- **Beamforming Results**
- **Spectral Comparisons**
- **Lessons Learned**
- **Summary**
- **References**



# Flight Test Overview

*Objective: Acquire baseline AFN measurements on a regional jet class of transport*

- **Gulfstream G450 and G550 aircraft**
- **Flight testing performed at NASA Wallops Flight Facility on the Eastern Shore of Virginia**
- **Measurements acquired using NASA electret microphone phased array and Gulfstream certification microphones**
- **Unique feature of this study was the acquisition of airframe noise data on isolated components and combinations of components (component interaction)**
- **Only G550 array measurements are shown here**

# Gulfstream G550



*Photo courtesy of Gulfstream*

- **Wing Span: 93.5 feet**
- **Flap Span: 25.6 feet**
- **MGTW: 91,000 lb**
- **Comparable wing span to Boeing 737-300**

# Test Matrix

- **Airspeed: 132, 147, 170, 200 kts**
- **Flap Deflection: 0, 20, 39 degrees**
- **Landing Gear: retracted, fully deployed, nose only, main only**

Flap Deflection	Gear Position	Airspeed ~KCAS	No. of Flights
0	Up	147	4
0	Up	170	3
0	Up	200	3
0	Main only	132	2
0	Main only	147	2
0	Main only	170	2
0	Nose only	132	2
0	Nose only	147	2
0	Nose only	170	2
0	Full gear	147	4
20	Up	147	3
20	Main only	147	2
39	Up	132	3
39	Up	147	4
39	Up	170	3
39	Main only	147	2
39	Nose only	147	2
39	Full gear	132	3
39	Full gear	147	4
39	Full gear	170	3
<b>Total</b>			<b>55</b>

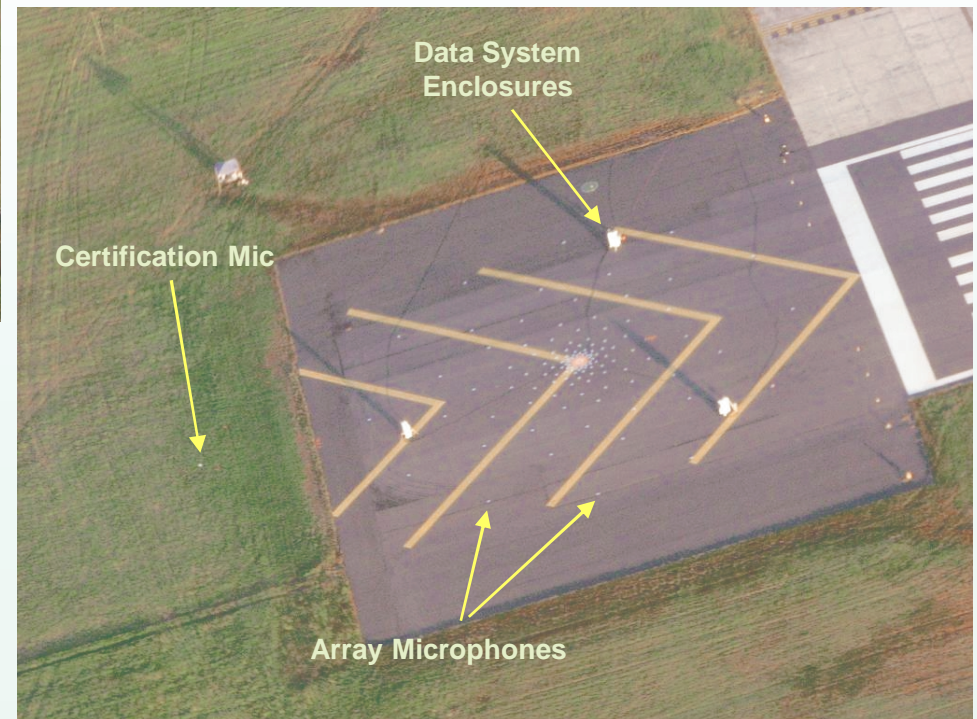


# Testing Site – NASA Wallops



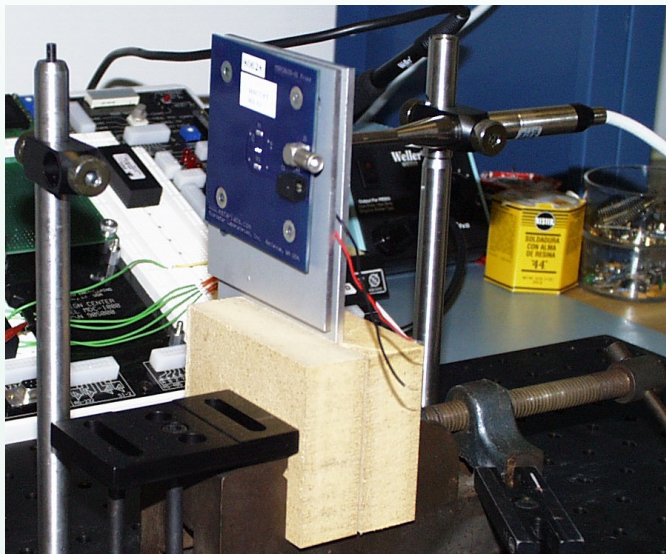
WFF Runway 4 Threshold Area

## Closeup of Overrun Area and Instrumentation

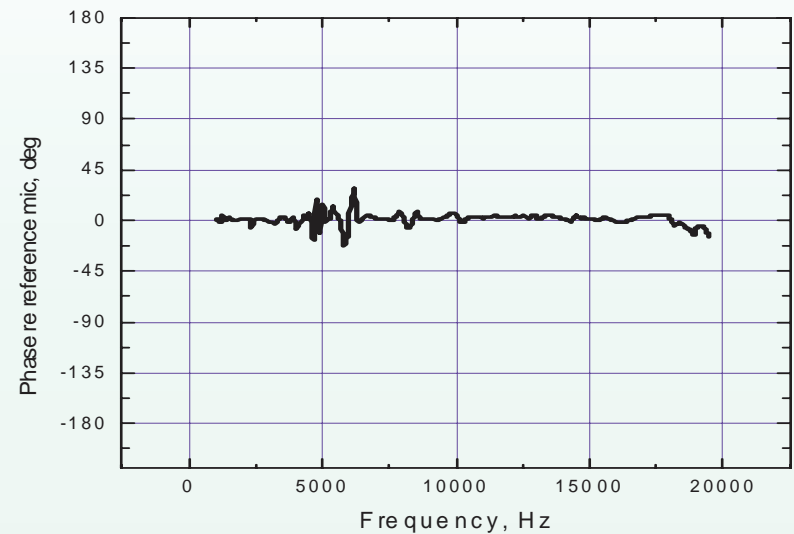
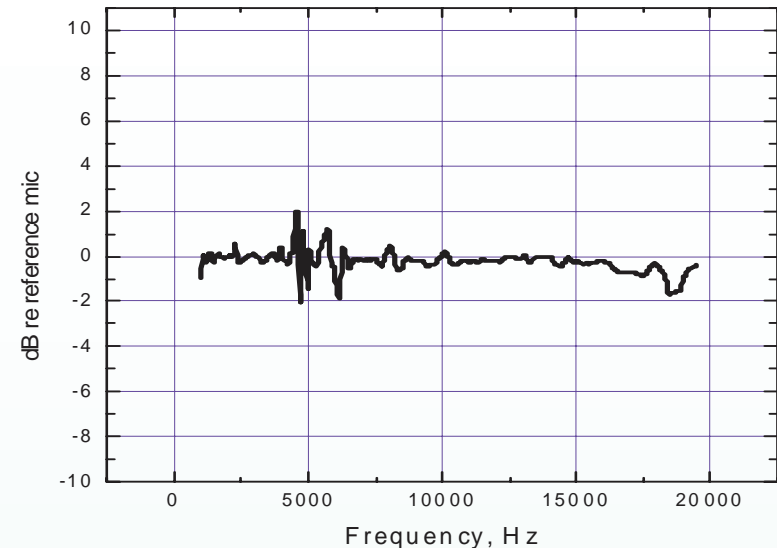


# Array Microphones

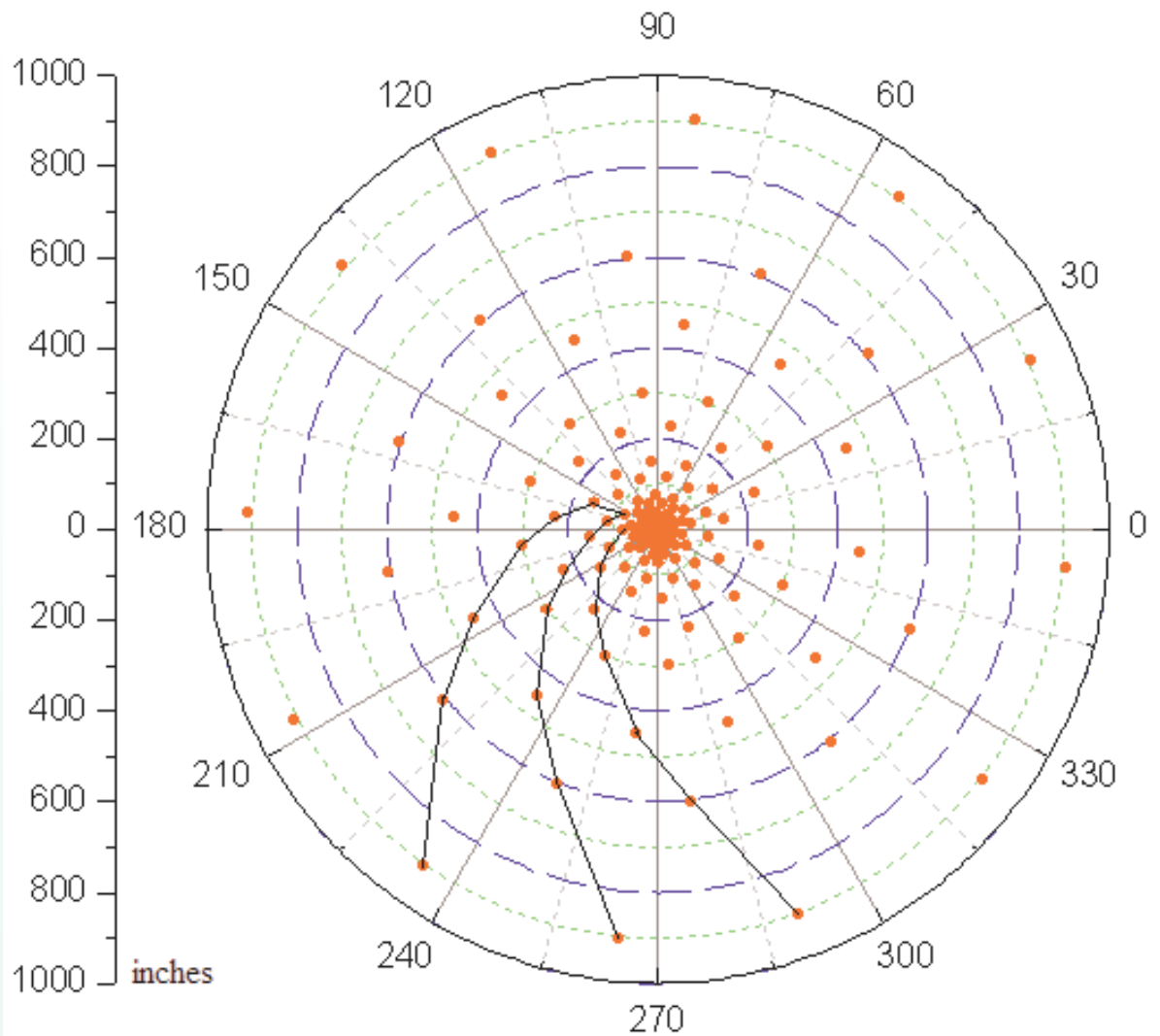
- Commercial Panasonic WM-61A sensors
- Originally used for wake vortex acoustic measurements at Denver airport in 2003
- Nominal sensitivity of 15 mV/Pa
- Flat frequency response to 15 kHz
  
- All microphones calibrated in lab pre- and post-test
- Piezo-electric cavity calibration



Piezo-electric Cavity Calibrator

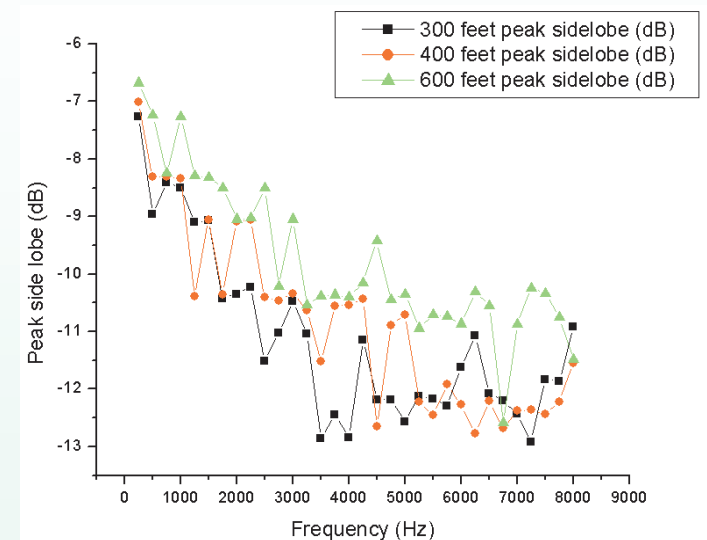


# Array Design



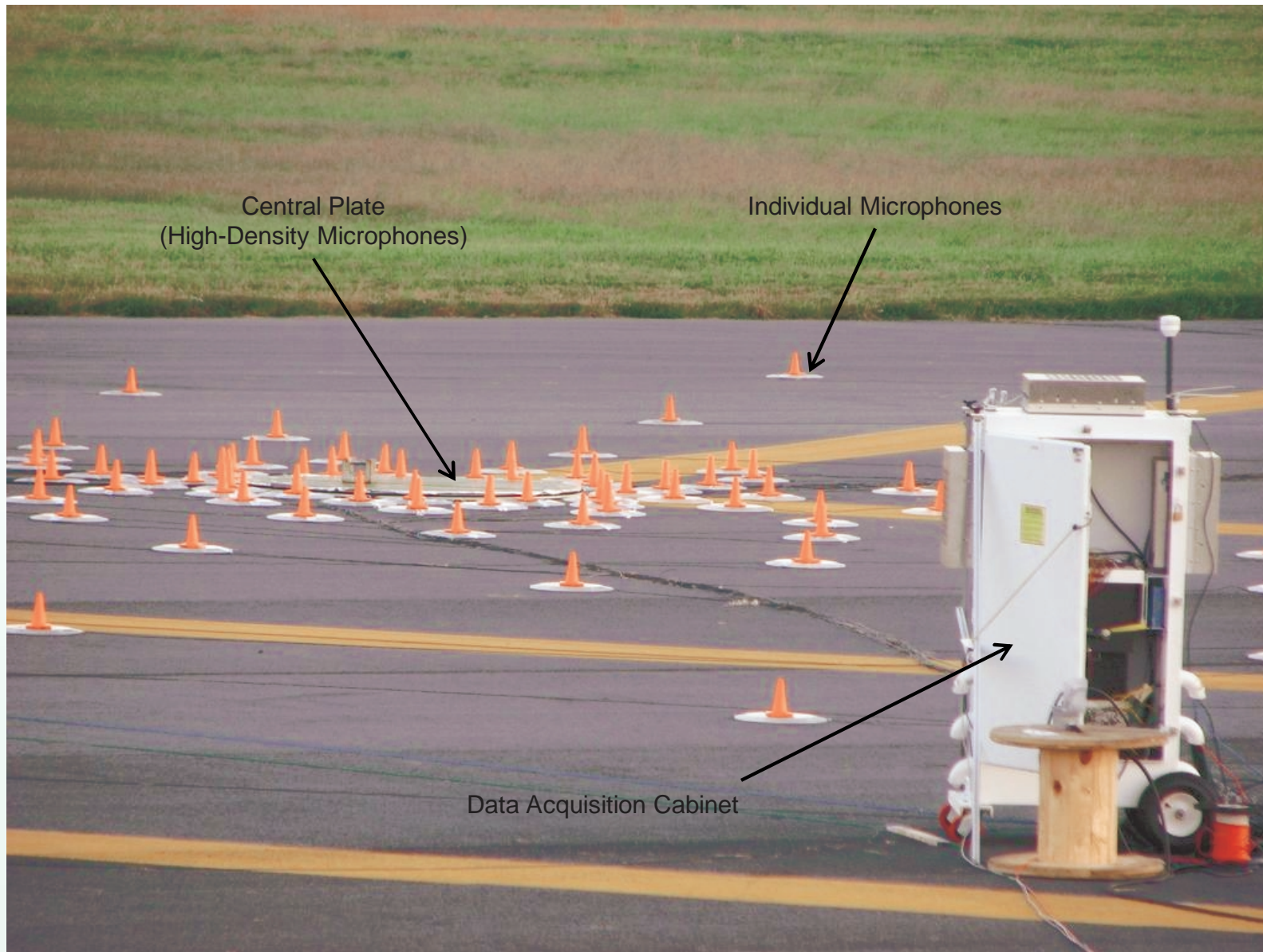
Array Pattern

- 167-channel array
- 12 spiral arms



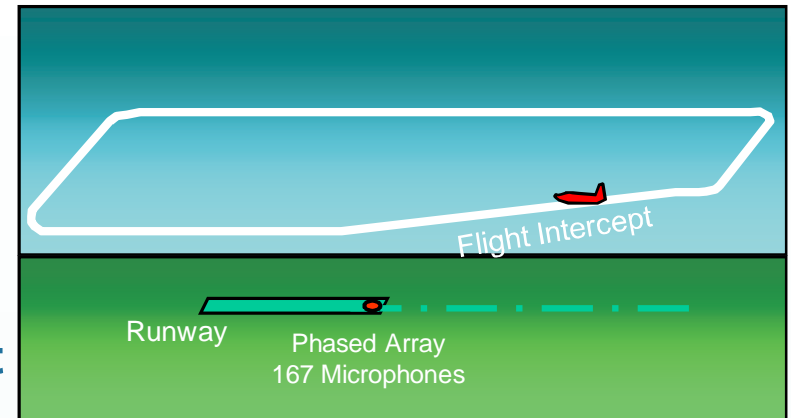
Peak sidelobe level versus frequency

# Array Deployment



# Data Acquisition

- Racetrack flight pattern
- Aircraft flight parameters synchronized with array data system via differential GPS
- Array acquisition cycle triggered when aircraft passed visual reference marker
- Typical acquisition duration - 30 seconds
- Array sampling rate - 76.8 kHz
- Array analog bandwidth - 30 kHz
- Atmospheric conditions sampled once per minute using a ground weather station (25 foot altitude) and once per hour using a tethered weather balloon (500 foot altitude)



# Beamforming Algorithm

- Algorithm is a modification of one developed by Boeing
- Conventional time-domain delay and sum approach:

$$b_{TD}(\mathbf{x}_m) = \frac{1}{T} \int_0^T \left[ \sum_{i=0}^{N-1} p_i(t - \tau_{im}) \right]^2 dt = \left\langle \left[ \sum_{i=0}^{N-1} p_i(t - \tau_{im}) \right]^2 \right\rangle$$

- De-Dopplerization and resampling performed on time history data
- Array aperture was inversely weighted as a function of frequency
- Direct Fourier Transform (DFT) used to convert to frequency domain
- 81 x 81 (6561-point) planar grid covering 130 feet on a side
- Results scaled to 394-foot aircraft altitude and corrected for wind drift and atmospheric absorption

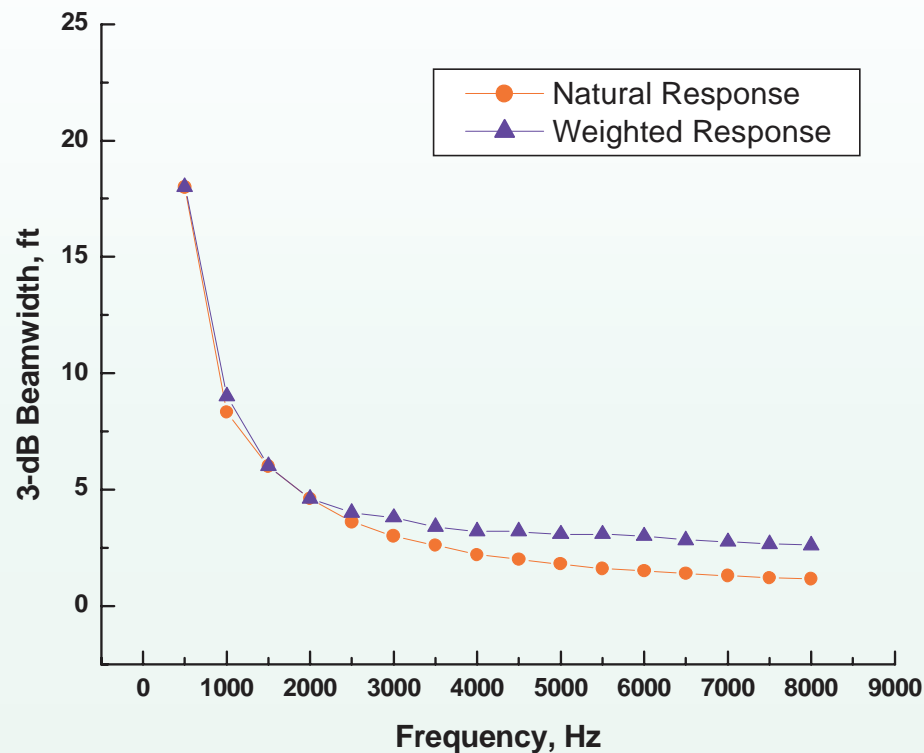
# Array Weighting

- Simple hyperbolic tangent function:

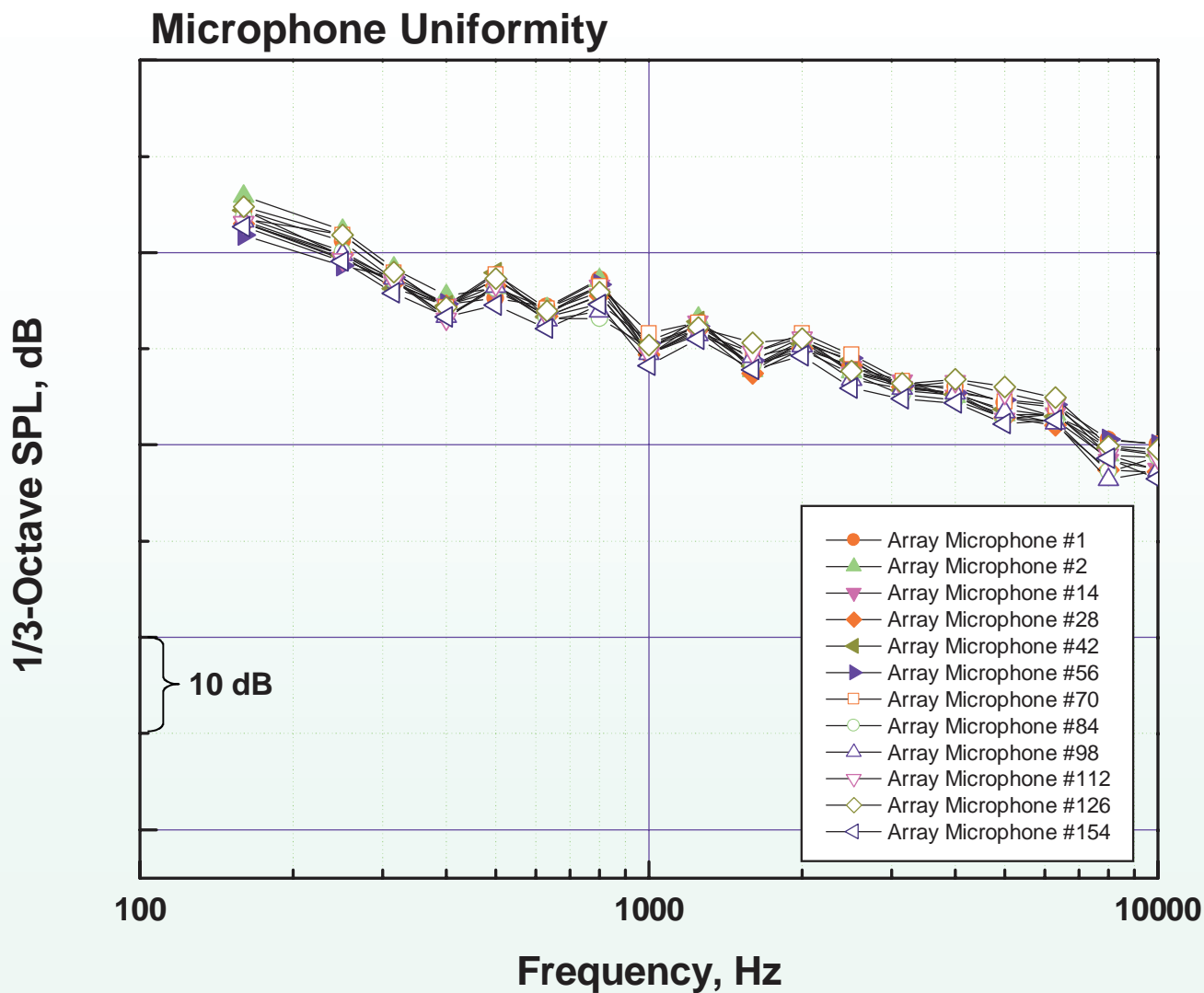
$$W(f, r) = 1.0 - \frac{1}{2} [1.0 + \tanh[0.000025(f * r - 200000.0)]]$$

where  $f$  = beamform frequency,  $r$  = microphone radius

- Used to maintain approximate 3-foot beamwidth above 2 kHz



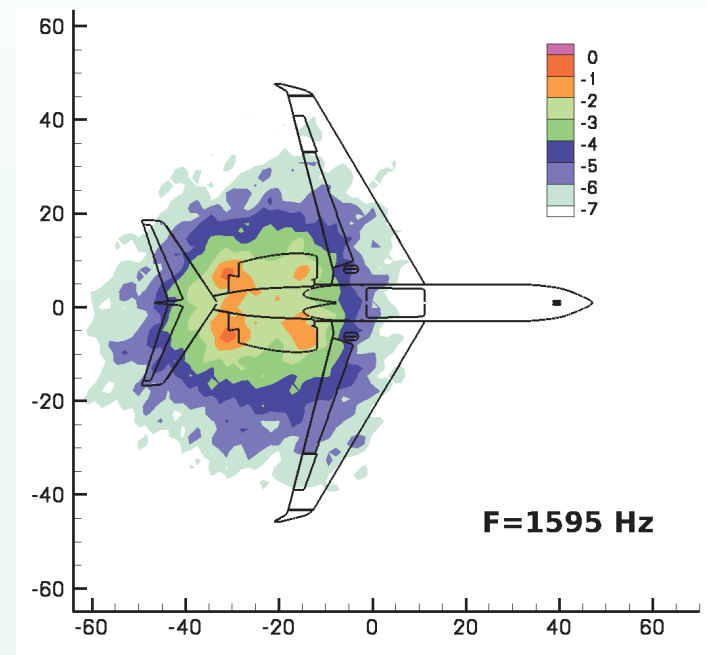
# Array Sensor Performance



# Beamform Contours

## Clean Configuration

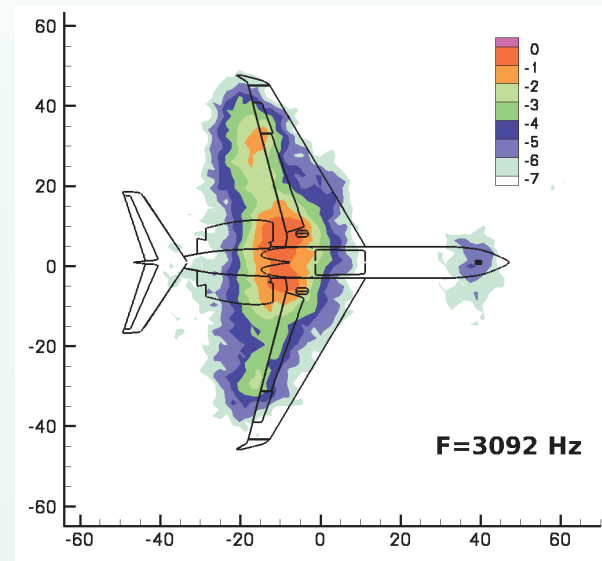
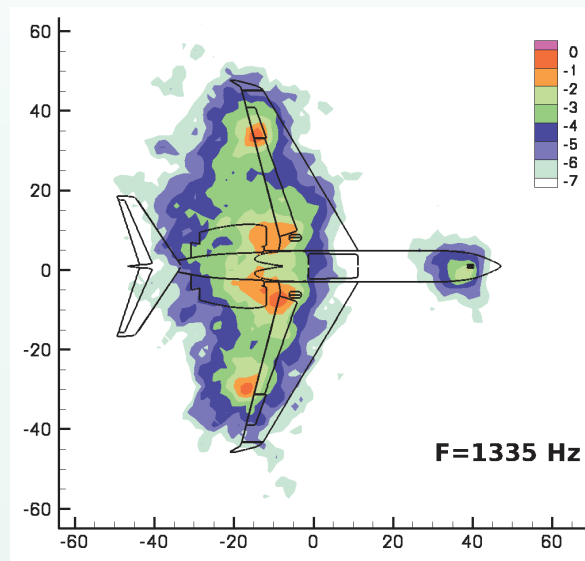
- Flaps and Gear Retracted
- Airspeed 147 kts



# Beamform Contours

## Landing Configuration

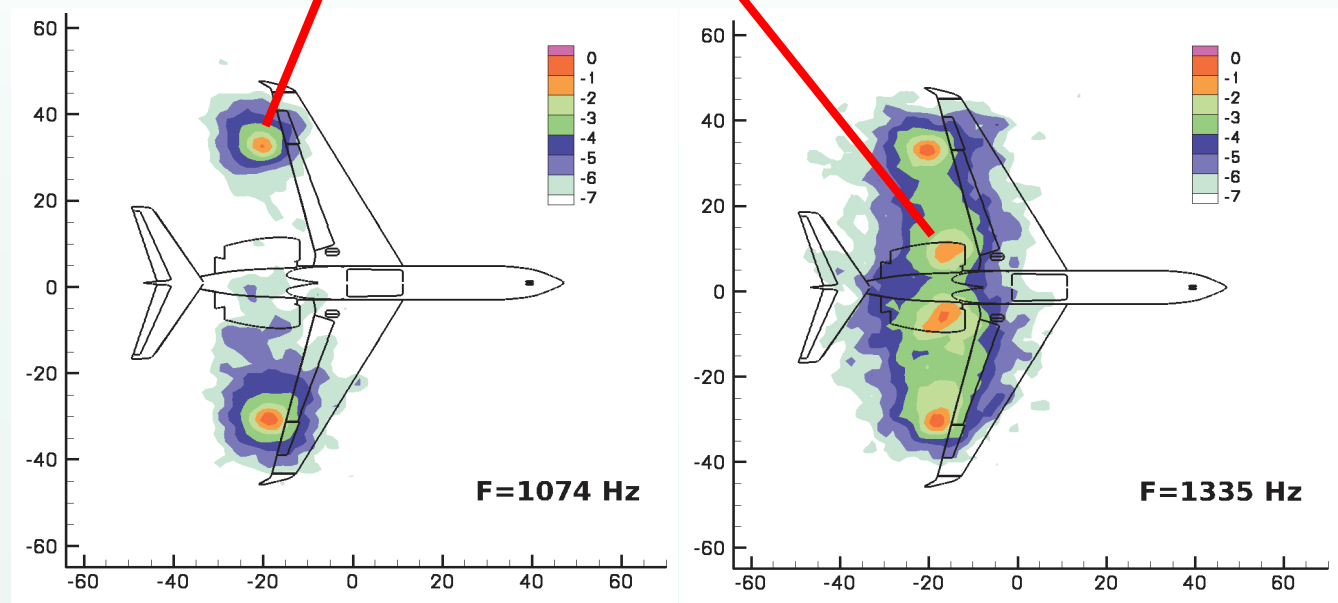
- Full Flaps and Gears
- Airspeed 147 kts



# Beamform Contours

## Flaps Only

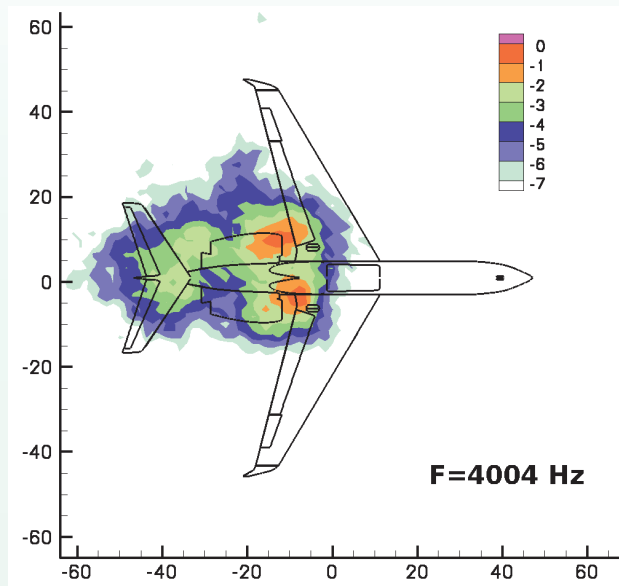
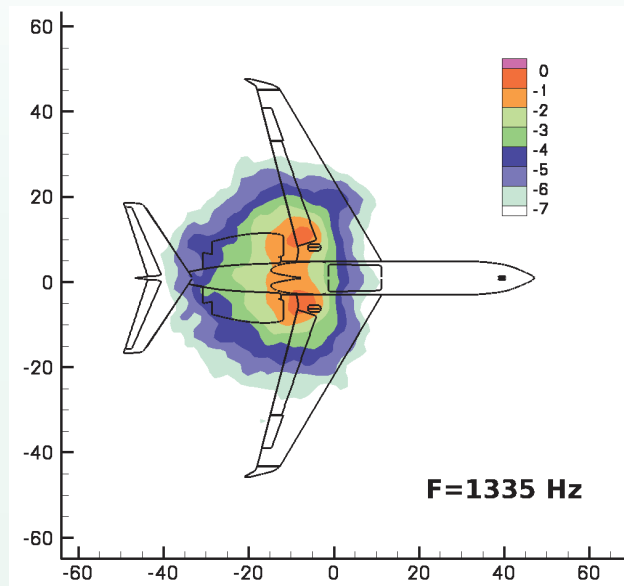
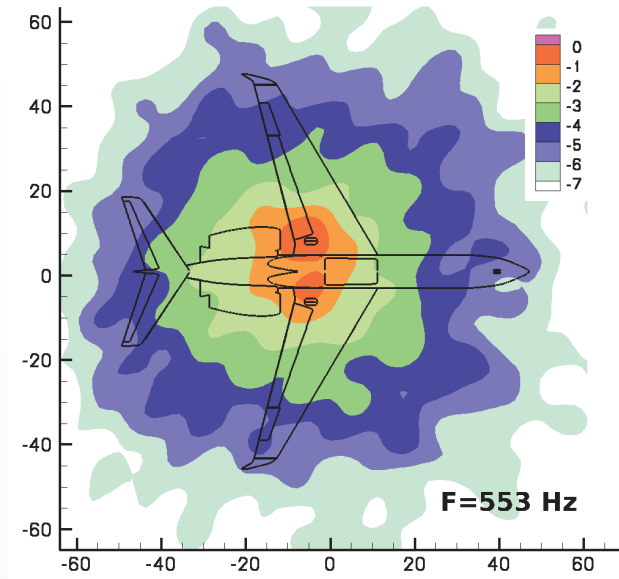
- Flaps at 39 degrees
- Airspeed 147 kts



# Beamform Contours

## Main Gear Only

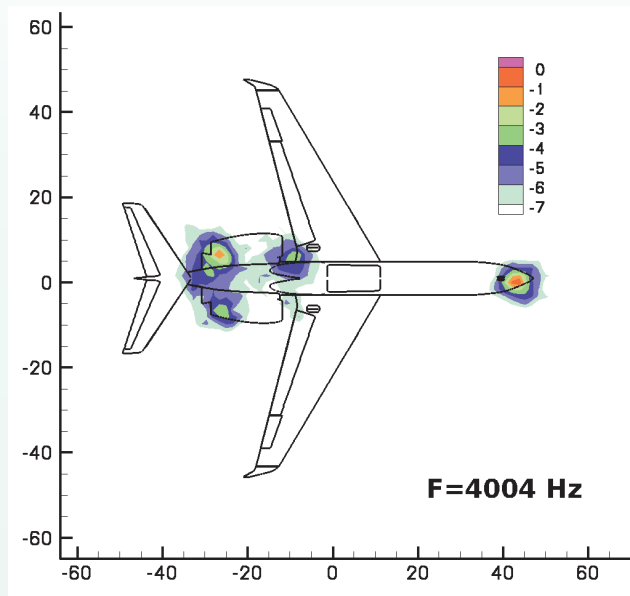
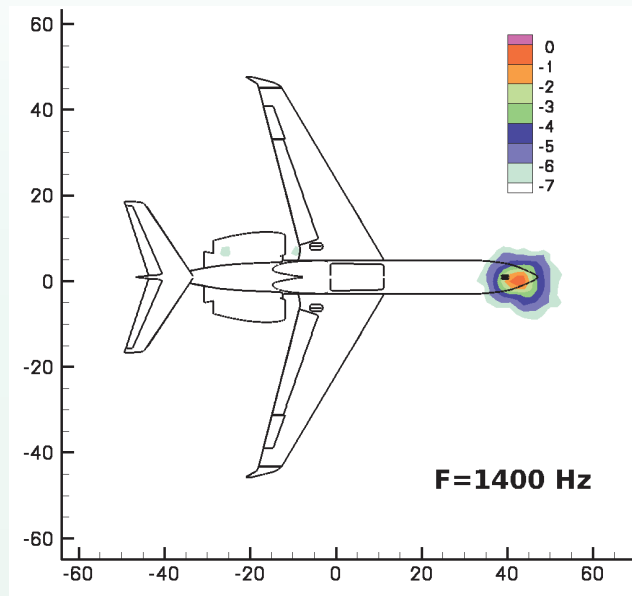
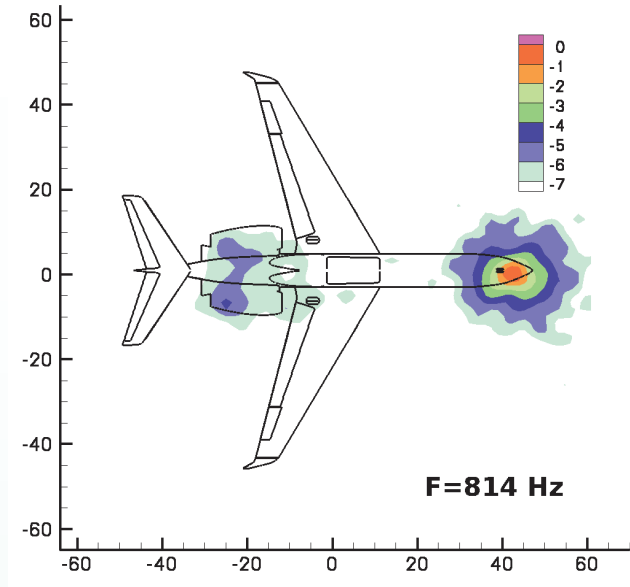
- Airspeed 147 kts



# Beamform Contours

## Nose Gear Only

- Airspeed 147 kts



# Source Integration Analysis

$$P_T = \sum_{l=l_L}^{l_U} \sum_{n=n_L}^{n_U} [P_{l,n} / C_{l,n}]$$

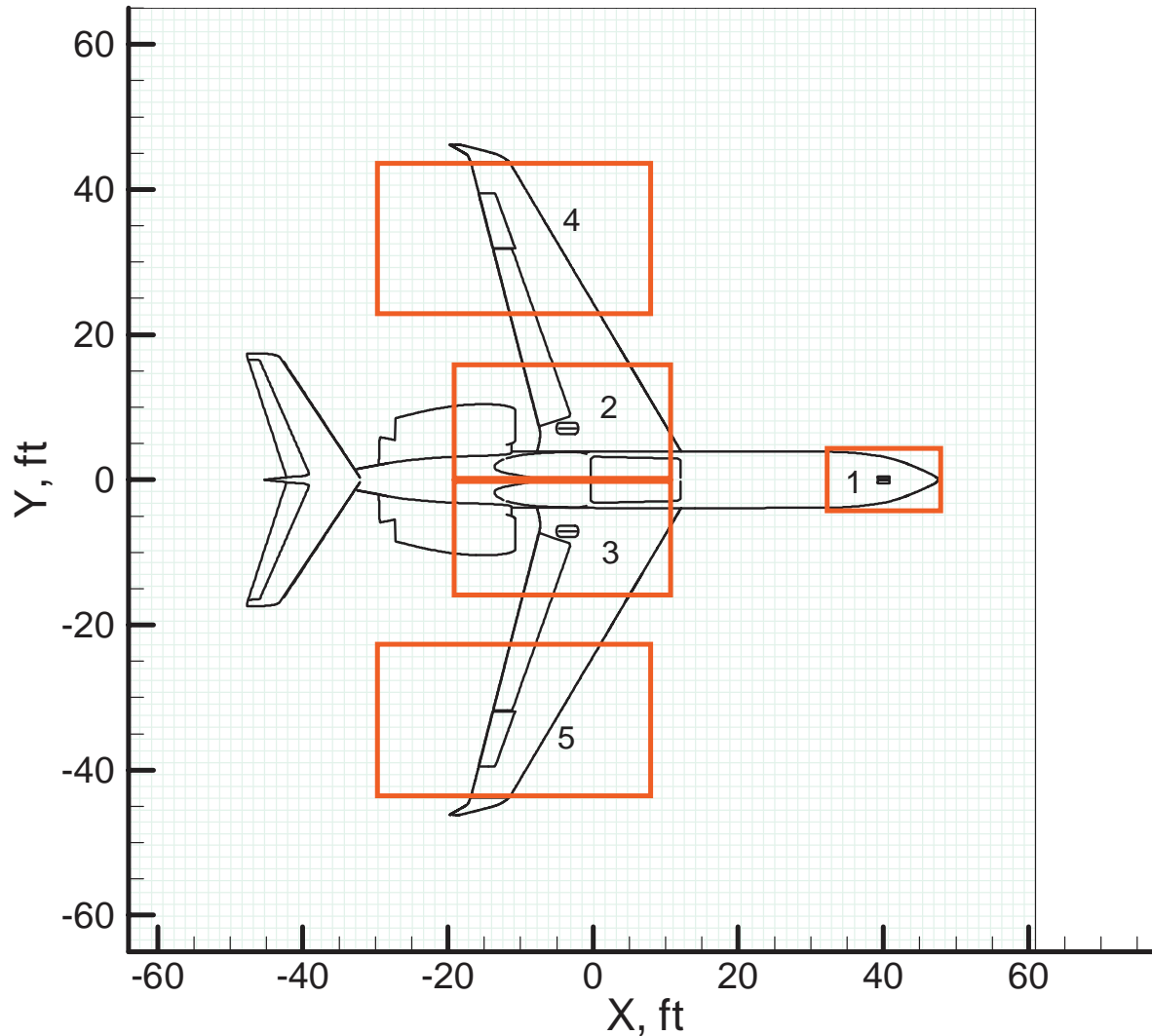
$$C_{l,n} = \left[ \sum_{l'=l'_L}^{l'_U} \sum_{n'=n'_L}^{n'_U} Q_{l',n'} \right]_{l,n}$$

$$Q_{l',n'} = \left[ \frac{\hat{e}^T \hat{W} \hat{G}'_{l,n} \hat{W}^T \hat{e}}{\left( \sum_{m=1}^{m_0} w_m \right)^2} \right]_{l',n'}$$

$$\hat{G}'_{l,n} = \begin{bmatrix} (e_1^* e_1)^{-1} & (e_1^* e_2)^{-1} & \cdots & (e_1^* e_{m_0})^{-1} \\ & (e_2^* e_2)^{-1} & & \vdots \\ & & \ddots & \vdots \\ & & & (e_{m_0}^* e_{m_0})^{-1} \end{bmatrix}_{l,n}$$

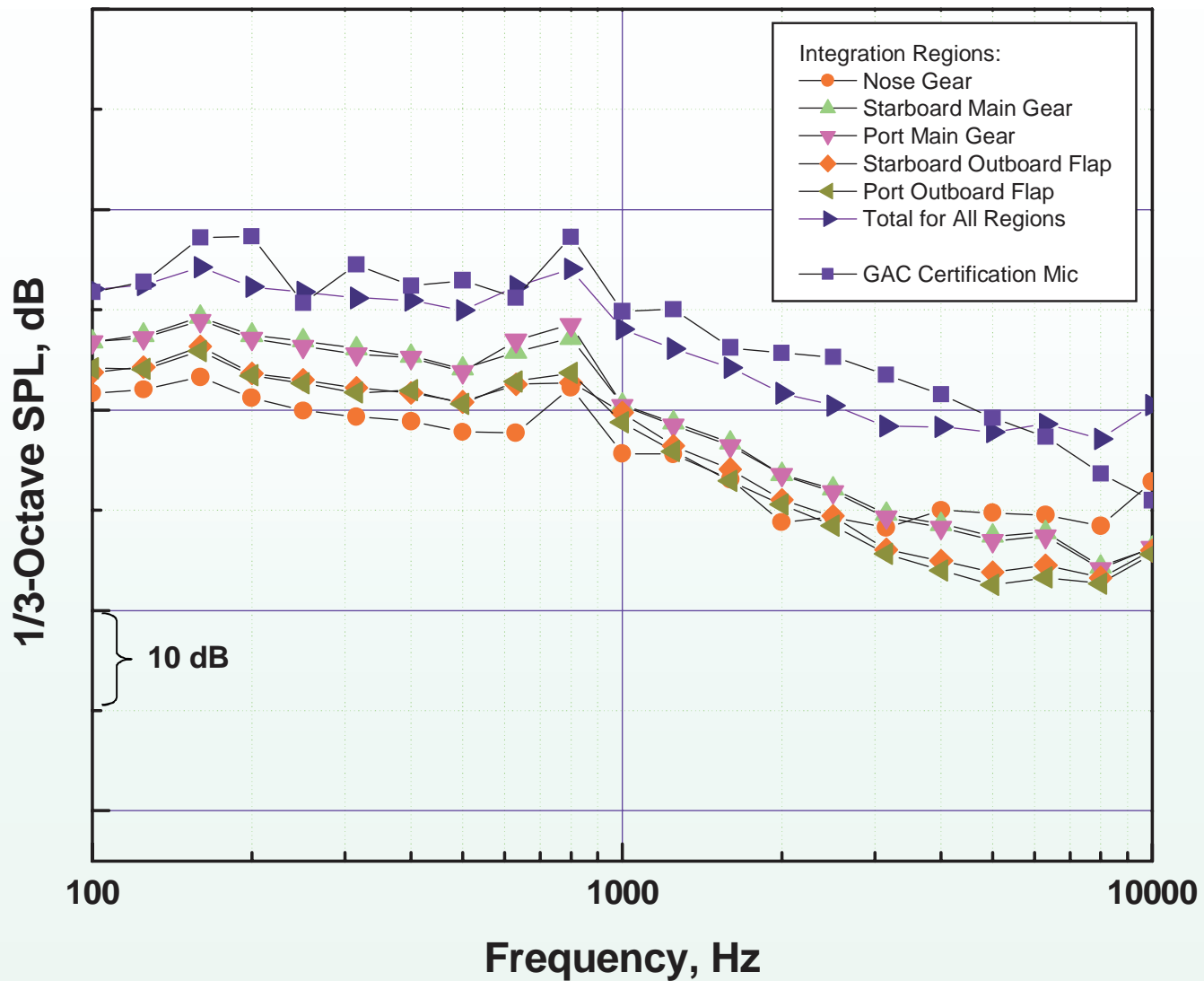
- Method of Brooks and Humphreys, 1999
- $C_{l,n}$  represents integrated beampattern characteristics over the integration region wrt the  $l,n$  measurement grid location
- Assumes a quasi-uniform distributed source strength over the integration region

# Source Integration Regions



Region	Component
1	Nose Gear
2	Starboard Main Gear / Inboard Flap Edge
3	Port Main Gear / Inboard Flap Edge
4	Starboard Outboard Flap Edge
5	Port Outboard Flap Edge

# Component Spectra

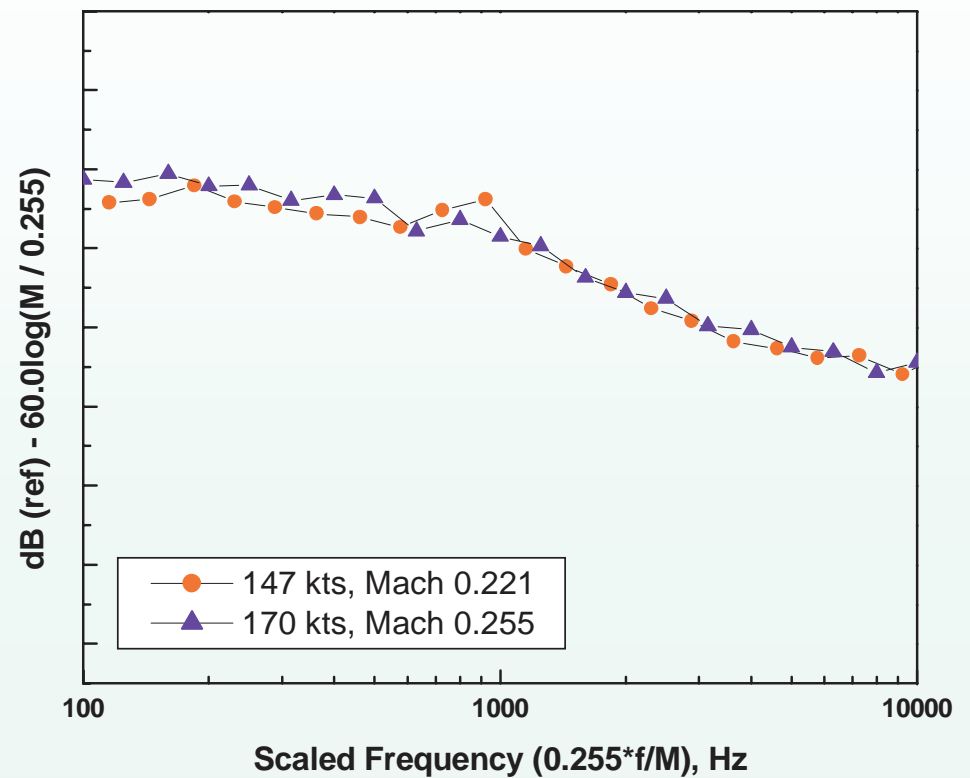
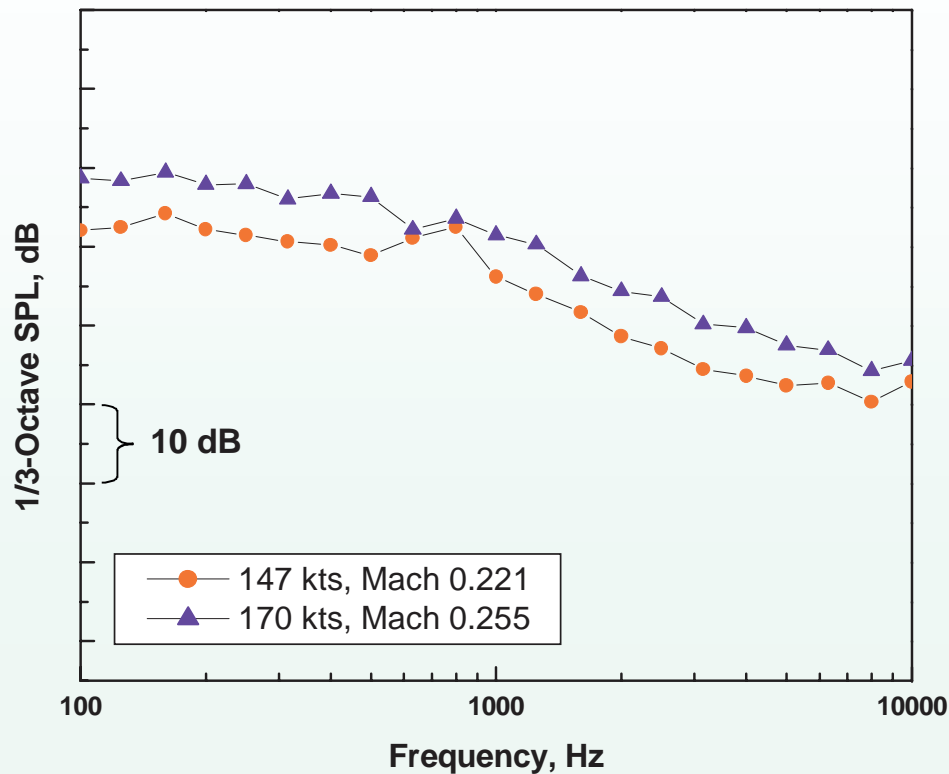


- Full Flaps and Gears
- Airspeed 147 kts

# Mach Number Effect

## Full Flaps and Gear

- Integration of TD Beamformer Output
- Summed Spectra for 5 Defined Integration Regions
- Two Highest Airspeeds Represented



# Lessons Learned

- Overall performance of the electret array system was nominal – some lessons learned and areas for improvement are:
  - Weatherproofing (protection of diaphragms from dew and rain)
  - Choice of sensors (standard electret, MEMS electret, piezoelectric, etc.)
  - Calibration of array (both laboratory and in-situ)
  - Data system positioning and configuration (remote versus local)

# Summary

- **Study represents one of the few conducted where noise measurements have been obtained in flight for isolated AFN components and selected component combinations**
- **Very good identification of aircraft AFN sources using time domain beamforming**
- **Preliminary source integration using classical approach yielding new information**



# References

- Humphreys, W.M., Jr., Brooks, T.F., Hunter, W.W., Jr., and Meadows, K.R., “Design and Use of Microphone Directional Arrays for Aeroacoustic Measurements”, *AIAA Paper 1998-0471, 36th Aerospace Sciences Meeting*, Reno, Nevada, 1998.
- Brooks, T.F., and Humphreys, W.M., Jr., “Effect of Directional Array Size on the Measurement of Airframe Noise Components”, *AIAA Paper 1999-1958, 5th AIAA/CEAS Aeroacoustics Conference*, Bellevue, Washington, 1999.
- Dougherty, R., “Advanced Time-Domain Beamforming Techniques”, *AIAA Paper 2004-2955, 10th AIAA/CEAS Aeroacoustics Conference*, Manchester, U.K., 2004.
- Khorrami, M.R., Lockard, D.P., Humphreys, W.M., Jr., Choudhari, M.M., and Van de Ven, T., “Preliminary Analysis of Acoustic Measurements from the NASA-Gulfstream Airframe Noise Flight Test”, *AIAA Paper 2008-2814, 14th AIAA/CEAS Aeroacoustics Conference*, Vancouver, Canada, 2008.