Low-cost Phased Microphone Array Design for Moderate-Scale Aeroacoustics Tests

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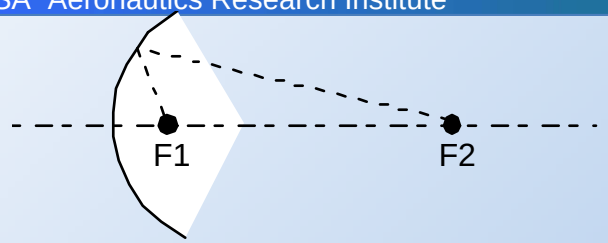
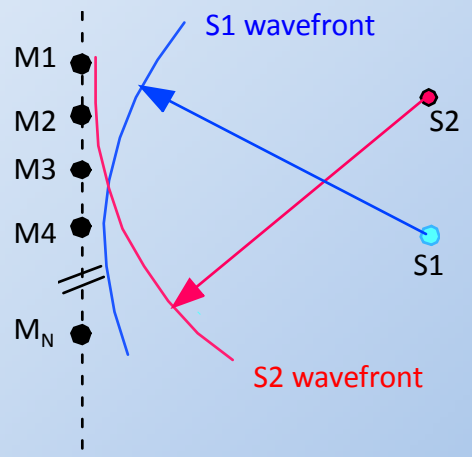
Topics

- Background: Aeroacoustic research with phased microphone arrays
- Current project motivation and objective
- New array design
- Preliminary test results
- First Research Application – full-scale active rudder test
- Summary and Future plans

Optical/Acoustic Source Location Methods



Elliptical mirror

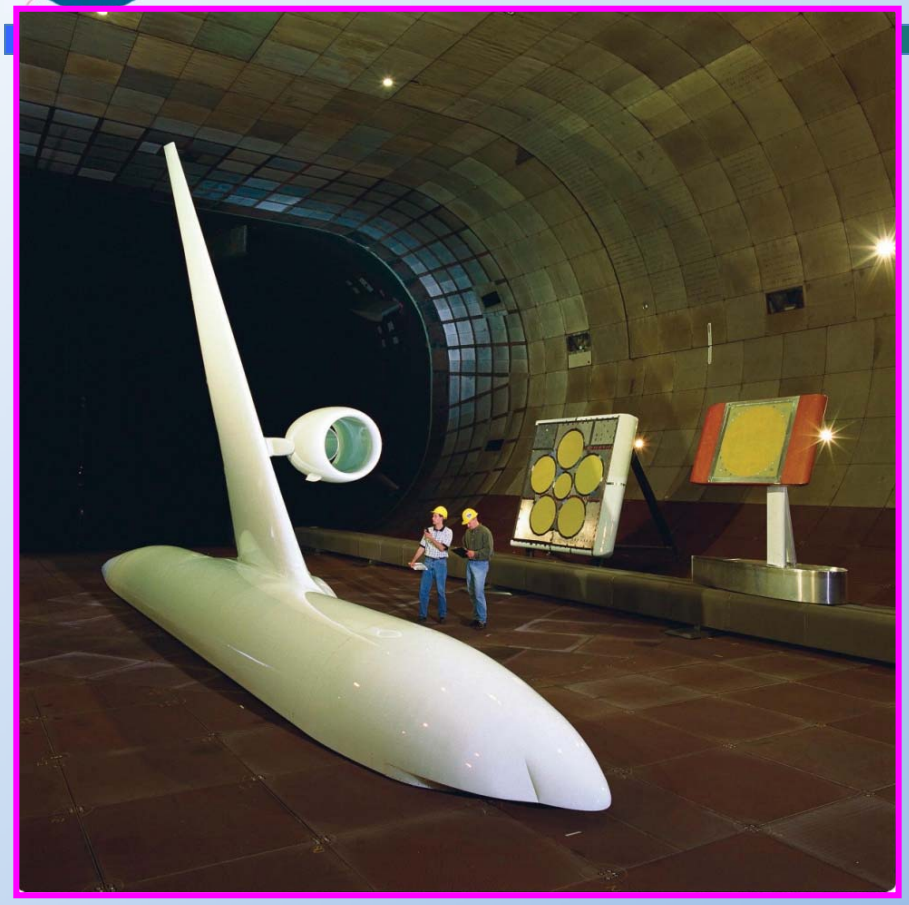


Phased Array with N microphones

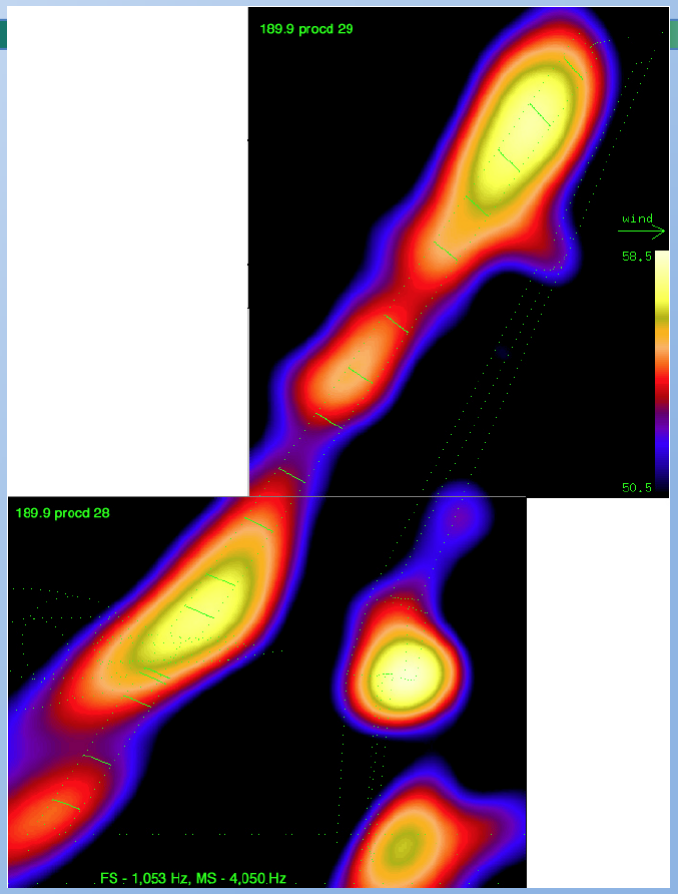
- Elliptical mirror geometry ensures that acoustic rays from source at F2 to sensor at F1 have the same path length (and propagation delay) and add together. Rays from sources at other locations do not focus on F1.
- Time-domain phased microphone array – each sensor records signals from all sources. Select target source locations by applying appropriate time delays to the sensor records and adding the time-shifted signals. Correct time delays for convection effects.
- Frequency-domain phased microphone array – apply appropriate phase shifts to FFT's of microphone signals, add the phase-shifted signals.

Benefits: 1) Location of sources and 2) level measurements with improved signal-to-noise ratio

Acoustic Field Mapping with a Traversing Array in an Closed-Section Wind Tunnel

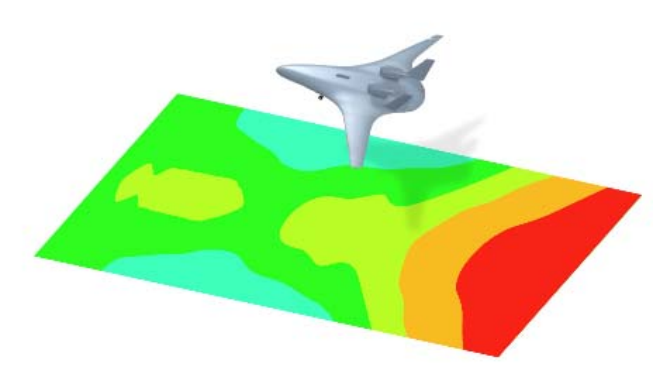


26% Boeing 777 Airframe noise test with 96” fixed array and 40” traversing array (70 element each)

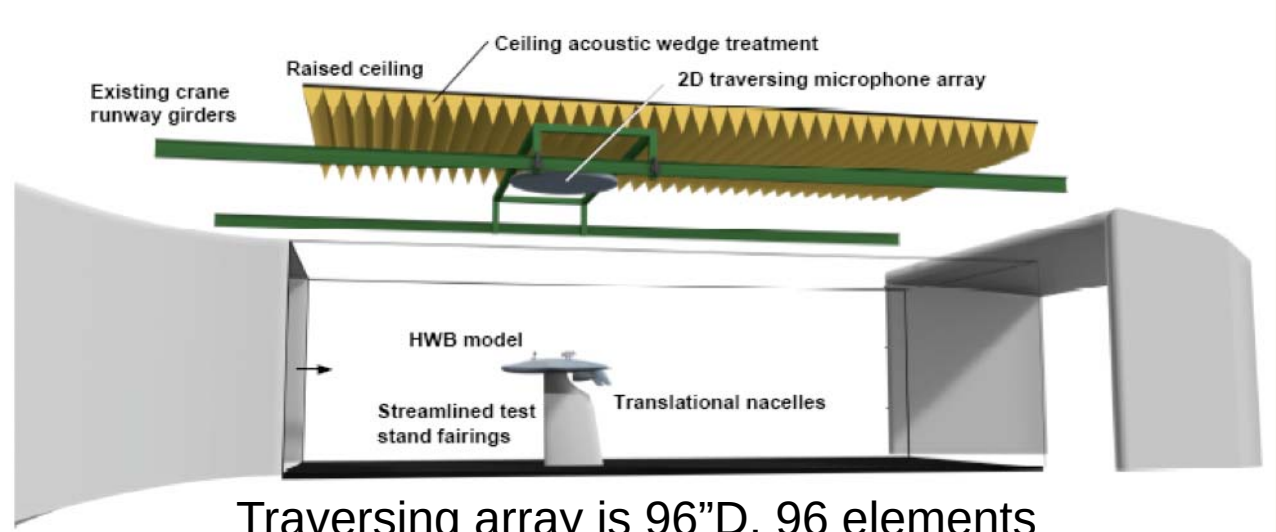


Scan of wing plane for acoustic sources: slats, inboard flap

Acoustic Field Mapping with a Traversing Array in an Open-Section Wind Tunnel



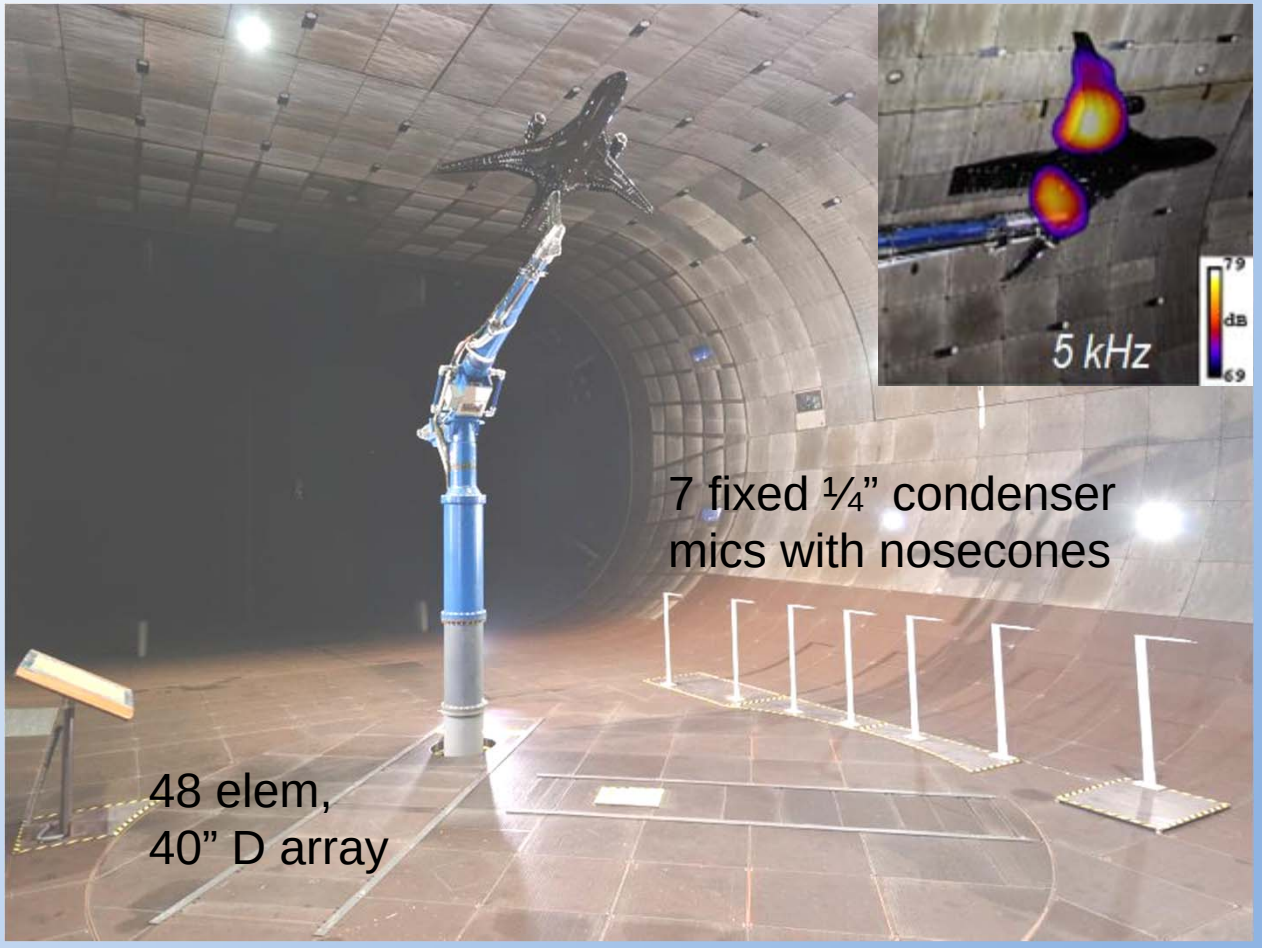
- Need to map out complex noise footprints to compare with predictions
- Traversing a single array can provide high spatial resolution but requires sufficient test time



Traversing array is 96”D, 96 elements

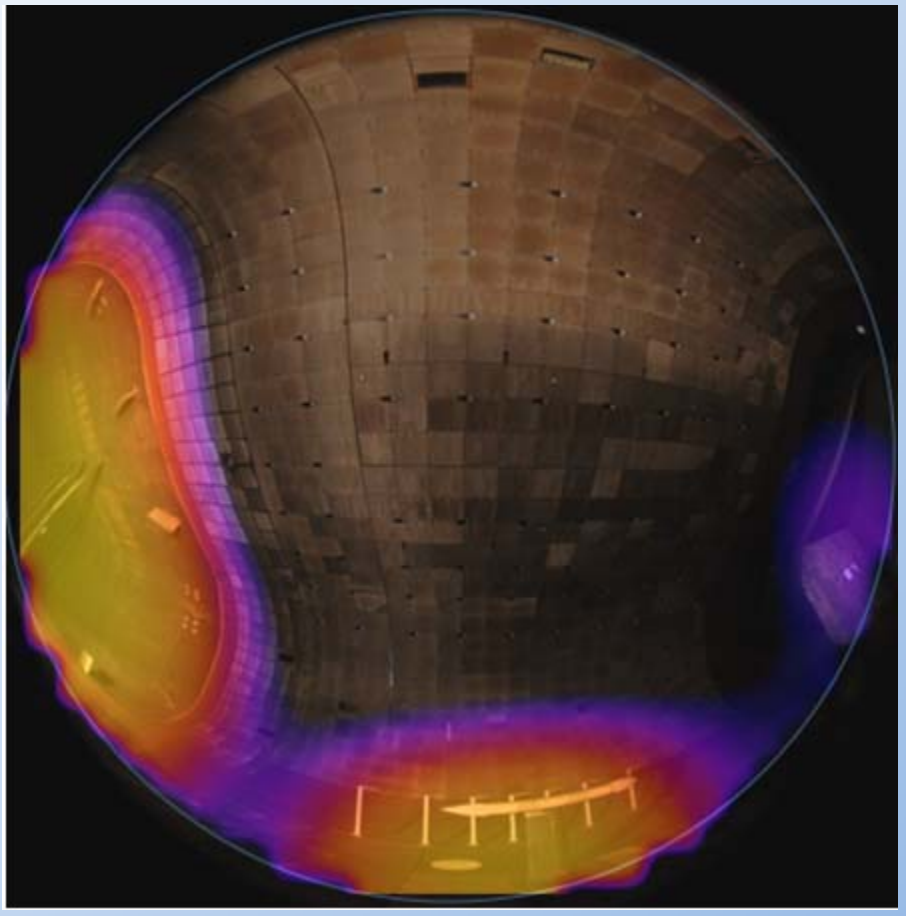
Acoustic survey set-up at LaRC 14x22’ WT for Hybrid Wing Body test.

Cruise Efficient Short Take-off and Landing (CESTOL) Active Lift Aeroacoustics Test (2011-12)



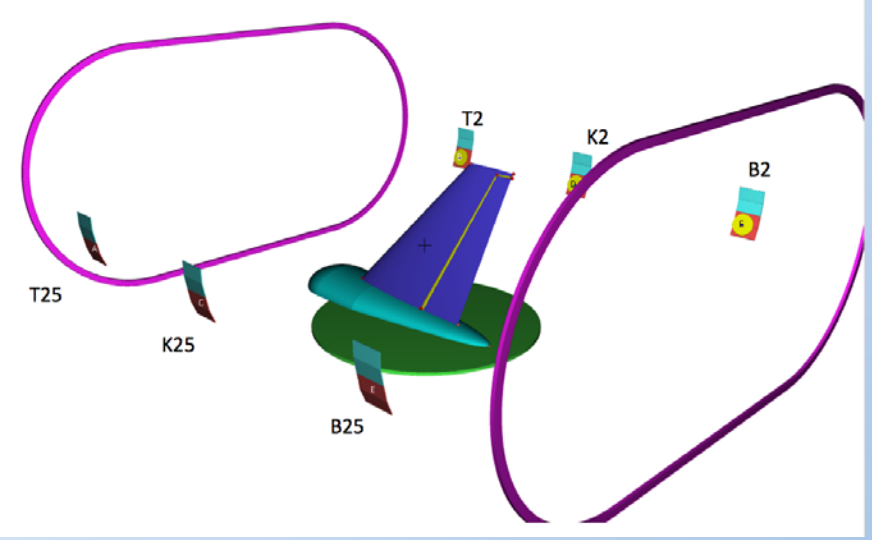
- New Optinav Array48® microphone pattern with 48 mics vs 70 for 777 test
- Used same array fairing and Kevlar screen.
- Array fixed to floor near 90˚ flyover location for source location, directional levels from fixed microphones
- After CESTOL test, we conducted an empty tunnel/in-flow speaker calibration and background noise assessment

Post-CESTOL Array Calibration Test Hemispheric Source Map – 100 kts



- 2012 test fisheye photo from array POV and superposed beamform map, 100 kts, 800 Hz
- Left source is wind-tunnel drive noise
- Bottom source is microphone strut noise and in-flow speaker source
- Integrate levels over hemisphere (or sub-region of interest) for equivalent omni-directional level

New approach: survey acoustic field in wind tunnel with multiple fixed arrays



Placement of six level-sensing arrays in a closed section wind tunnel (NFAC 40x80) for measurement of vertical tail or semi-span wing configuration

- Use arrays rather than single microphone to improve signal-noise of in-flow measurements
- Design arrays and acoustic system for cost-efficient, robust, operation
- Using multiple fixed arrays rather than traversing a single array to maximize test productivity
- Applicable to open or closed test section wind tunnels
- Survey acoustic field with arrays optimized for accurate level measurement rather than high spatial resolution – smaller aperture, lower sensor count possible. Need for cost effective design and operations

Objectives of the NARI seedling project

- "The objective of the proposed work is to develop, build and test working prototypes of a novel acoustic level sensor for use in closed or open test section wind tunnels for aeroacoustic studies of moderate- to large-scale quiet, next generation aircraft configurations." (proposal objective)
- Document performance of the new array designs in anechoic chamber and wind tunnel tests.
- Assess relative performance of flush microphone plate vs Kevlar wind-screen design (passive wind-noise suppression)
- If possible, demonstrate use of the new array design in an appropriate aeroacoustic research test
- Goal/Impact: Expand opportunities for acoustic assessment of revolutionary aero vehicle concepts beyond planned tests dedicated to acoustics research in a wide variety of test facilities with good coverage of acoustic field at controlled cost and minimal impact to test productivity.

Level-sensing vs Source-location arrays

Source location arrays

- Large diam. for good resolution at low frequencies: $\Delta\theta \sim 70^{\circ}\lambda/D$. $\Delta\theta \sim 15^{\circ}$ for 32" D array at 2 kHz. Level measurement uncertainty due to variations in directivity, coherence over sensor area
- Often consist of nested arrays for consistent resolution over wide frequency band – large microphone count
- Select array patterns and processing methods for highest spatial resolution
- Use deconvolutional post processing to improve spatial resolution

Level-sensing arrays

- Smaller diameter and solid capture angle to minimize effects of spatial directivity and coherence
- Accept lower resolution at low frequencies
- lower microphone count – use post processing to suppress sidelobes
- Select array patterns and processing methods for highest level accuracy over desired frequency range
- Post-process for optimum level accuracy (integrated levels)

Level-sensing array configurations

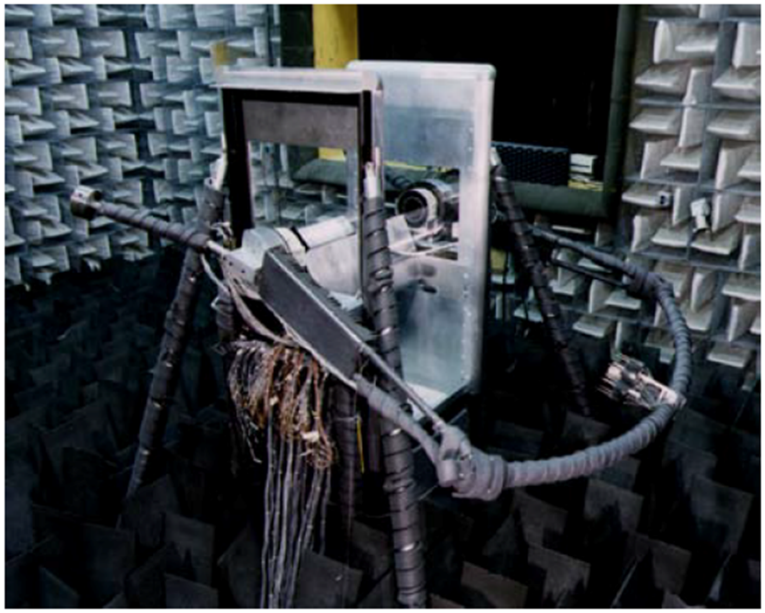
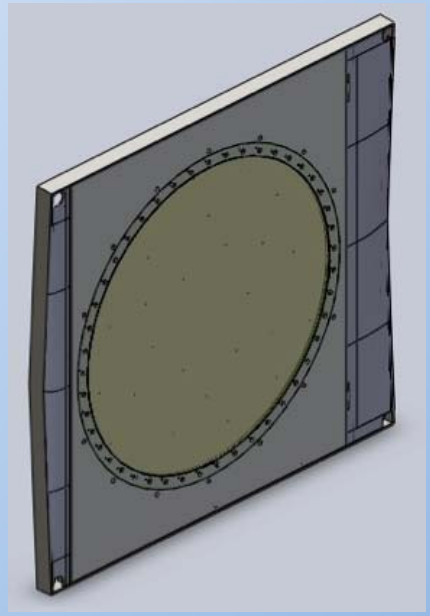
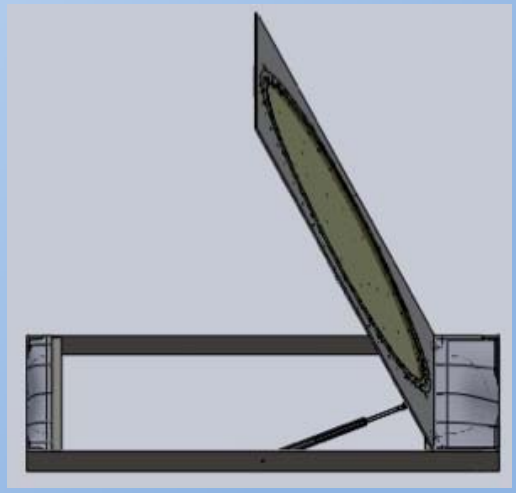


Figure 1. Test apparatus with phased microphone array mounted on pivotal boom in QFF.





Trailing edge noise study in QFF by Hutcheson and Brooks with Small Aperture Directional Array (SADA) out-of flow array with 33 sensors, c = 16”, M = 0.17, R = 5’, AIAA 2002-2472

Modular wall array concept of the current study configured as a closed section wind tunnel wall-mounted array with 24 sensors in a 32” diameter pattern.

System elements for multiple fixed array configuration selected for controlled cost and high test productivity

Small Aperture Directional Array Concept (Brooks et al)
Emphasize accurate level measurement over source field resolution -> small diam, lower sensor count. **Maximize S/N for in-flow applications**

DAQ.exe(N. Burnside)
MATLAB/NI based data acquisition – 200-500 ch avail for 6-20 24-ch fixed location arrays

Equal aperture spiral array pattern (Underbrink) – 8 mics on each of 3 arms

Assess wind tunnel acoustic test operational environment
- Integrate with aerodynamics testing
- Identify structural / instrumentation / operations interfaces

Optinav BeamformInteractive® array processing software
- Hemispheric beamforming
- Scriptable for tunnel environment
-variety of process options, conv. beamforming, TIDY® , DAMAS, CLEAN-SC, linear/functional beamforming,
-CSM background subtraction.
-Superpose beamform maps on fisheye photo or CAD images (VINCI-Schairer)

Background Noise Reduction approach

- Noise from convecting boundary/shear-layer eddies adjacent to array surface (Jaeger et al):

Recess microphones behind porous screen:

Subsonic wavy wall analogy: $20\log_{20}\left(\frac{p_{turb}}{p_{ref}}\right) \approx -17.2\left(\frac{\pi f y}{U_c}\right)$

f = freq, y = recess depth, Uc = convection speed

- Propagating noise from fan drive, in-flow struts (Humphreys, et al)

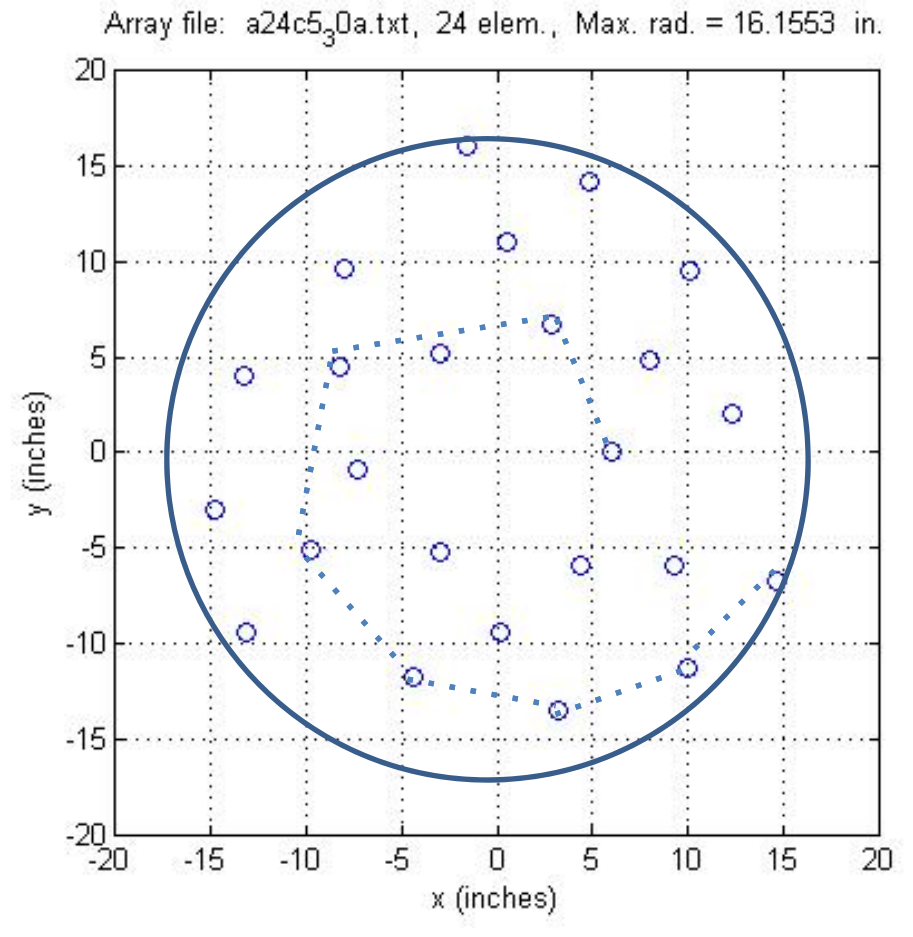
$< P_{cbf}^2 > = e' SS' e$; e = steering vector of phase shifts

SS' = MxM cross spectral matrix(CSM)

$SS')_{total} = SS')_{source} + SS')_{background}$

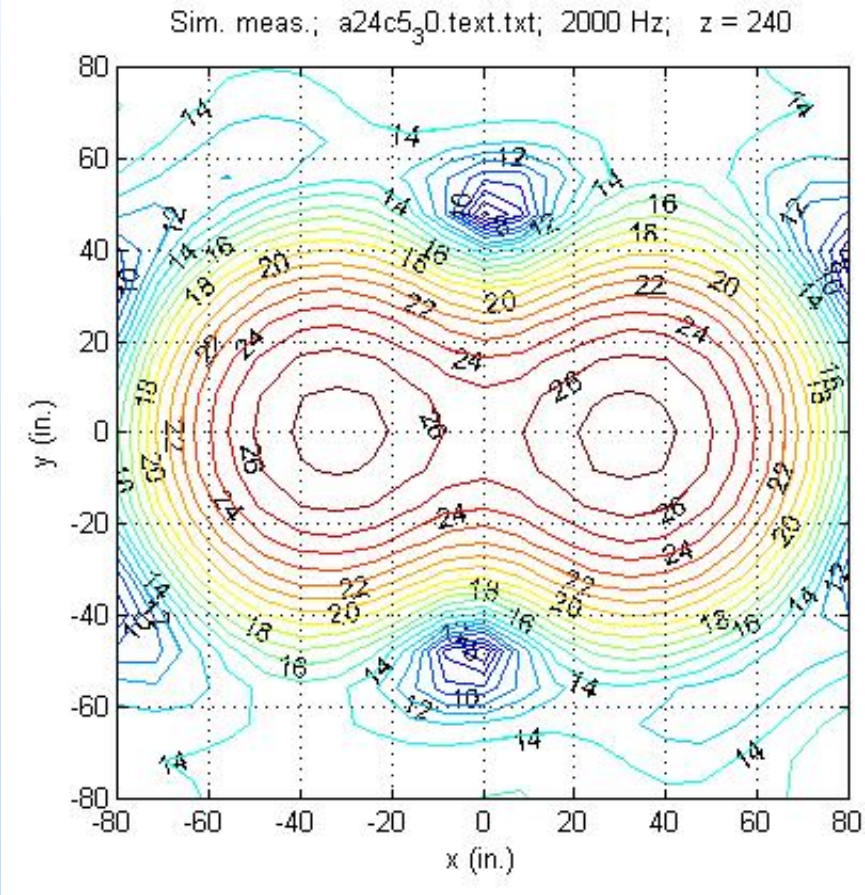
$SS')_{source} = SS')_{total} - SS')_{background}$: CSM background noise subtraction

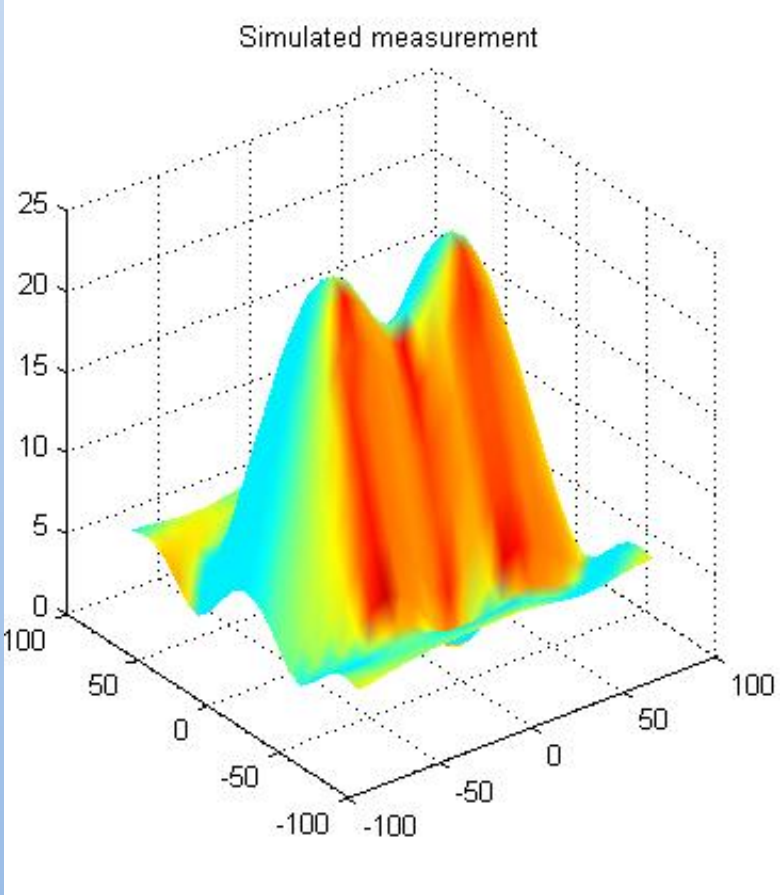
Array Design



- 24 sensor count a compromise between wide frequency bandwidth and array cost/complexity (sensors, amplifiers, cables, and A/D chanels) – good results from Optinav Array24jr®
- 32” diameter array pattern size is a good fit in many wind tunnels used for aeroacoustics research
- Source location: 2-20 kHz
- Level sensing: 0.2-20 kHz

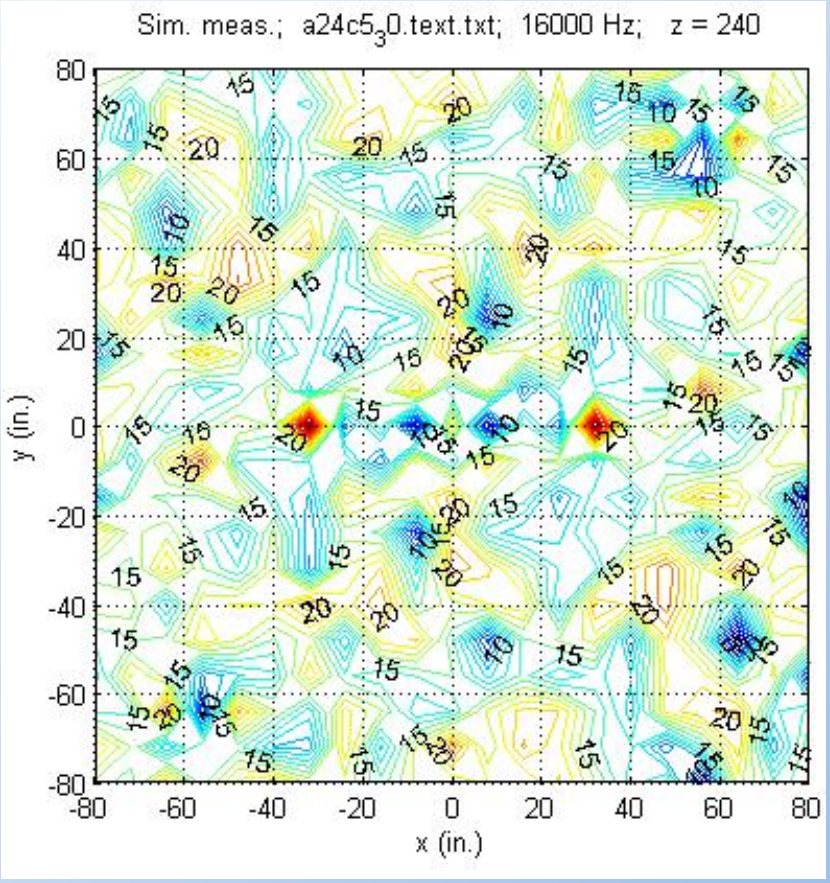
Typical array response patterns

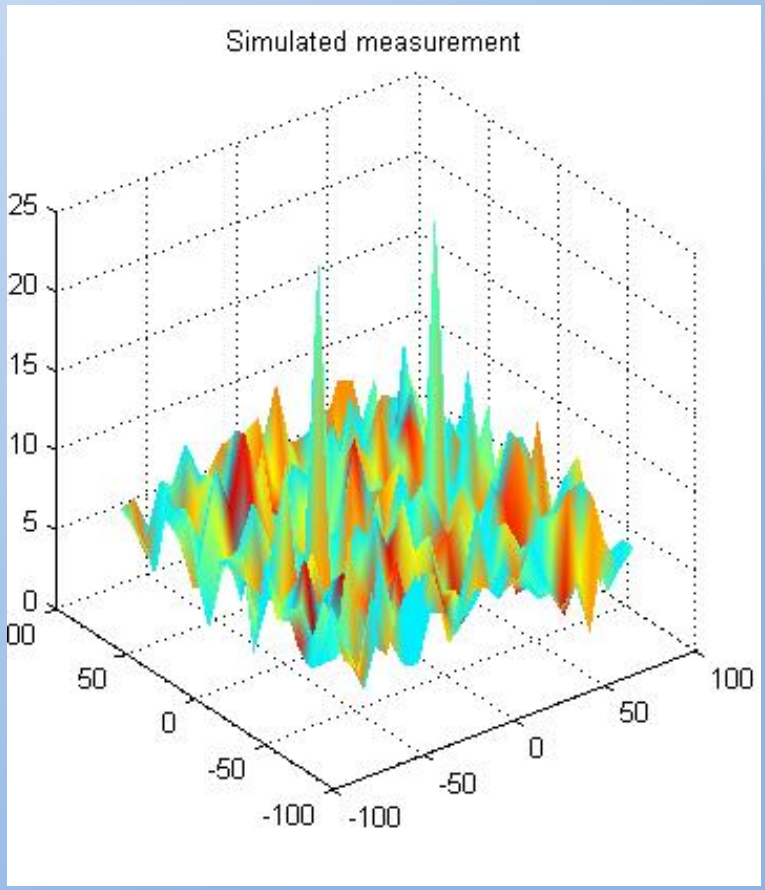




Simulated response of 2 incoherent sources, 15˚ separation, 2 kHz (Rayleigh limit)

Typical array response patterns





Simulated response of 2 incoherent sources, 15˚ separation,16 kHz

Implementation in a closed section wind tunnel

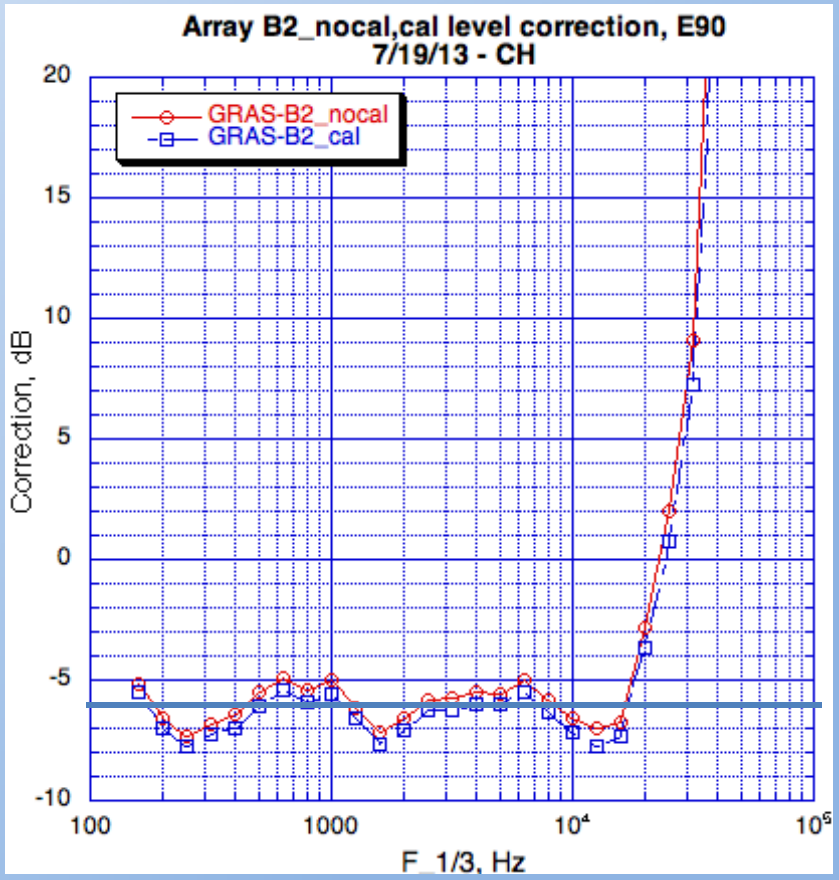
- Designed and built 2 new wall-mounted arrays with fairings
  - Ver. 1: microphone plate flush with flow (lower flow noise)
  - Ver. 2: microphone plate recessed ½” behind porous Kevlar screen (higher accuracy)
  - Same pattern for each: 24 electret sensors, 32” D spiral
- Designed and built new microphone preamps and cable bundles

Sound Level Measurement – Sources of Error

- Source wavefront scattering through turbulent shear layer (open-section) or array boundary layer (closed section)
- Reduced spatial coherence of far-field sound from distributed sources such as a jet plume
- Diffraction from array plate edges
- Porous wind screen transmission loss, reverberation within plate-screen cavity

Anechoic Chamber Calibrations

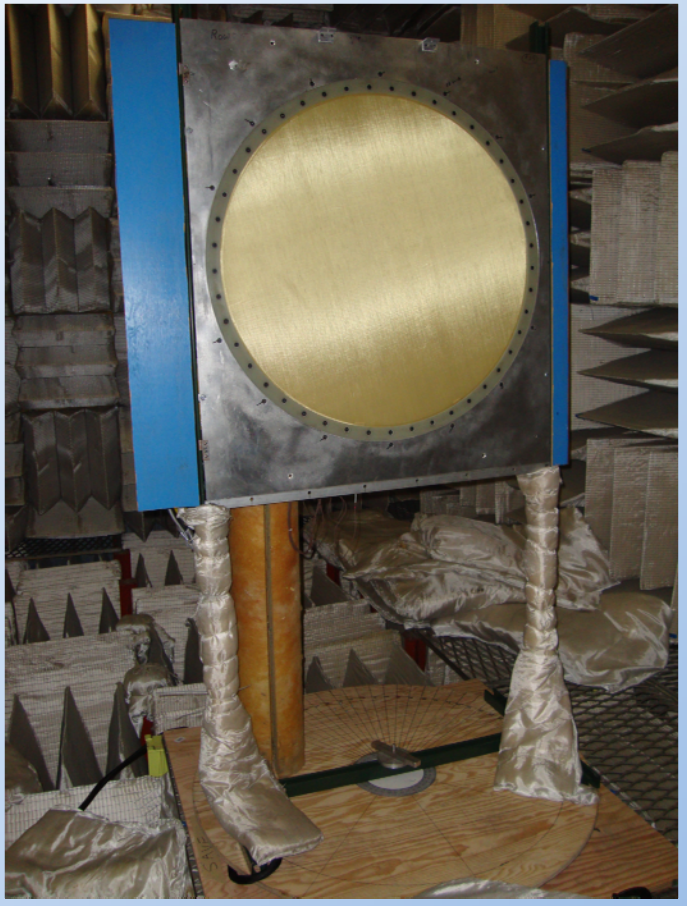
Array panel calibration fixture on turntable in AOX Anechoic chamber



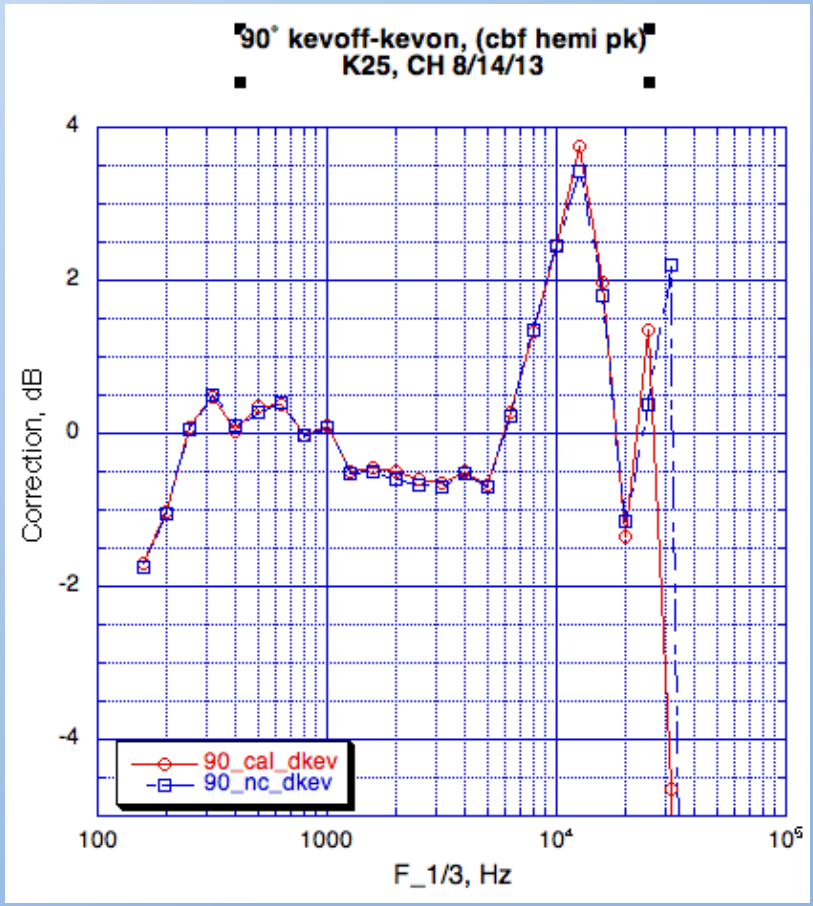
Measured correction spectra

- Array mics (electret) 20 – 20000 Hz
- Ref mic (condenser) 2 – 80,000 Hz

Kevlar Windscreen Effect

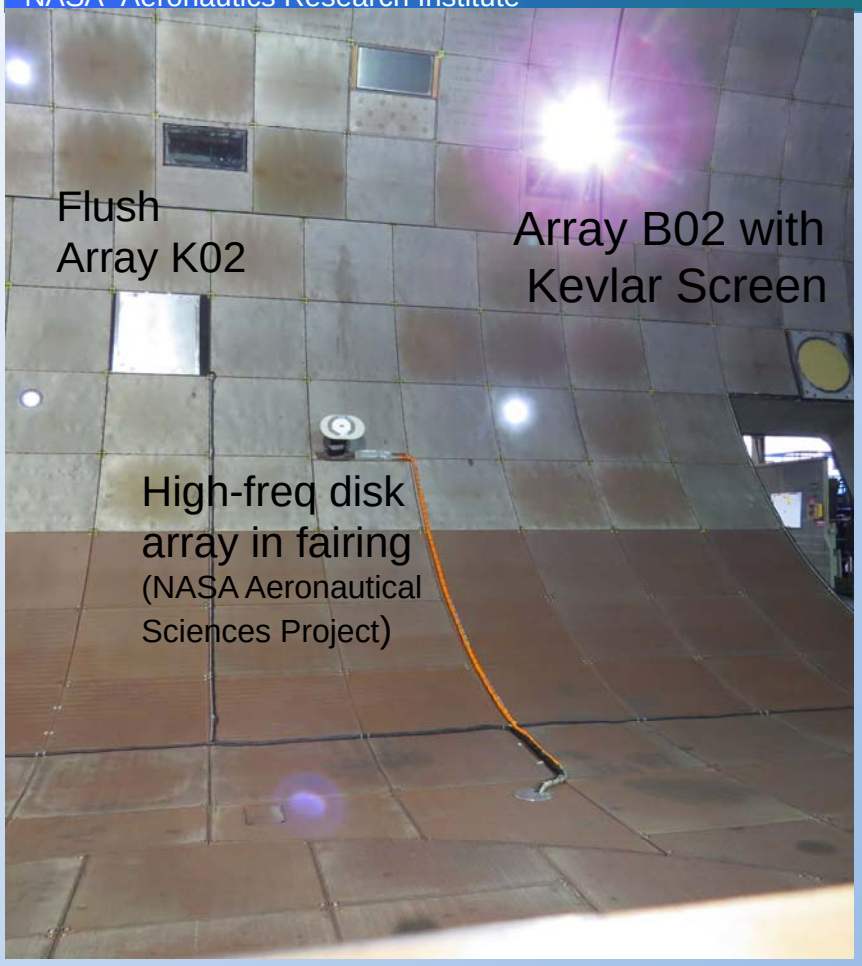


Wall array with Kevlar screen installed



Kevlar correction source at 90°

Demonstration/calibration setup in NFAC 40x80 Ft Wind Tunnel



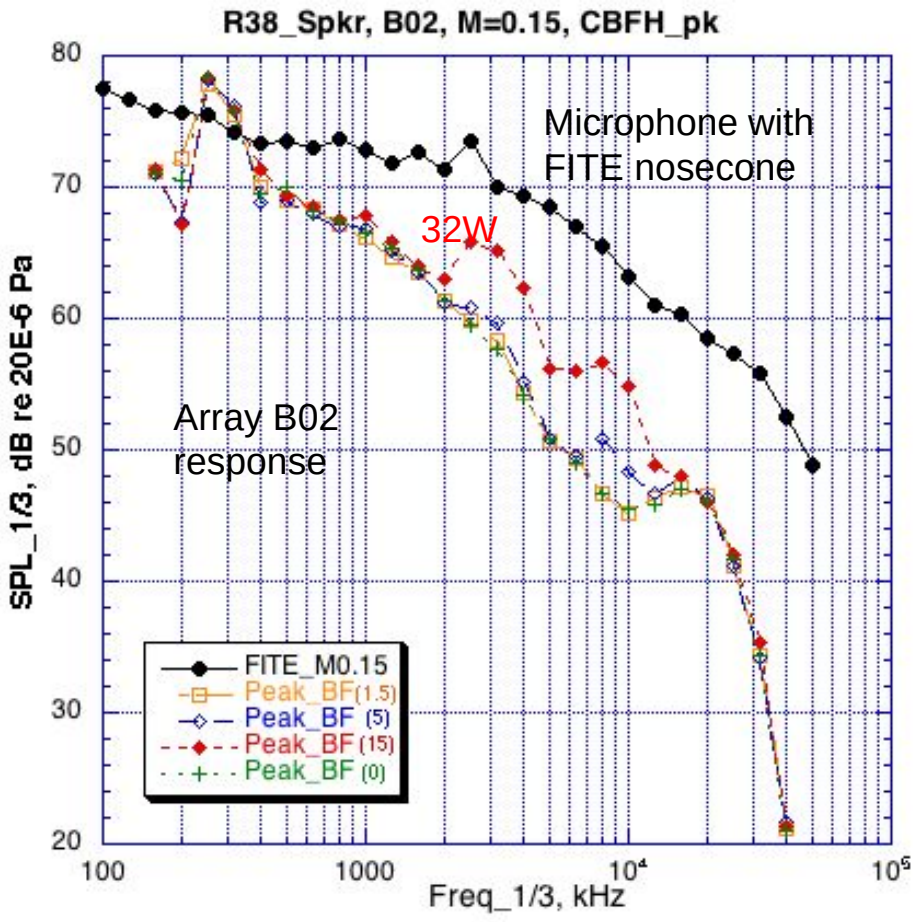
- Measured empty tunnel background noise 0.05<M<0.4
- Measured response to an in-flow speaker 0.05<M<0.3
- Re-measured Kevlar screen effect in-situ with speaker source

Empty Tunnel/Speaker Calibration of New Arrays (NARI funded)

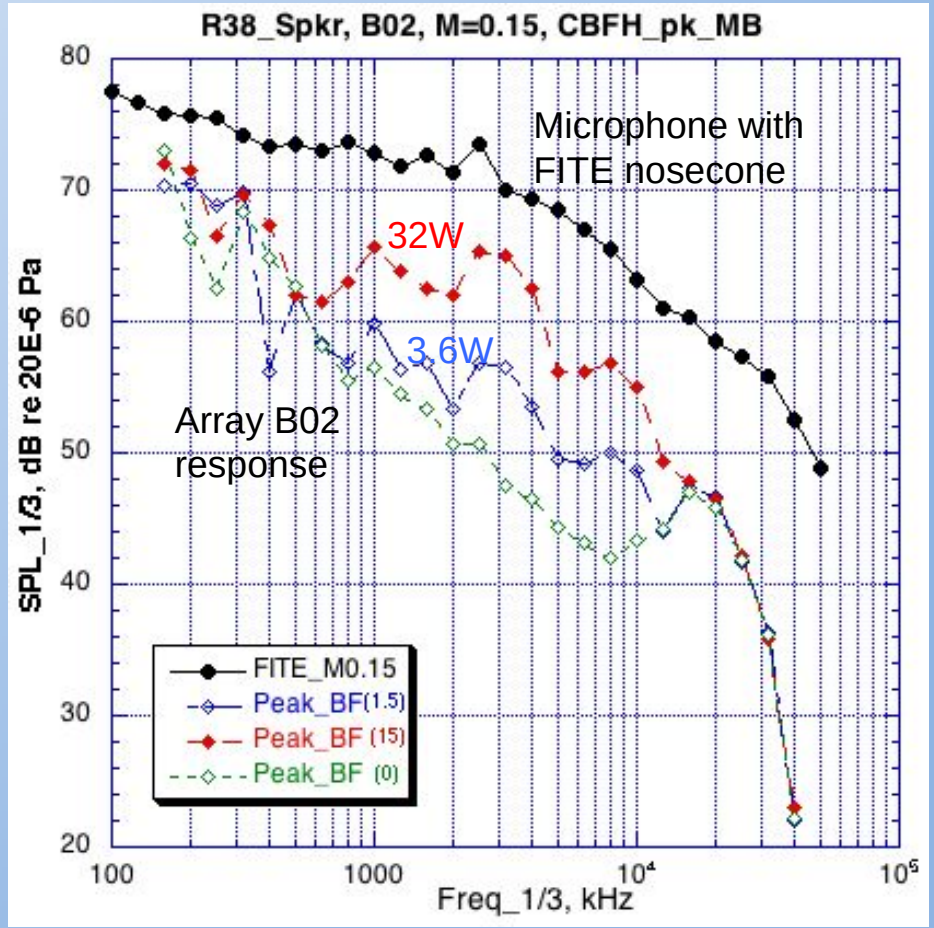
Speaker enclosure fairing in center of wind tunnel test section

- Array measurements of in-flow speaker source for 0.05 < M < 0.3.
  - Speaker source: 3 120W ceiling speakers 80 Hz – 50 kHz
- Measured spatial response and compared background noise limit of individual microphones with integral of array response with/without background noise subtraction
- Source inputs include broadband pink noise as well as square wave tonal source with harmonics to study turbulent boundary layer scattering effects.

100 kt Response to in-flow speaker



CBFH peak



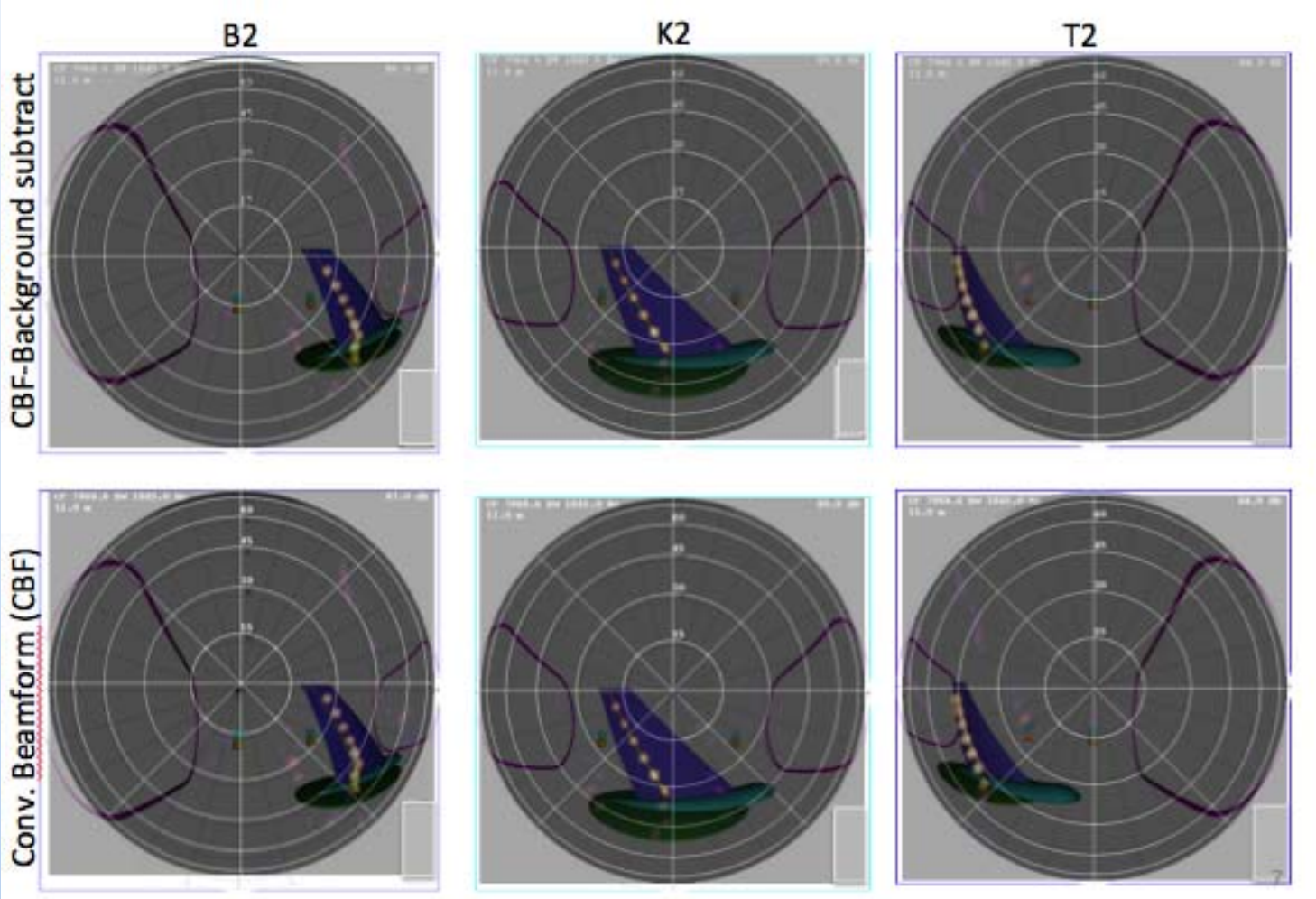
CBFH peak with background noise subtraction

2013 NASA-ERA*/Boeing Active Control Rudder Test

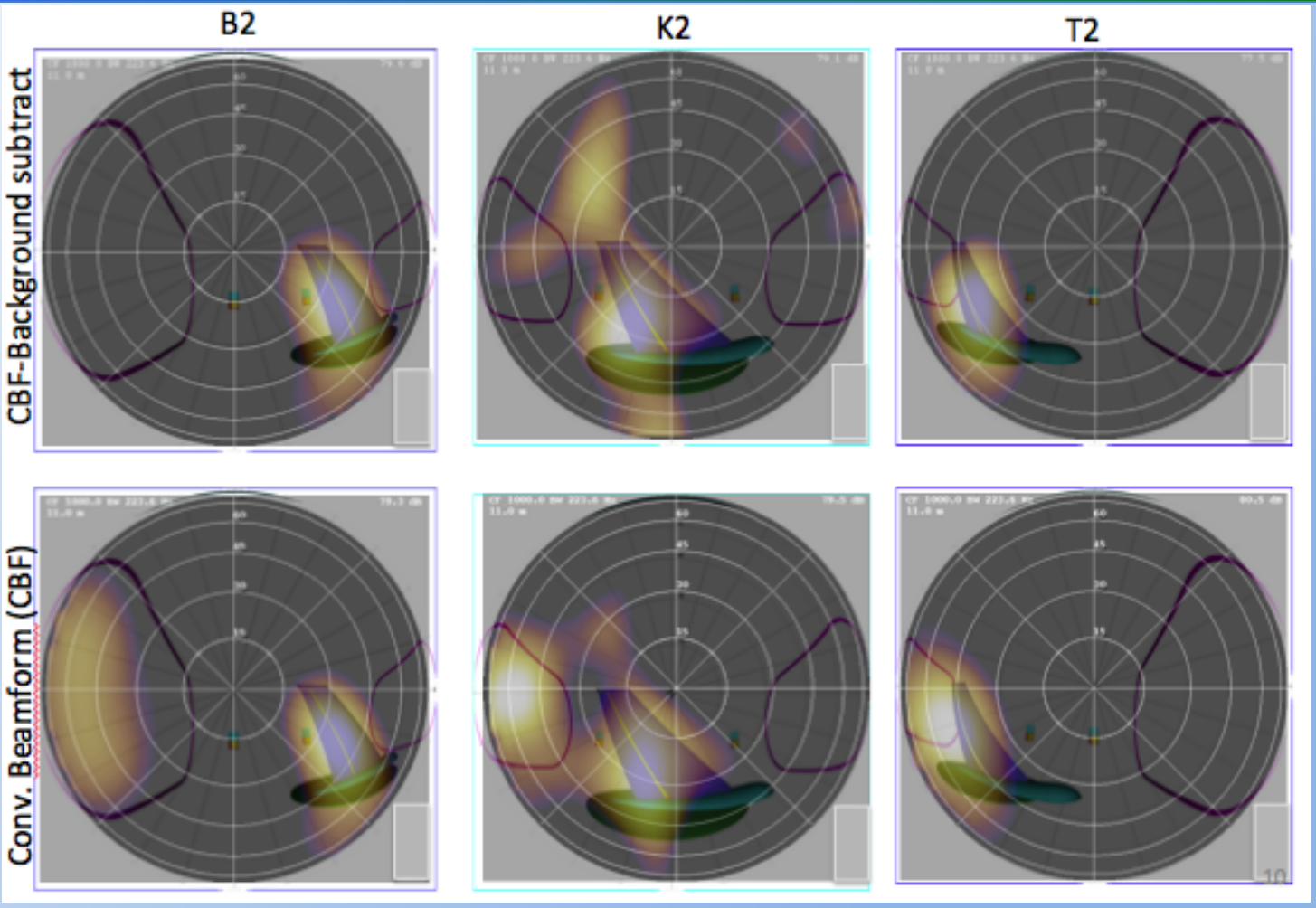
*Environmentally Responsible Aviation

- Full-scale 757 rudder from salvage fitted with 37 sweeping jet actuators to keep rudder flow attached at high yaw/rudder deflections at which flow is normally separated
- We installed 6 wall-mounted arrays (2 seedling fund, 4 ARMD Fixed Wing); 3 on each side at mid-rudder height
- Acoustic data taken on “non-interference” basis – no additional sampling time, independent data systems, etc
- Array calibration test (seedling fund) conducted after model was removed in mid-Dec, 2013

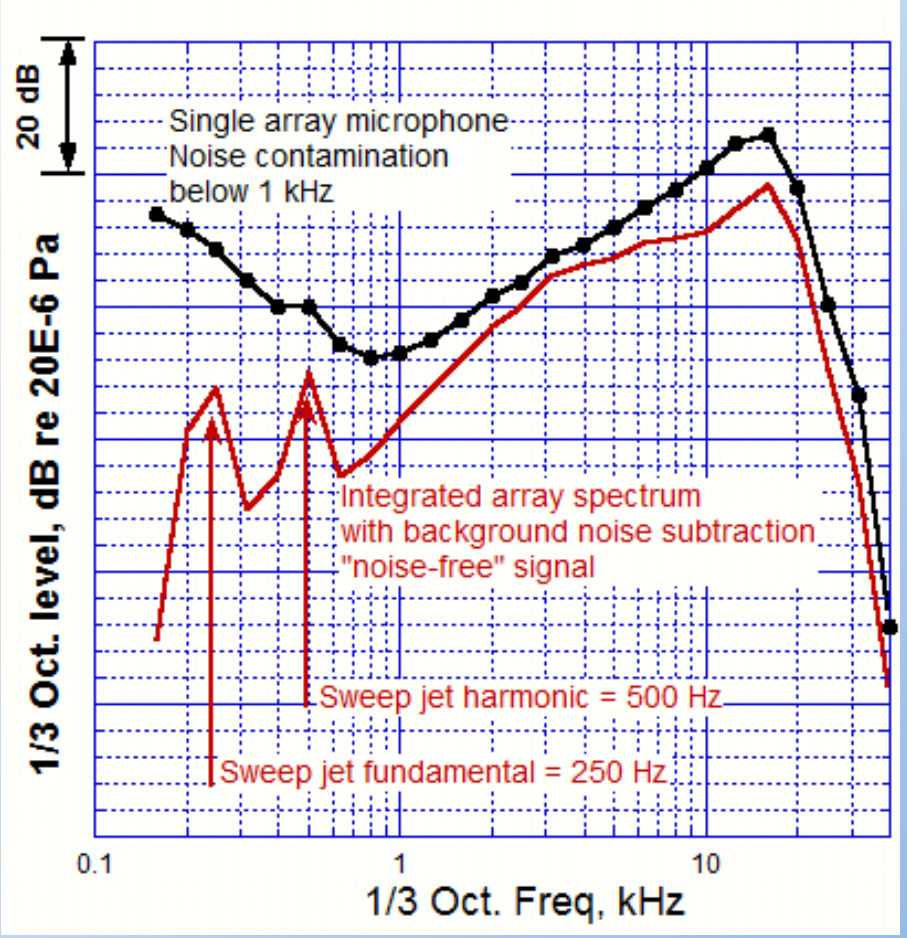
Active Rudder Test – Typ. Meas
6 actuators on, 100 kts, 8 kHz



Active Rudder Test – Typ. Meas
6 actuators on, 100 kts, 1 kHz



Active Rudder Test – Typ. Meas
6 actuators on, 100 kts, Spectrum from Array B2



- Sweeping jet actuator is a fluidic oscillator with fundamental frequency of 250 Hz at test condition
- Actuator noise consists of :
  - sweeping jet fundamental (250 Hz)
  - 1st harmonic (500 Hz)
  - jet noise (15 kHz peak)
- Array processing with background noise subtraction is needed to measure actuator noise below the tunnel background level

Summary: accomplishments

- New level sensing array systems have been designed, built, calibrated and tested in a closed section wind tunnel (NFAC 40x80). Can be adapted to other closed/open test section wind tunnels.
- Kevlar design with ½" plate recess provides up to ~20 dB background noise reduction rel. to single in-flow microphone using background subtraction method. Background levels comparable to 48 element in-flow array above 2 kHz
- 2 seedling fund arrays + 4 additional ARMD Fixed-Wing funded arrays used to acquire data in NASA-Boeing active rudder control test with sweeping jet actuators Six array system is scalable and can be expanded for future research.
- First wind-on acoustic measurements of novel sweeping-jet actuator source

Plans Going Forward

- Phase 1
  - Complete processing and analysis of data, including comparison of flush vs recess design (3 mo wind tunnel test delay)
  - Publish final report
- Phase 2
  - Use Phase 1 measurements to motivate improved designs for optimal bandwidth, background noise suppression, and level measurement accuracy
  - Select optimal new design to build and calibrate. Optimize processing/visualization software for rapid turnaround of results
  - demonstrate improved array and apply to measurement of aeroacoustic source in anechoic chamber and wind tunnel

References

Horne, W., et al, “Measurements of 26%-Scale 777 Airframe Noise in the NASA Ames 40- by 80 Foot Wind Tunnel”, AIAA-2005-2810

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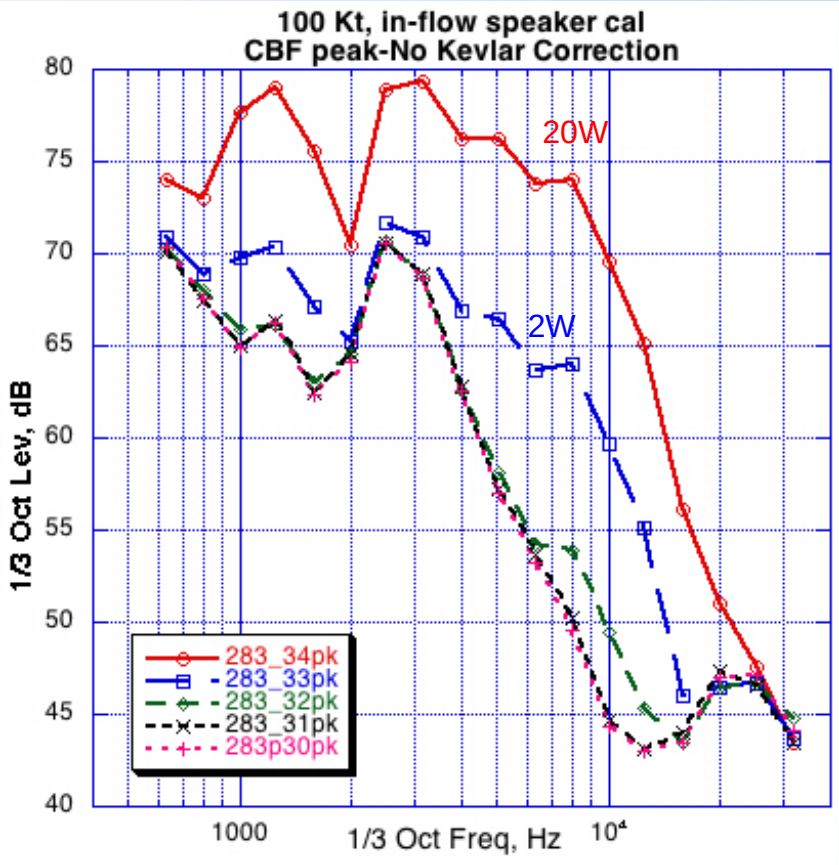
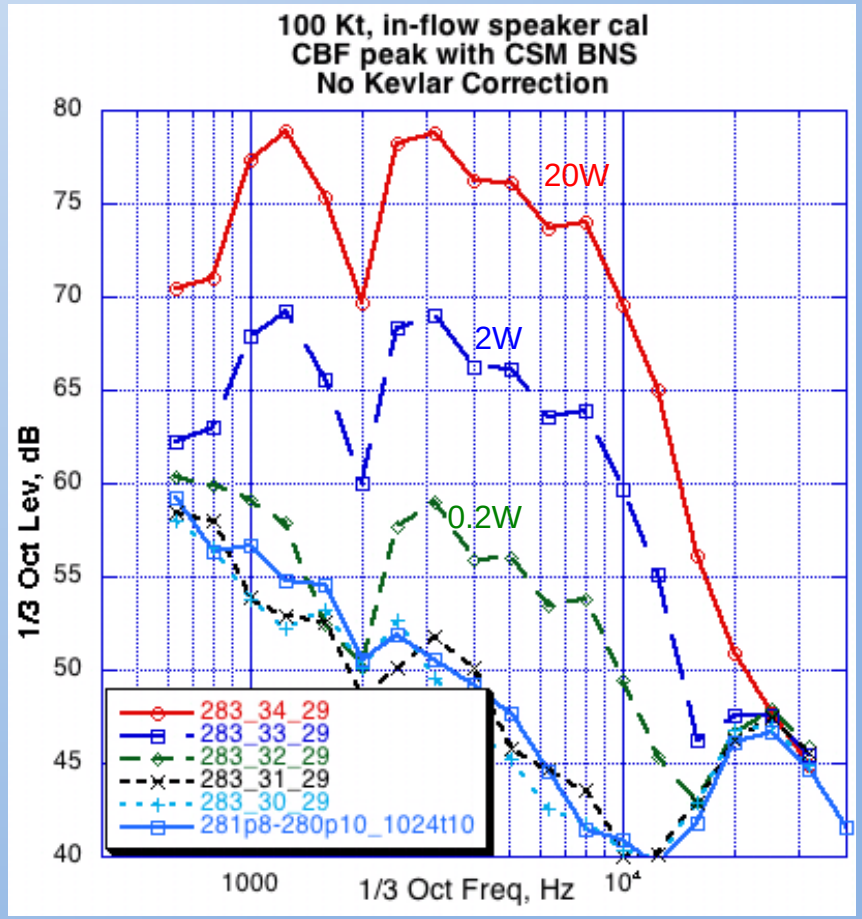
Dougherty, R., Optinav website: www.optinav.com (BeamformInteractive, Array24, Array48, publications)

Array48, 100 kts, response to in-flow speaker source (2012)

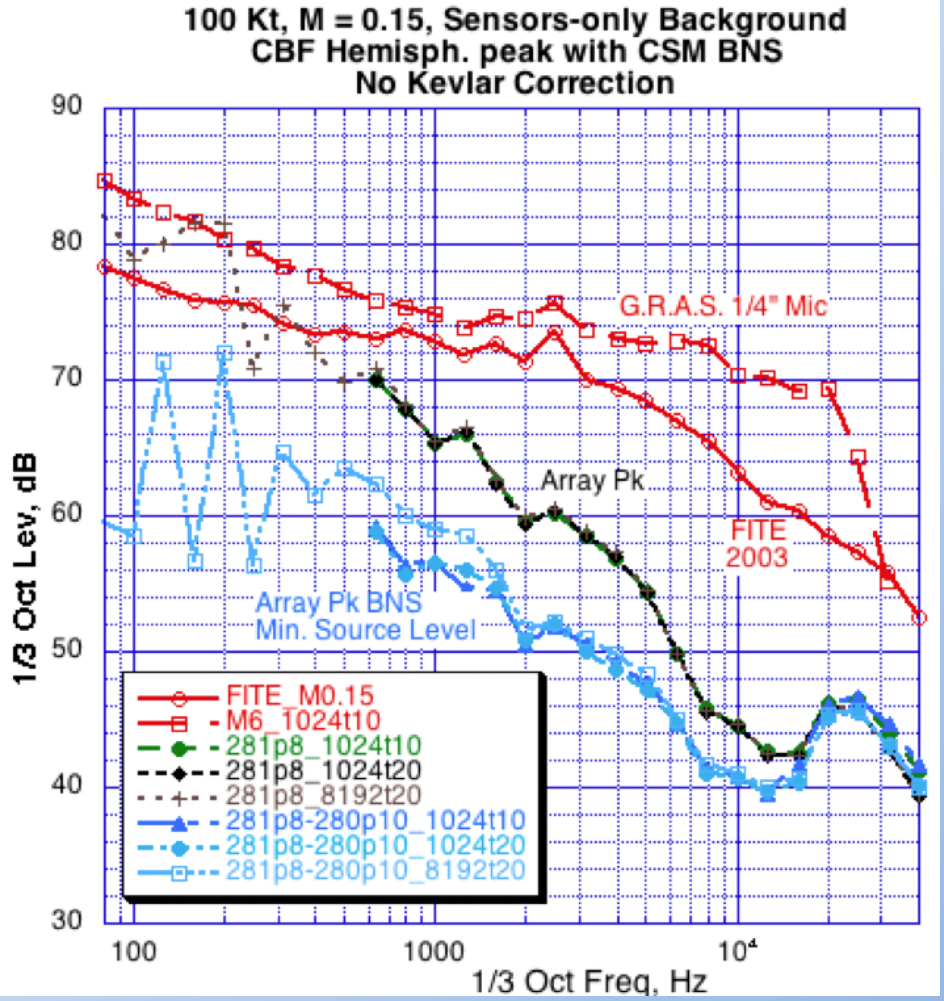


Conventional beamform hemispheric (CBFH) peak



CBFH peak with background noise subtraction (acoustic tare)

In-flow Array48 Background Noise Comparison with Fixed Microphones (2012)



- Red curve – single microphone with nosecone (2 types)
- Black – hemispheric peak of conventional beamform (CBFH) map
- Blue – peak of CBFH map with cross spectral matrix (CSM) background noise subtraction