Berlin Beamforming Conference (BeBeC)
2008
19 and 20 February

What is Beamforming?

Bob Dougherty
President, OptiNav, Inc.

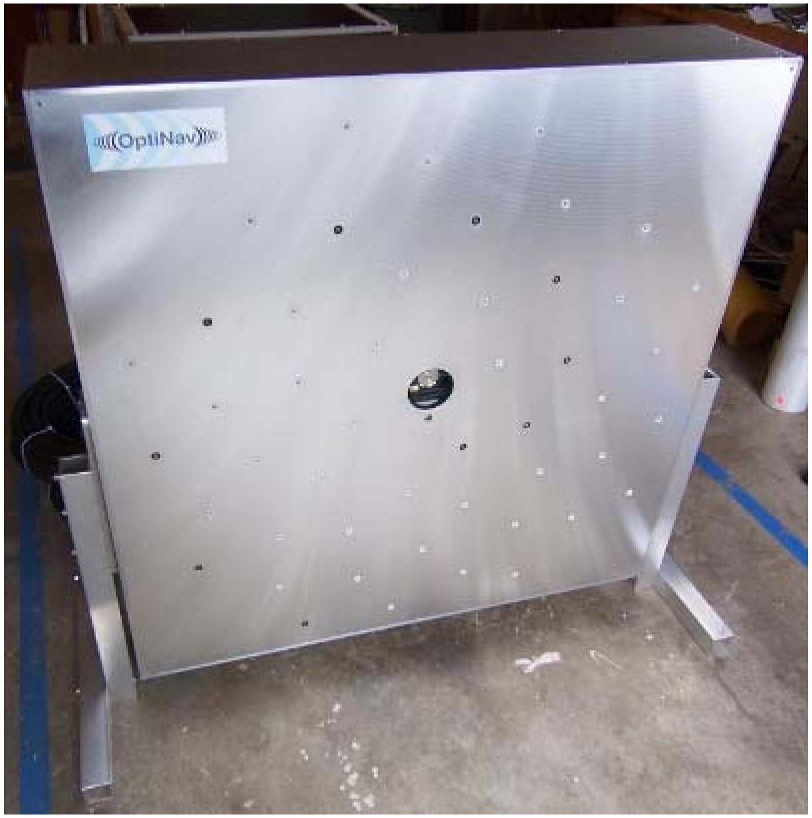
Overview

- Pictures
- Beamforming formulation
- Array design
- More pictures
    - Airframe noise
    - Fan noise
    - Jet noise
    - Wake vortex noise
- Open issues
- Conclusions

Bellevue, WA 2006

Array 48 (24 microphones)

Array-48



Array 48 (24 microphones)

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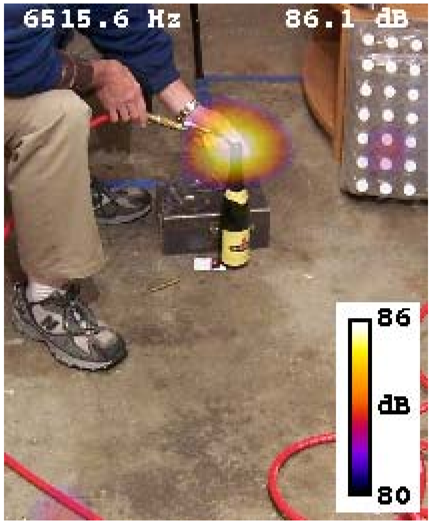
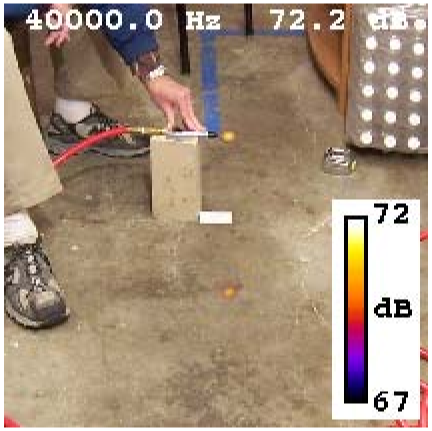
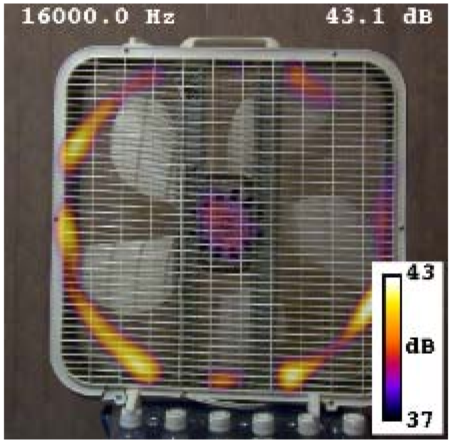


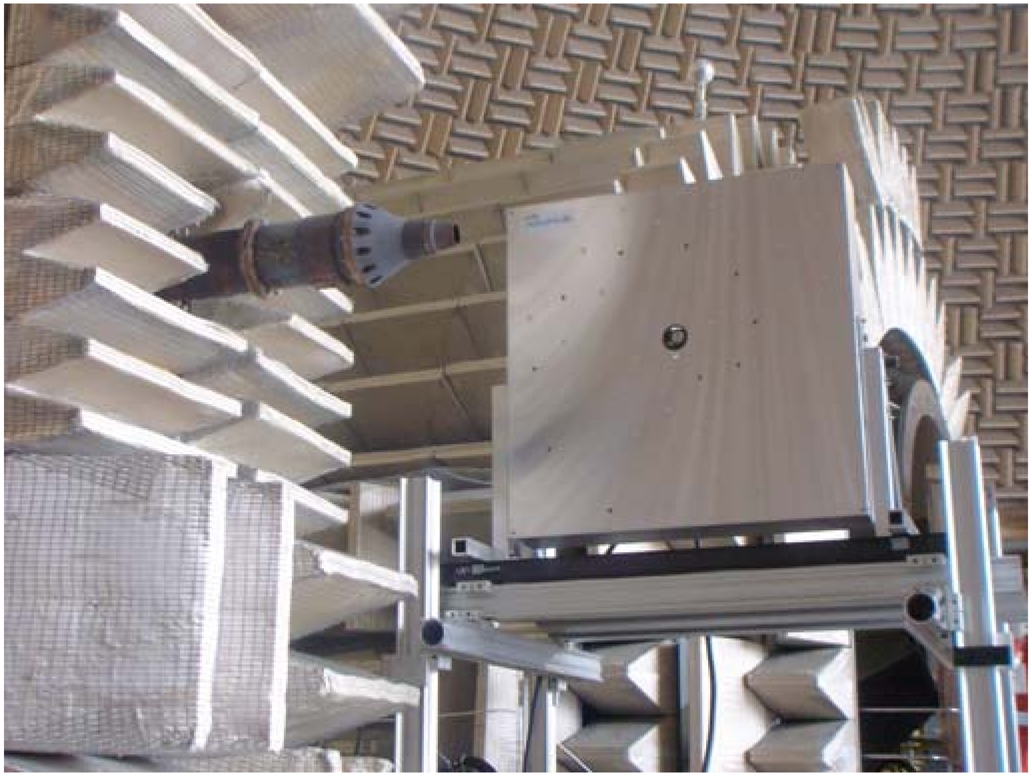


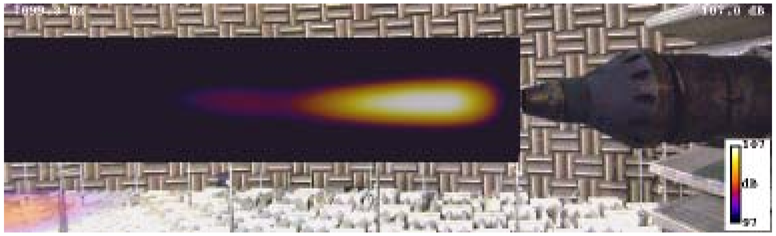

B060381
LS004334
12500.0 Hz
74
dB
68

Array 48 (24 microphones)



Array-48 at NASA-Glenn

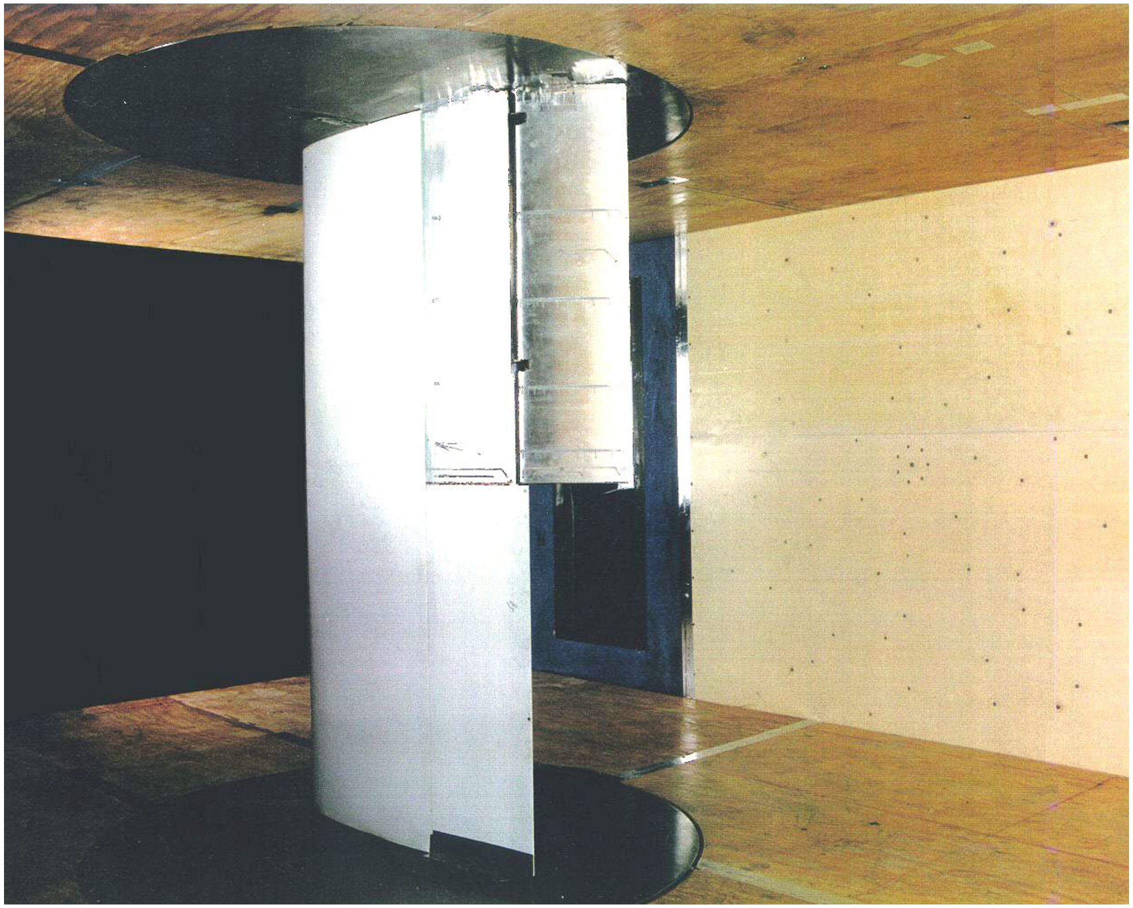


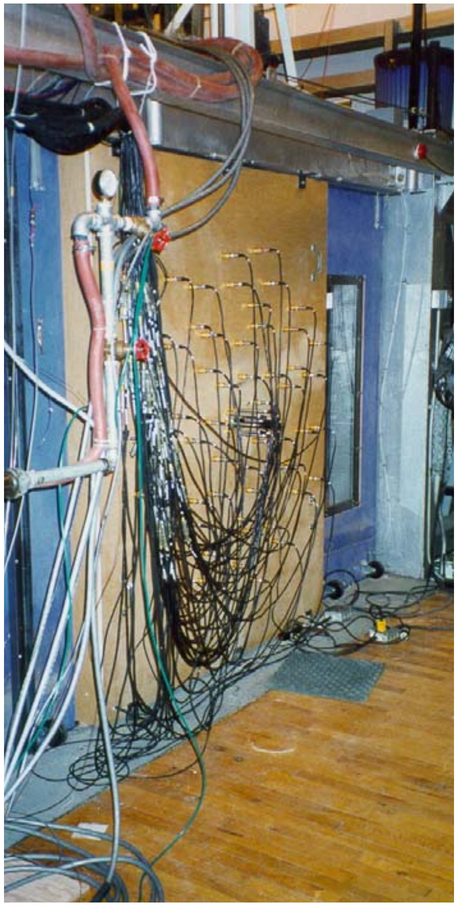


Dec. 2007, Gary Podboy

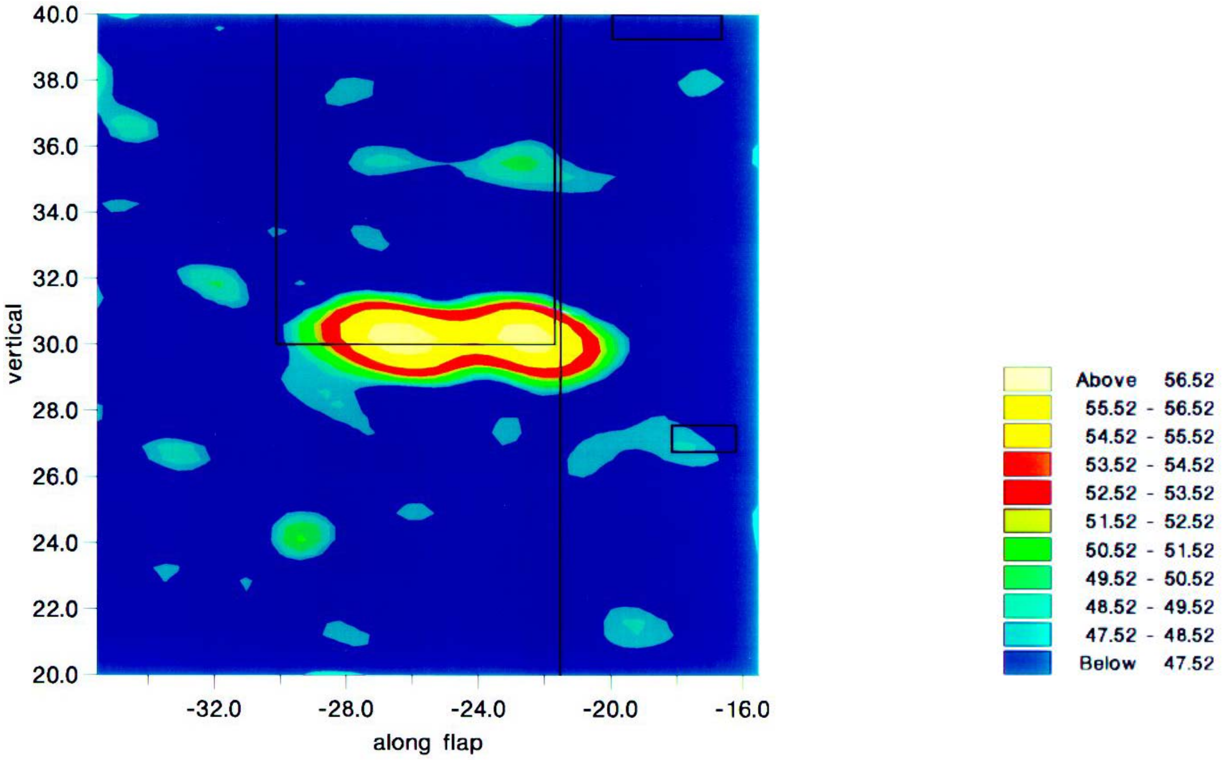

Martinair

7x10 test 1995





7x10 test 1995

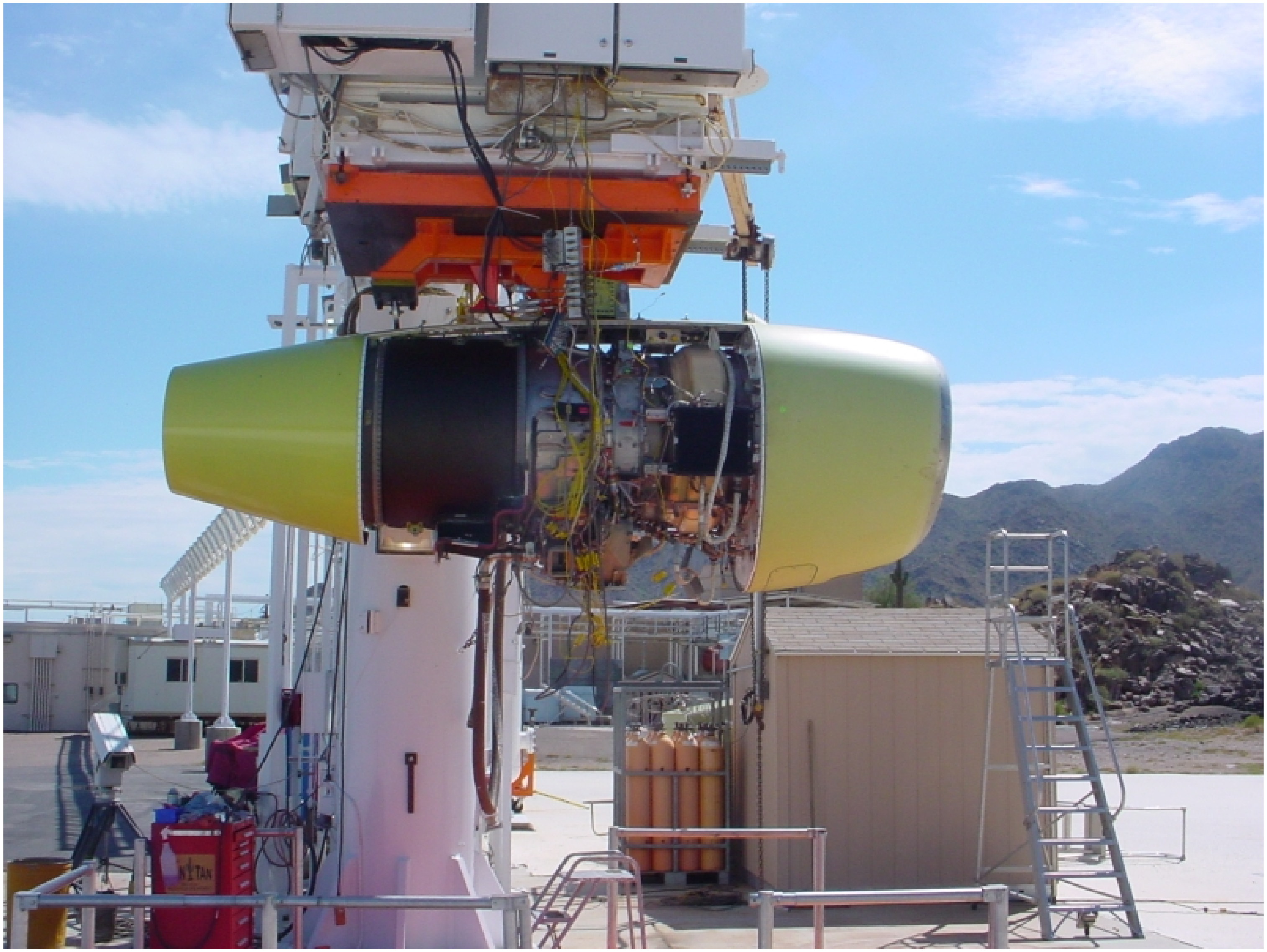


Inlet noise:
fan, low
pressure
compressor

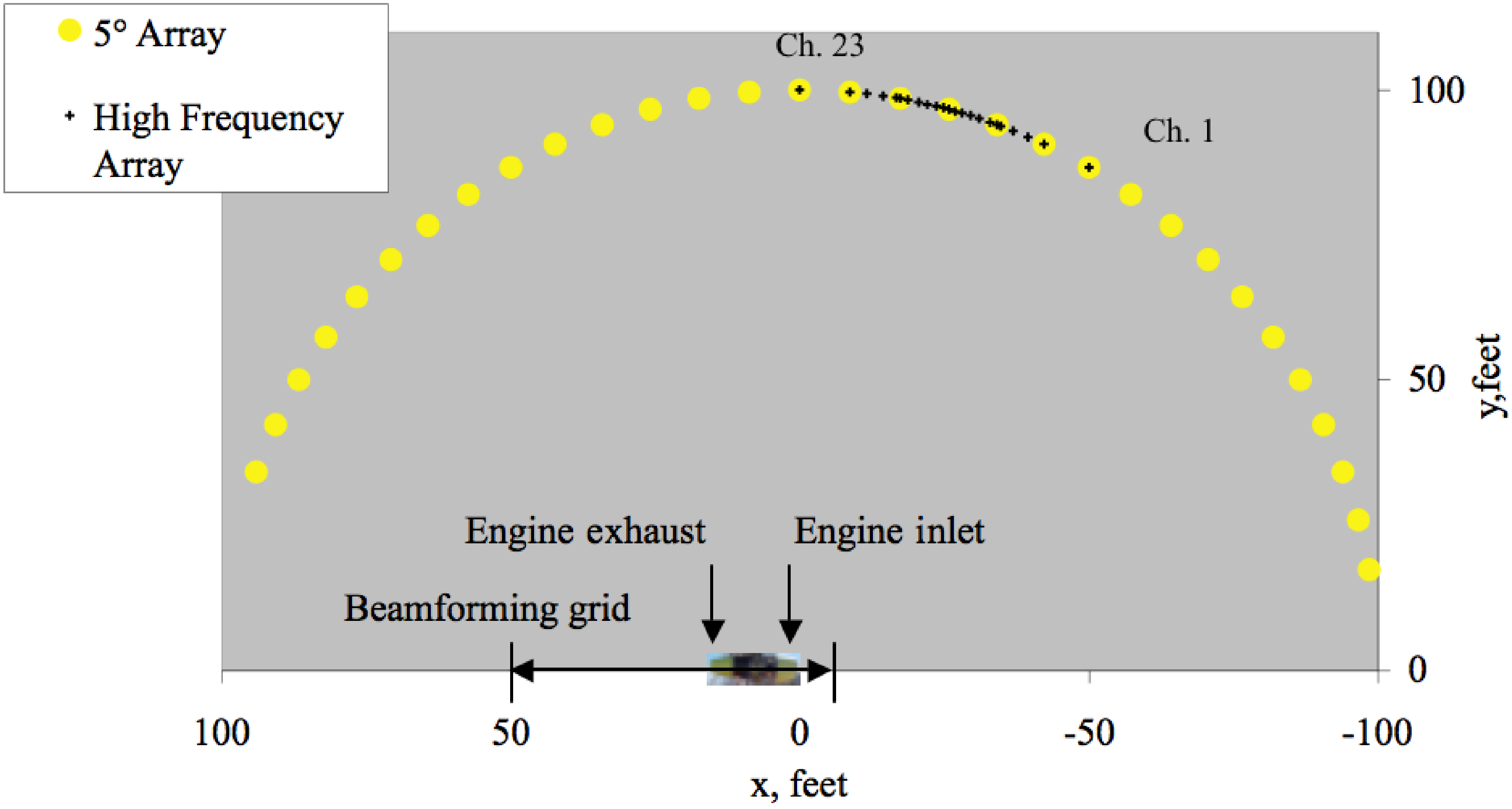
Aft fan, turbine,
combustor and
jet noise

NASA/Honeywell EVNERT 2006

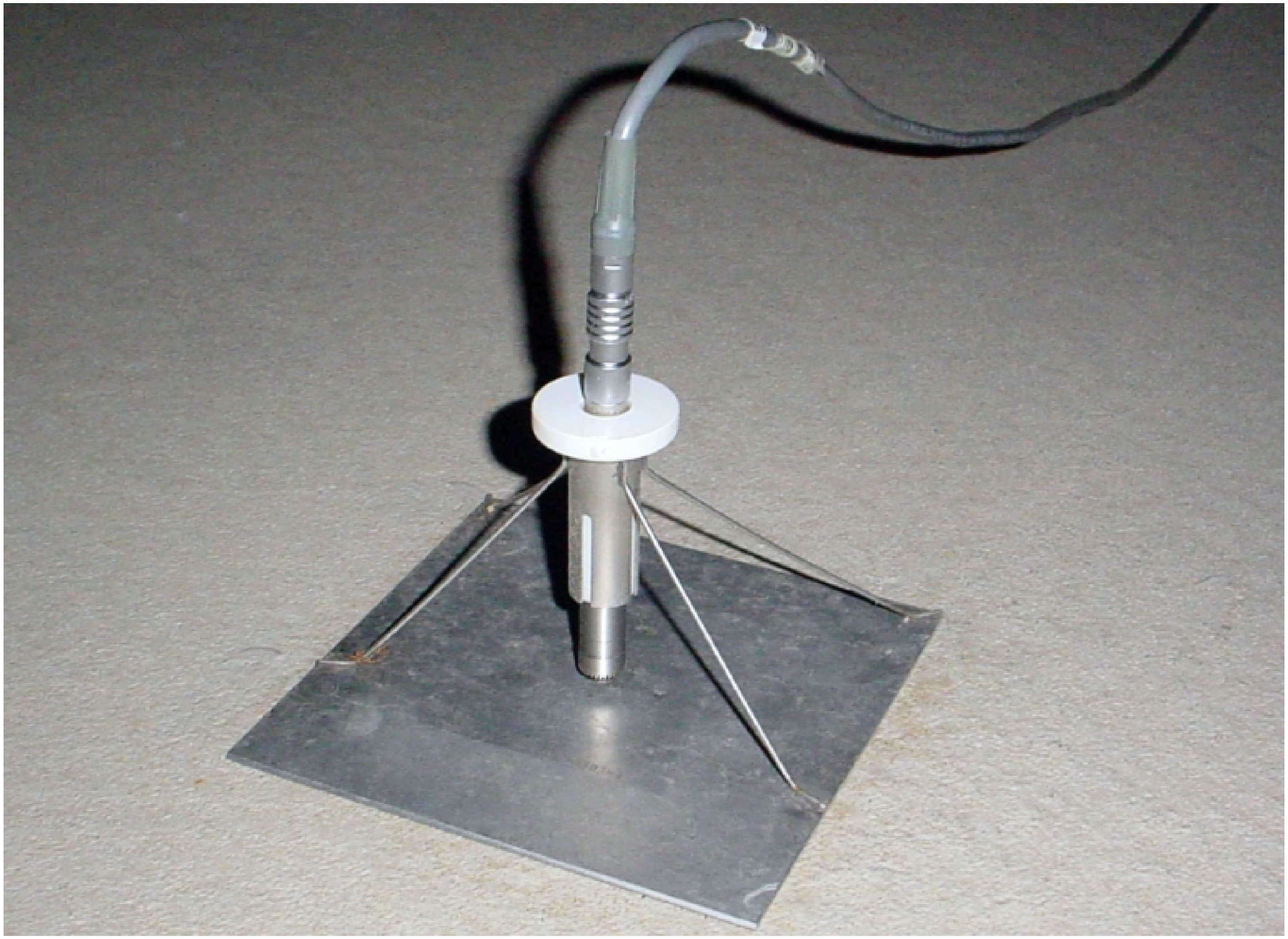
NASA/Honeywell EVNERT 2006



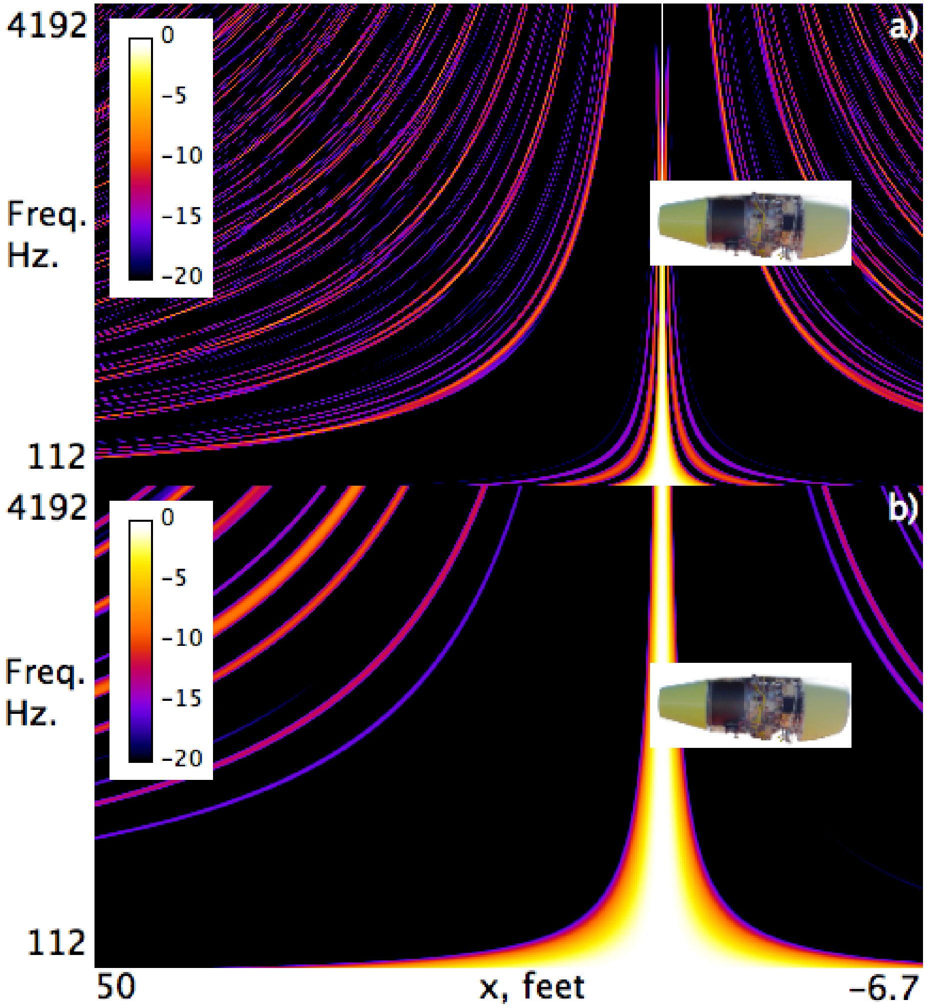
30.48 m Polar Arrays



Inverted B&K 4134



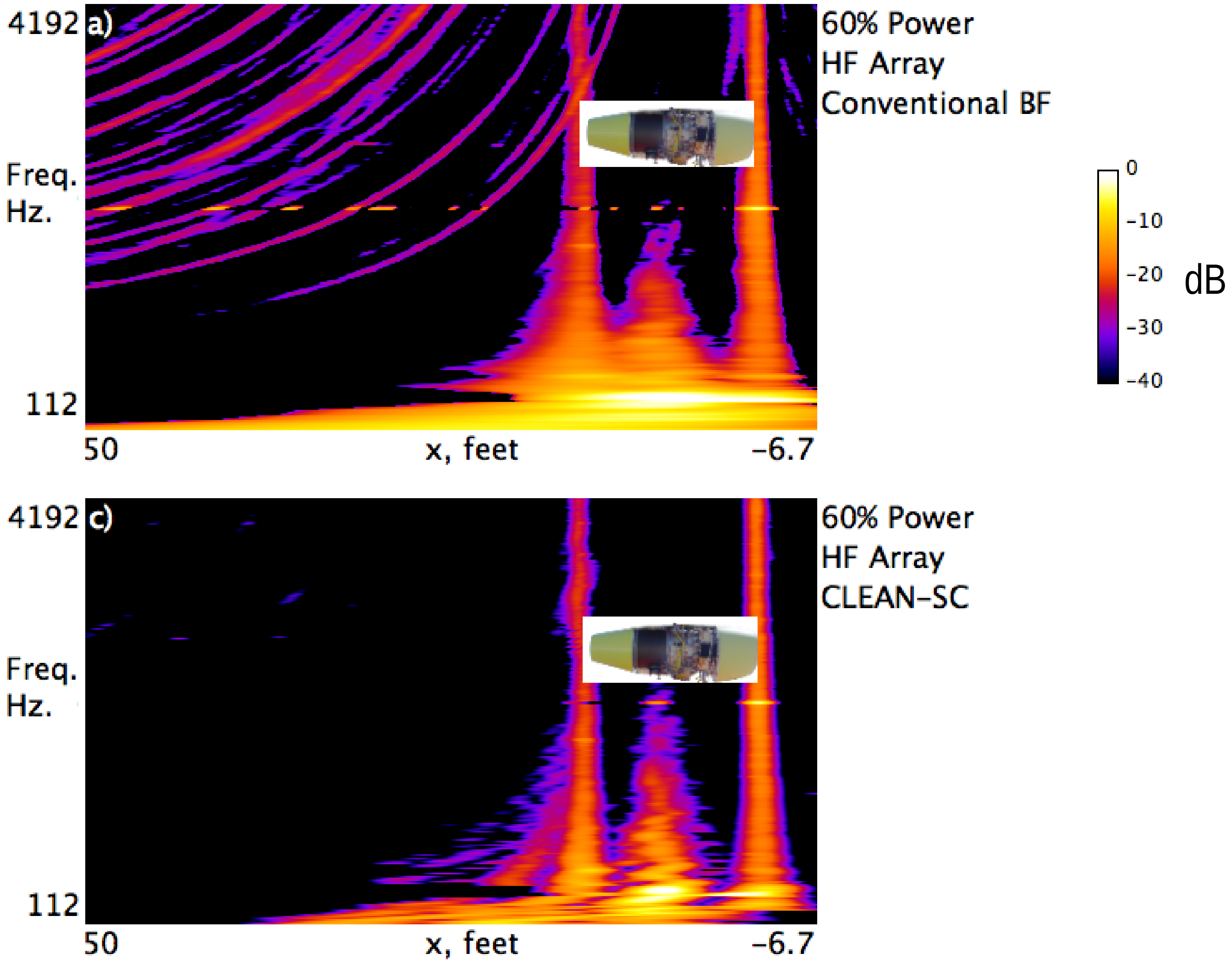
Point Spread Function



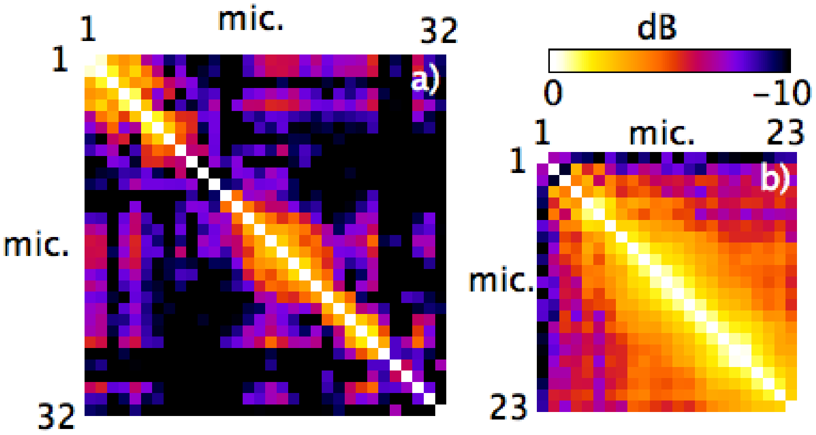
5° Polar Array

HF Array

60% Power, 5° High Frequency Array



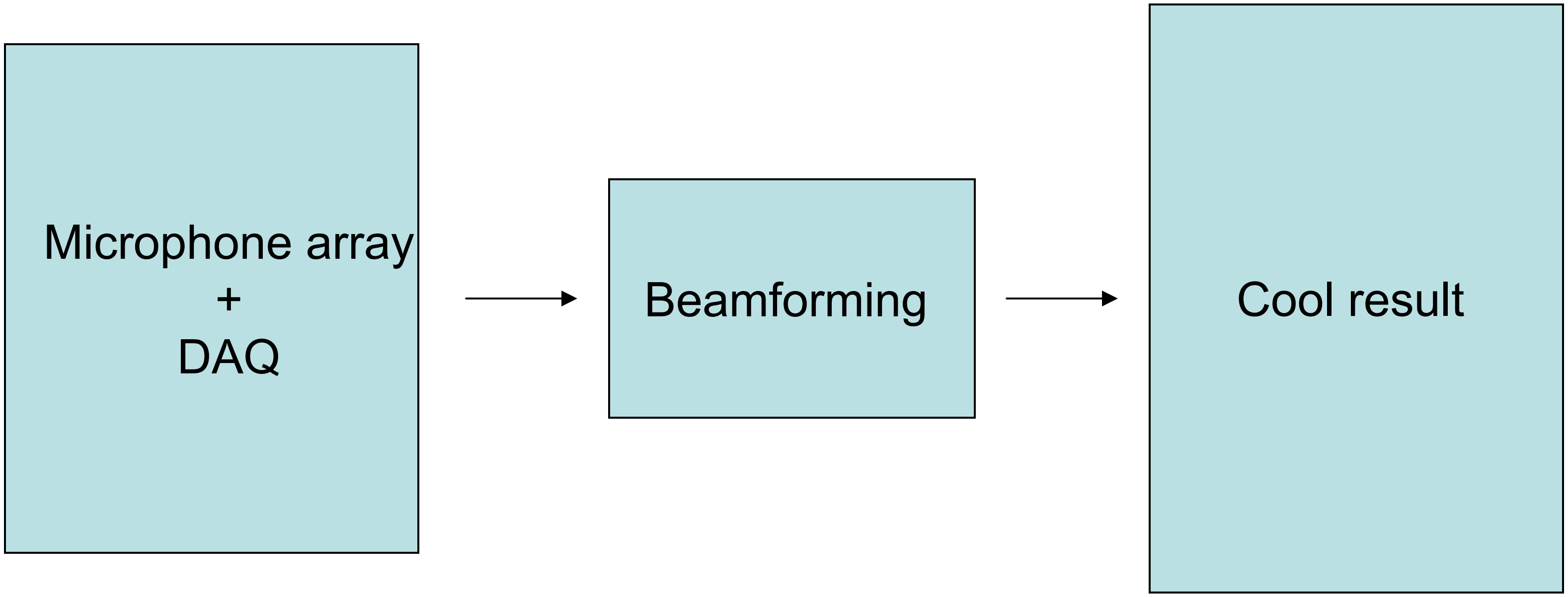
Array Coherence, 2048 Hz



5° Polar Array

HF Array

What is beamforming?



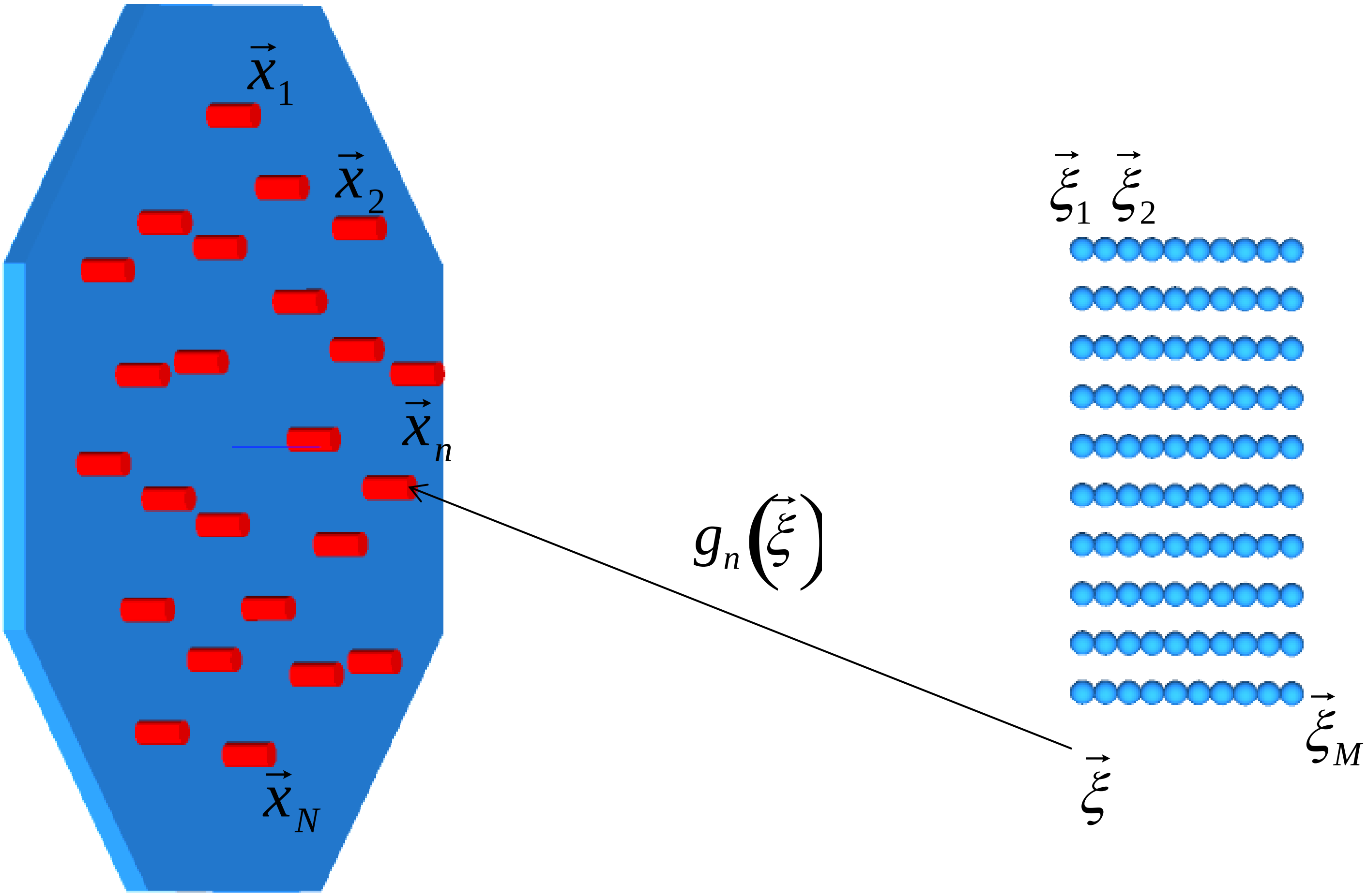
Microphone array
+
DAQ

→

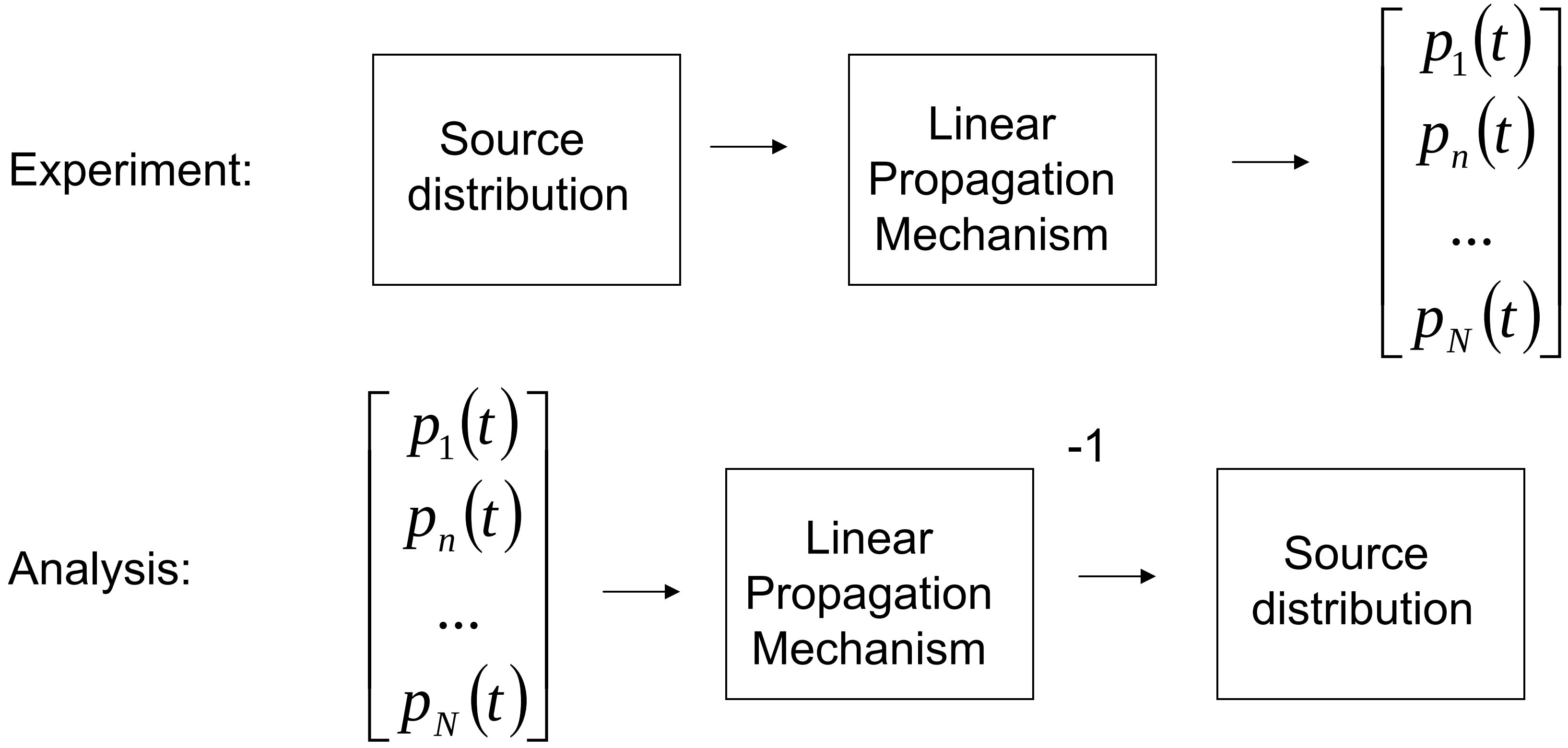
Beamforming

→

Cool result


$\vec{x}_1$
$\vec{x}_2$
$\vec{x}_n$
$\vec{x}_N$
$g_n(\vec{\xi})$
$\vec{\xi}_1$
$\vec{\xi}_2$
$\vec{\xi}_M$
$\vec{\xi}$

If the number of source points were ≤ *N*, it would be linear algebra problem



Experiment:

Source distribution → Linear Propagation Mechanism →

$$\begin{bmatrix} p_1(t) \\ p_n(t) \\ \dots \\ p_N(t) \end{bmatrix}$$

Analysis:

$$\begin{bmatrix} p_1(t) \\ p_n(t) \\ \dots \\ p_N(t) \end{bmatrix}$$

→ Linear Propagation Mechanism -1 → Source distribution

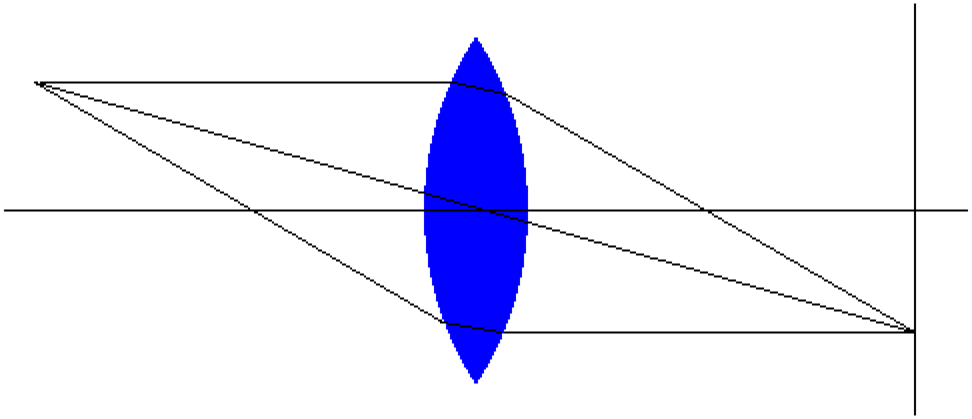
Examples of the linear algebra case (low frequency)

- Modes in cavities
- Modes ducts
- Antenna patterns
- Spherical waves near the source
- Nearfield Acoustic Holography (?)

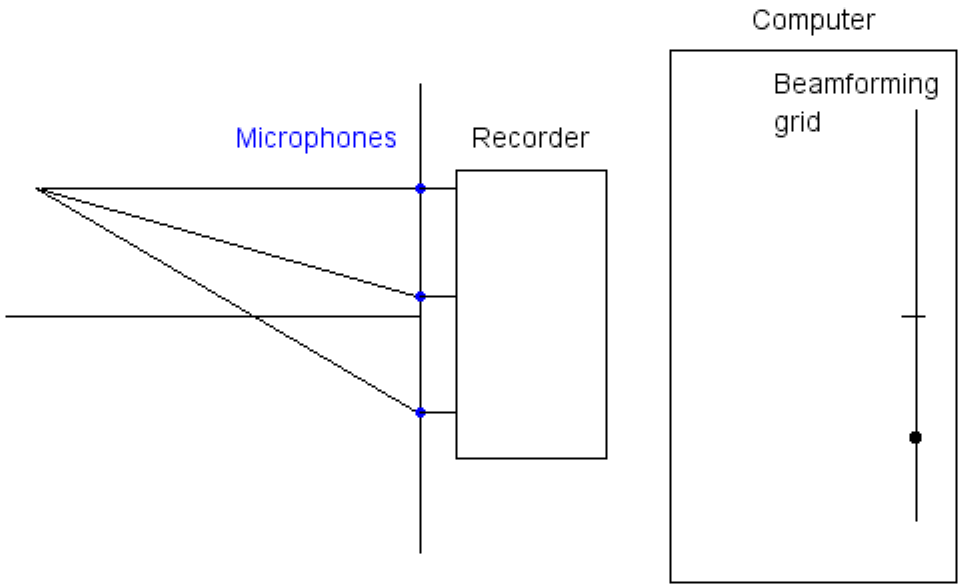
Beamforming is Different

- 2 m airframe noise model at 40 kHz
- Nacelle inlet with 10000 cuton modes
- All the stars in the sky

Optical Beamforming



Acoustics Beamforming



Time-Domain Beamforming

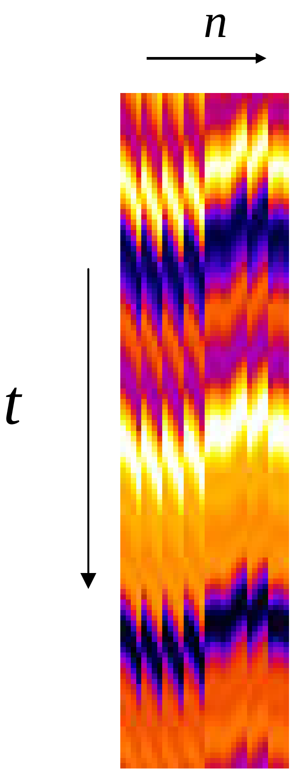
Delay and Sum:

$$b_{TD}\left(\vec{\xi}\right)=\frac{1}{T}\int_0^T\left[\sum_{n=1}^{N}p_n\left(t+\Delta_n\left(\vec{\xi}\right)\right)\right]^2 dt$$

$$=\left\langle\left[\sum_{n=1}^{N}p_n\left(t+\Delta_n\left(\vec{\xi}\right)\right)\right]^2\right\rangle$$

Idea

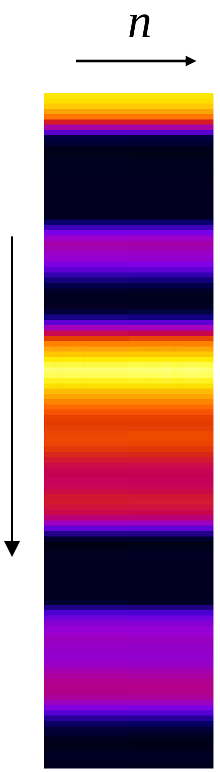
Case of one source at $\vec{\xi}_j$



Array data

Delay

$$t + \Delta_n\left(\vec{\xi}_j\right)$$



Array data in emission time

Frequency-Domain Model

$$\mathbf{p} = \sum_{j=1}^{M} q_j \mathbf{g}\left(\vec{\xi}_j\right) + \mathbf{R}$$

N_I complex *N*-vectors of data p

M complex source time histories $q_j,\ j = 1, \ldots, M$

each of which has N_I values

$N \times M$ complex propagation factors $g_n\left(\vec{\xi}_j\right)$

N_I complex *N*-vectors of microphone self noise $\mathbf{R}$

Beam Steering

$$u\left(\vec{\xi}\right) = \alpha\, \mathbf{g}'\left(\vec{\xi}\right)\mathbf{p} = \alpha \sum_{n=1}^{N} g_n'^{*}\left(\vec{\xi}\right) p_n$$

$$\alpha = \frac{1}{\left\|\mathbf{g}\right\|^2}$$

$$u\left(\vec{\xi}_k\right) = q_k + \alpha \sum_{j\neq k} q_j \mathbf{g}'\left(\vec{\xi}_k\right)\mathbf{g}\left(\vec{\xi}_j\right) + \alpha\, \mathbf{g}'\left(\vec{\xi}_k\right)\mathbf{R}$$

Some Free Space Models

$$g_n\left(\vec{\xi}\right) = -i\rho_0 \frac{\omega}{2\pi\left|\vec{\xi} - \vec{x}_n\right|} e^{ik\left|\vec{\xi} - \vec{x}_n\right|}$$

$$g_n\left(\vec{\xi}\right) = \frac{e^{ik\left|\vec{\xi} - \vec{x}_n\right|}}{\left|\vec{\xi} - \vec{x}_n\right|}$$

$$g_n\left(\vec{\xi}\right) = e^{ik\left|\vec{\xi} - \vec{x}_n\right|}$$

$$g_n\left(\vec{\xi}\right) = \frac{\left|\vec{\xi} - \vec{x}_{\mathrm{reference}}\right|}{\left|\vec{\xi} - \vec{x}_n\right|} e^{ik\left|\vec{\xi} - \vec{x}_n\right|}$$

Comments

$N \geq M$ could be the linear algebra case

$w_n\left(\vec{\xi}\right)=\left|\vec{\xi}-\vec{x}_{\mathrm{n}}\right|e^{ik\left|\vec{\xi}-\vec{x}_n\right|}$ indicates a lack of understanding

Classical Beamforming

$$b\left(\vec{\xi}\right) = \left\langle \left| u\left(\vec{\xi}\right) \right|^2 \right\rangle = \alpha^2 \mathbf{g}'\left(\vec{\xi}\right) \mathbf{C} \mathbf{g}\left(\vec{\xi}\right)$$

$$\mathbf{C} = \left\langle \mathbf{p}\mathbf{p}' \right\rangle$$

Classical Beamforming with Trimmed CSM

$$b\left(\vec{\xi}\right) = \alpha^2 \mathbf{g}'\left(\vec{\xi}\right)\overline{\mathbf{C}}\mathbf{g}\left(\vec{\xi}\right)$$

$$\overline{C}_{mn} = \left\langle p_m p_n^* \right\rangle \qquad S = \left\{(m, n) \middle| \overline{C}_{mn} \text{ is included}\right\}$$

$$\alpha = \frac{1}{\sqrt{\sum_{(m,n)\in S} \left|g_m\right|^2 \left|g_n\right|^2}}$$

Expectation Value and Variance

$$E\left[b\left(\vec{\xi}\right)\right]=\sum_{j=1}^{M}A_j\left(\vec{\xi}\right)s_j+\alpha^2\sum_{(m,n)\in S}g_m^*\left(\vec{\xi}\right)g_n\left(\vec{\xi}\right)\delta_{mn}r_n$$

s_j = power of source *j* = $E\left(q_j^*q_j\right)$

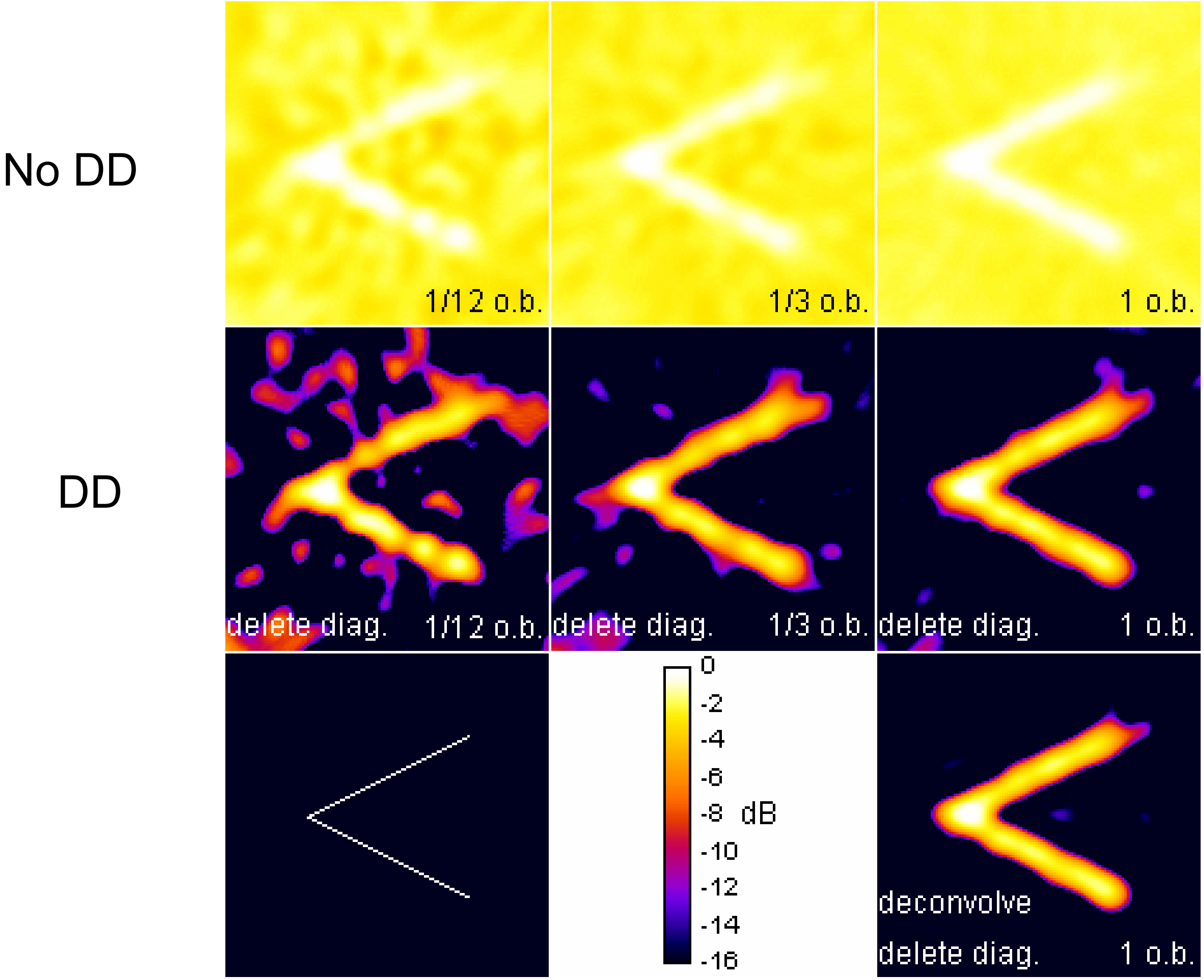
r_n = self noise power of microphone *n* = $E\left(R_n^*R_n\right)$

$$A_j\left(\vec{\xi}\right)=\alpha^2\sum_{(m,n)\in S}g_m^*\left(\vec{\xi}\right)g_m\left(\vec{\xi}_j\right)g_n^*\left(\vec{\xi}_j\right)g_n\left(\vec{\xi}\right)$$

$$A_j\left(\vec{\xi}_j\right)=1$$

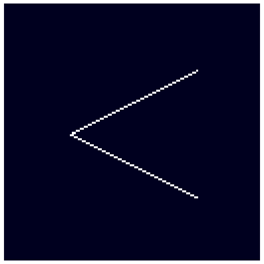
Beamforming peak variance $\mathrm{var}\left(\left|p_{bp}\right|^2\right)=\frac{2p^2}{N_I}+\frac{r^2}{N_I}$ (unit magnitude *g*)

Distributed Source Results

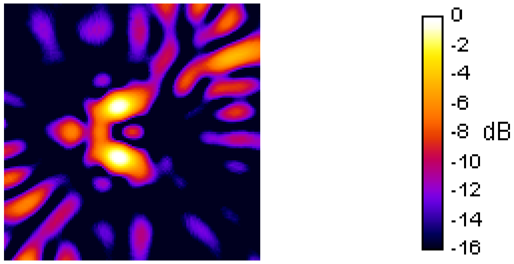


Distributed Coherent Source, no Self Noise

Source
4000 Hz tone



BF,
all source points +



Choice of Method

- Time-Domain
  - Delay and Sum
- Frequency Domain
  - Phase-Shift and Sum
  - Classical (Bartlett) Beamforming

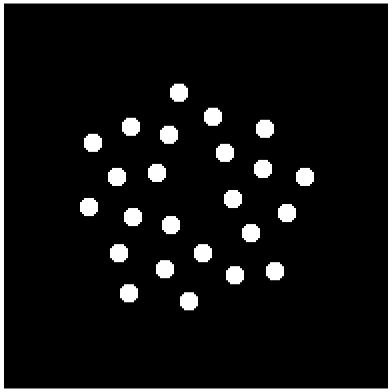
- Time-domain may be better for wide analysis bands
- Time-domain is simpler for moving sources
- Frequency-domain is faster (FFT)
- Bartlett is fastest for large grids
- Bartlett is simpler for advanced techniques
  - Linear algebra with the CSM
  - Optimization-based derivations
  - CLEAN-SC
  - Non-trivial Green’s functions

Array Design

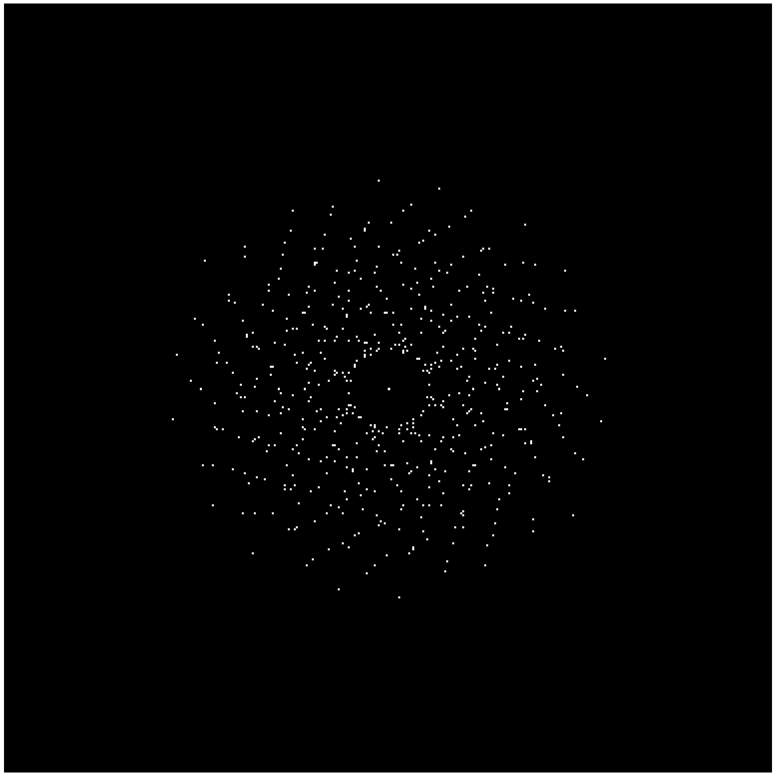
$$A_j\left(\vec{\xi}\right)=\alpha^2\sum_{(m,n)\in S}g_m^*\left(\vec{\xi}\right)g_m\left(\vec{\xi}_j\right)g_n^*\left(\vec{\xi}_j\right)g_n\left(\vec{\xi}\right)$$

Array48

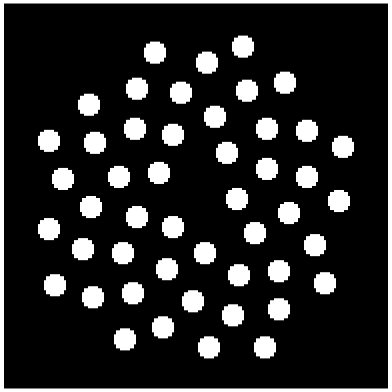
24 microphones

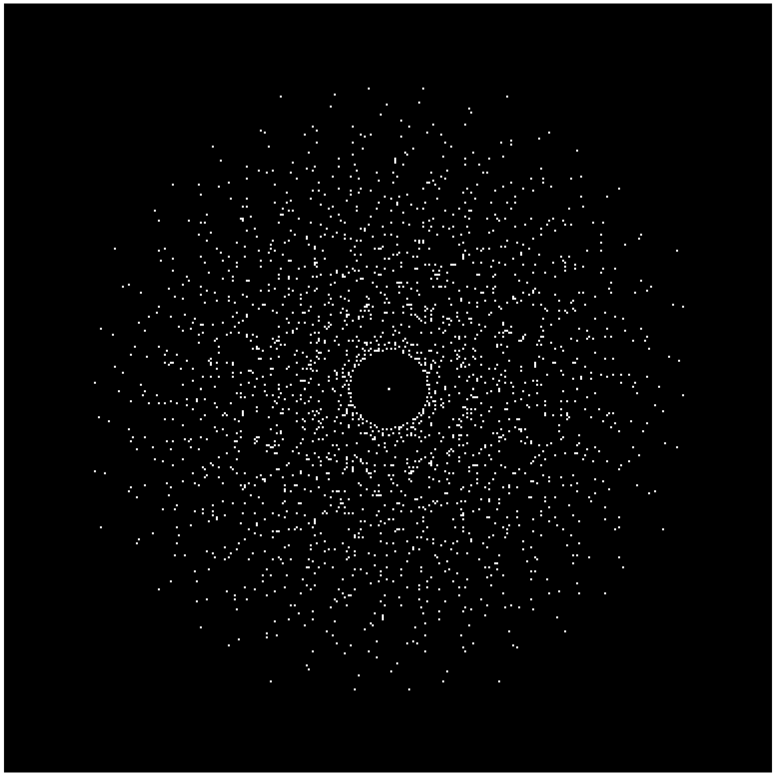


4 ft.



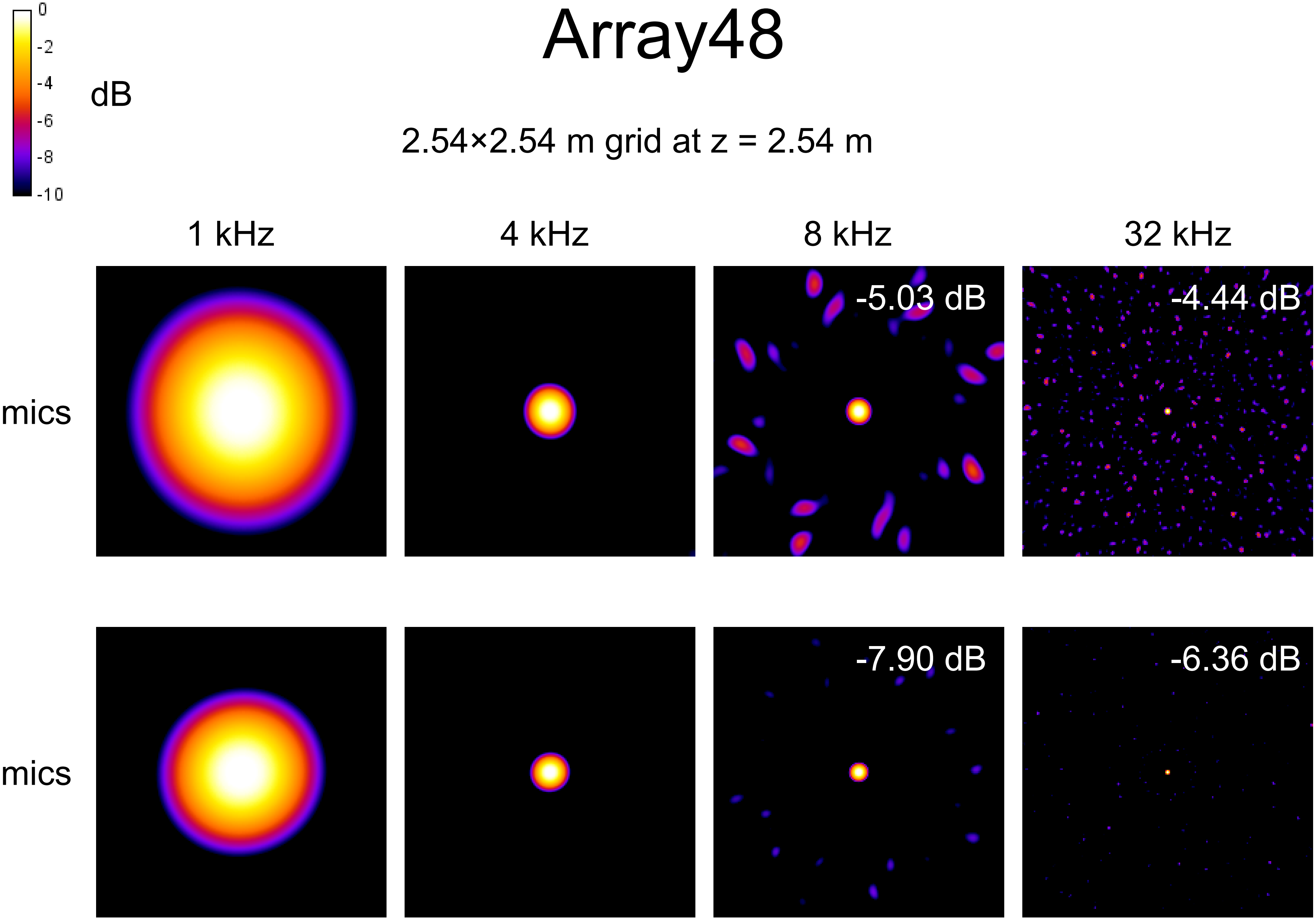
48 microphones





Array48

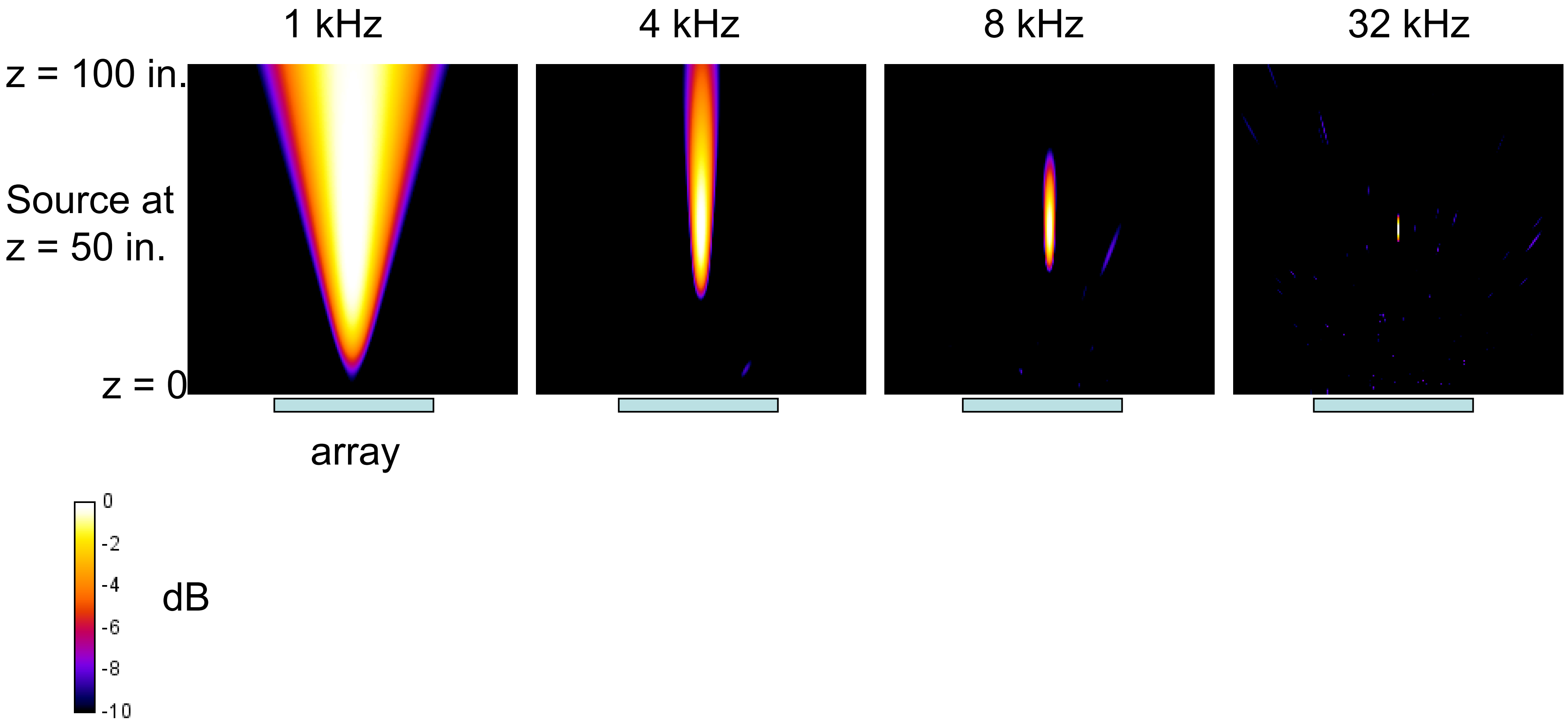
2.54×2.54 m grid at z = 2.54 m



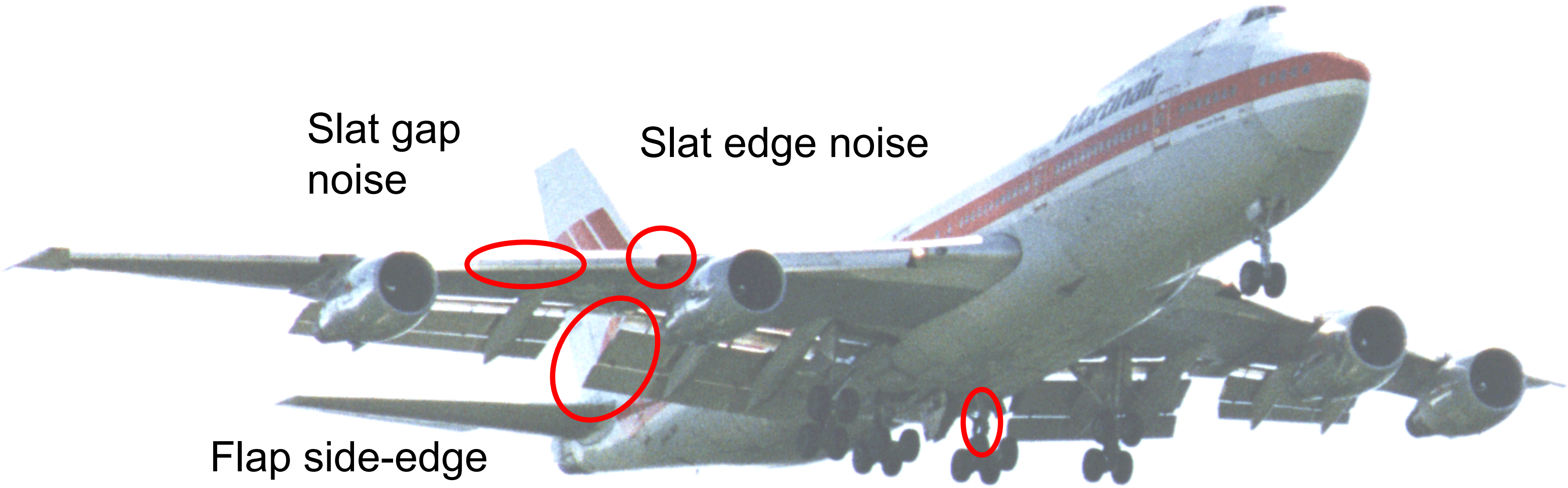
OptiNav

Array48: Depth Resolution

2.54×2.54 m grid at y = 0 m
48 microphones



Airframe Noise Applications

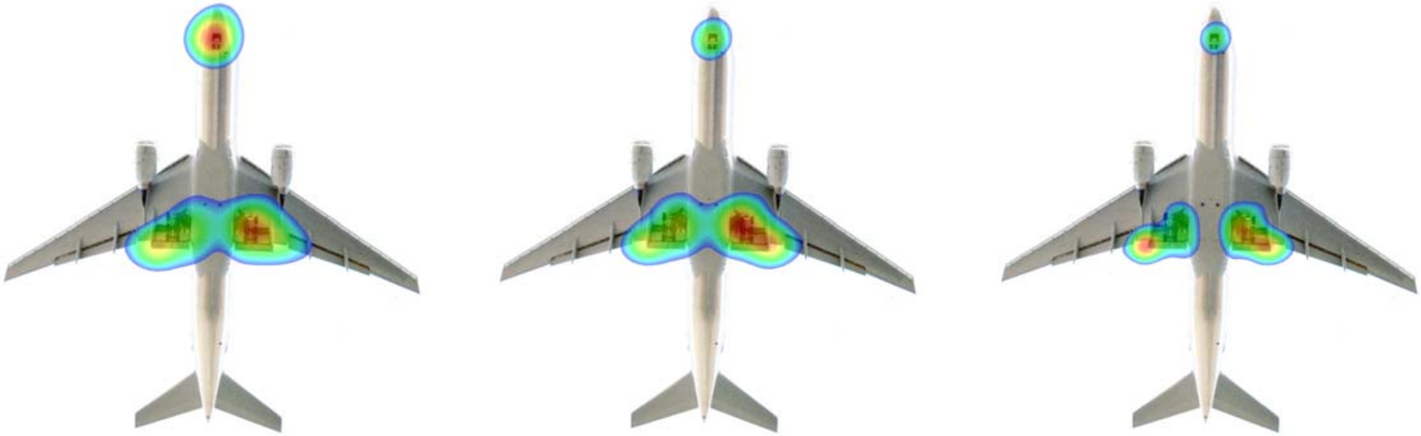


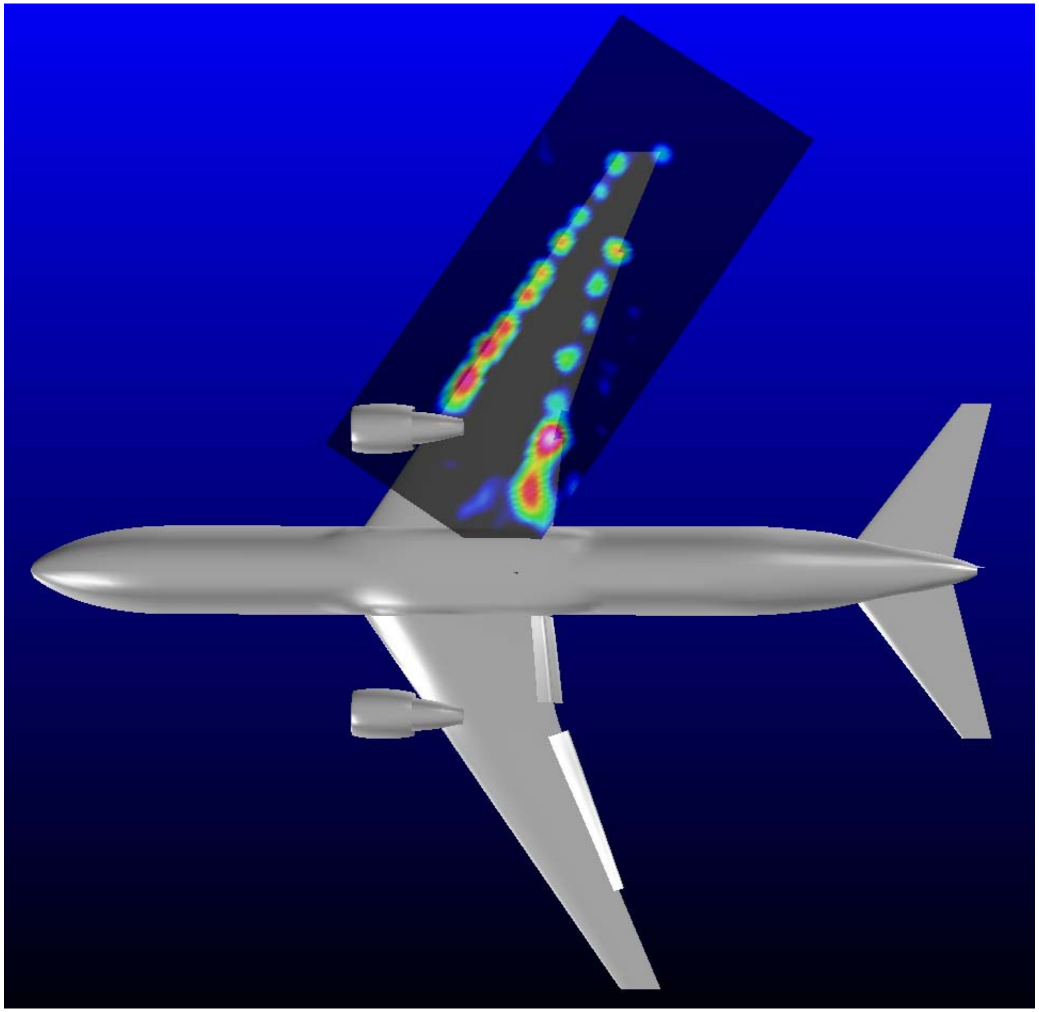
Slat gap noise

Slat edge noise

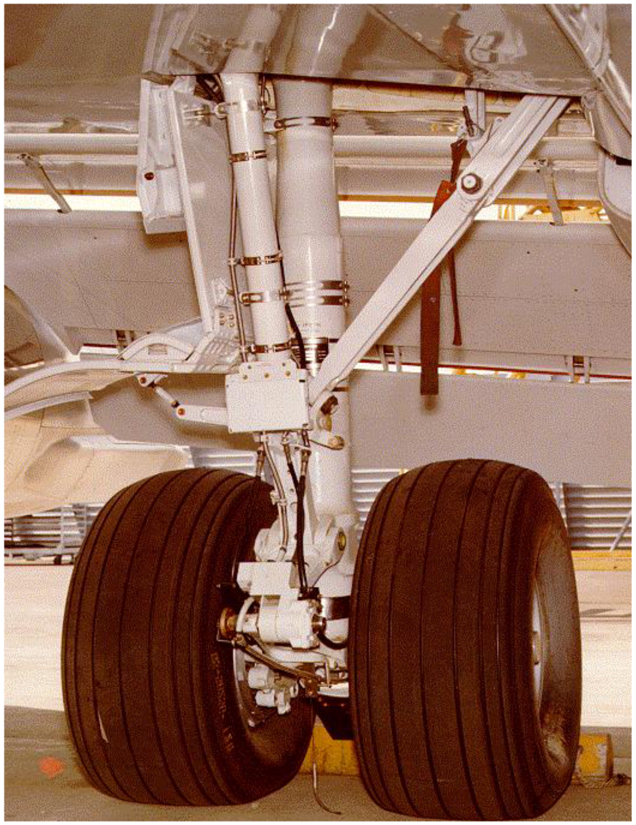
Flap side-edge noise

Gear noise





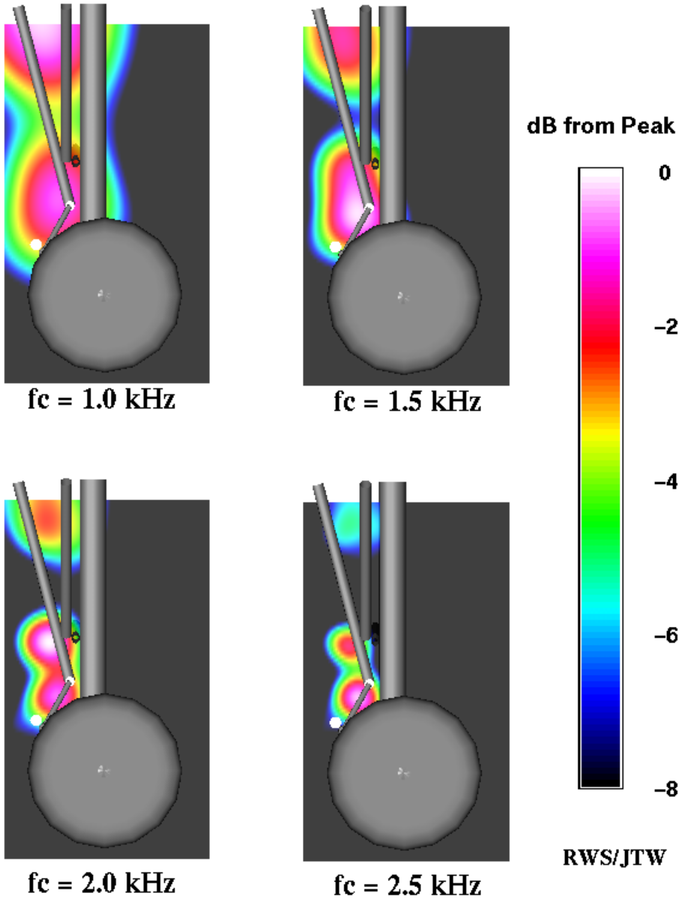
RWS



Full–Scale Landing Gear Noise Test

Mach: 0.24 Run: B061AN

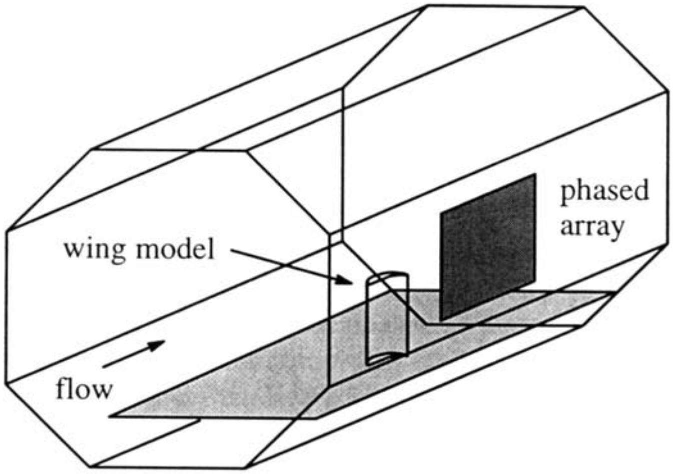
Array Position: 90 (deg) Configuration: Clean

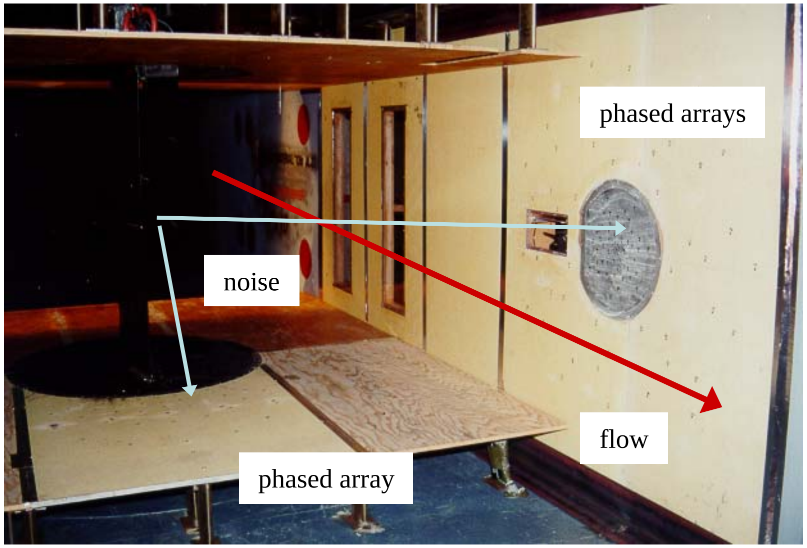


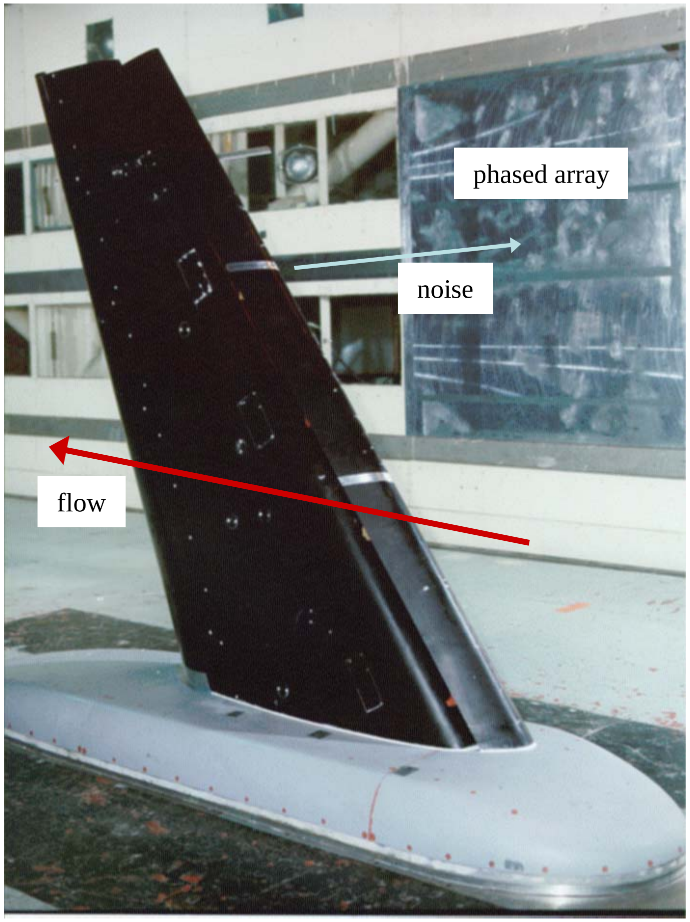
August 30, 1998 03:09:05 PM

Accounting for Convection

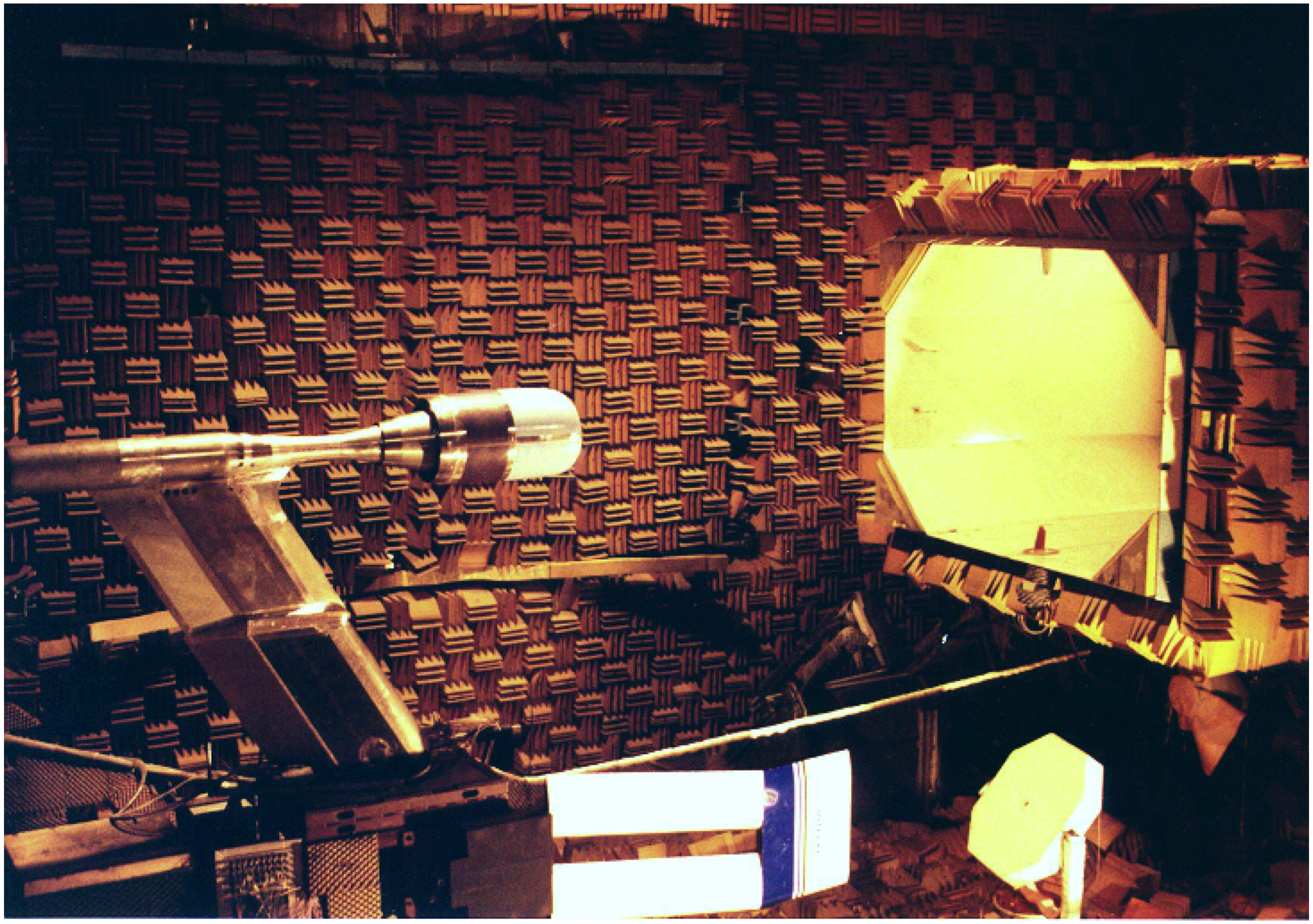
Wind tunnel testing: setup for a closed jet test



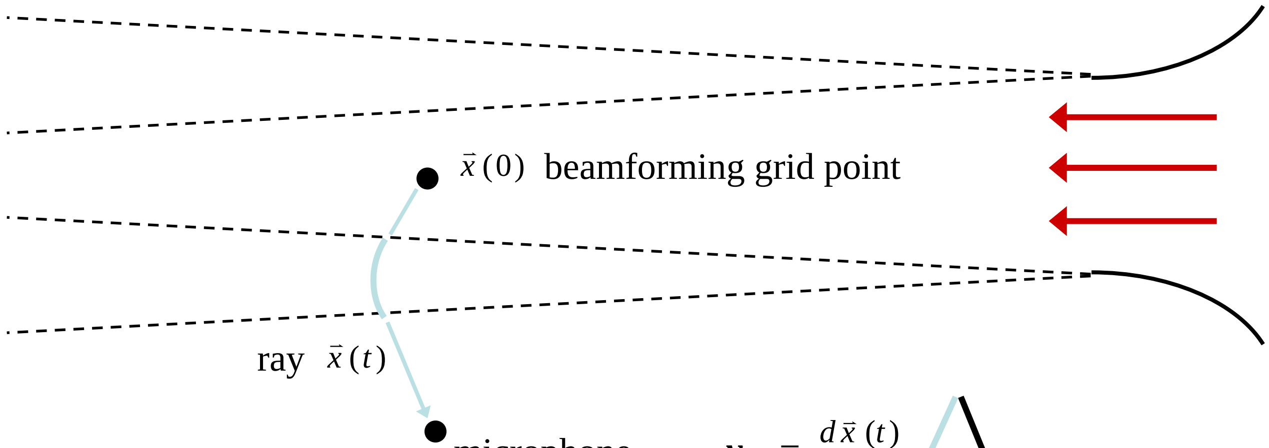




Boeing/GE LSAF Test 1993



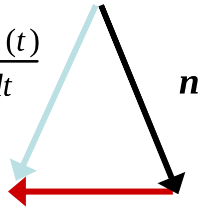
Wind tunnel testing: convection issues



$\vec{x}(0)$ beamforming grid point

ray $\vec{x}(t)$

microphone



$\boldsymbol{v}_{\text{ray}} = \frac{d\vec{x}(t)}{dt}$

$\boldsymbol{n}\,c$ (would be $\boldsymbol{v}_{\text{ray}}$ without flow)

$\boldsymbol{v} = \boldsymbol{M}\,c$

Ray tracing equations

$$\frac{d\boldsymbol{x}(t)}{dt} = \frac{c^2\boldsymbol{s}}{\Omega} + \boldsymbol{v}_0$$

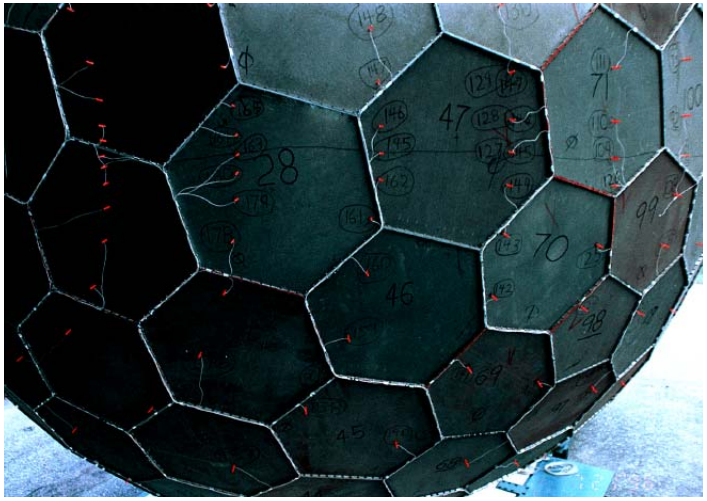
$$\frac{d\boldsymbol{s}(t)}{dt} = -\frac{\Omega}{c}\nabla c - \boldsymbol{s}\times\left(\nabla\times\boldsymbol{v}_0\right) - (\boldsymbol{s}\cdot\nabla)\boldsymbol{v}_0$$

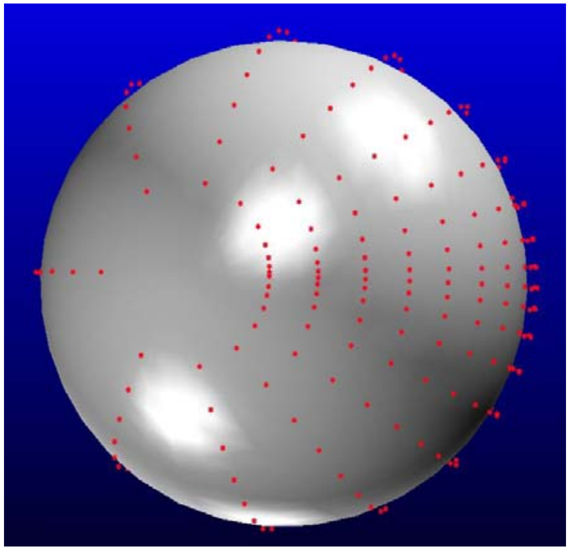
where $\boldsymbol{s} = \frac{\Omega\boldsymbol{n}}{c}$ and $\Omega = \frac{c}{c + \boldsymbol{v}\cdot\boldsymbol{n}}$

Fan and LPC Noise

Boeing/Rolls Royce

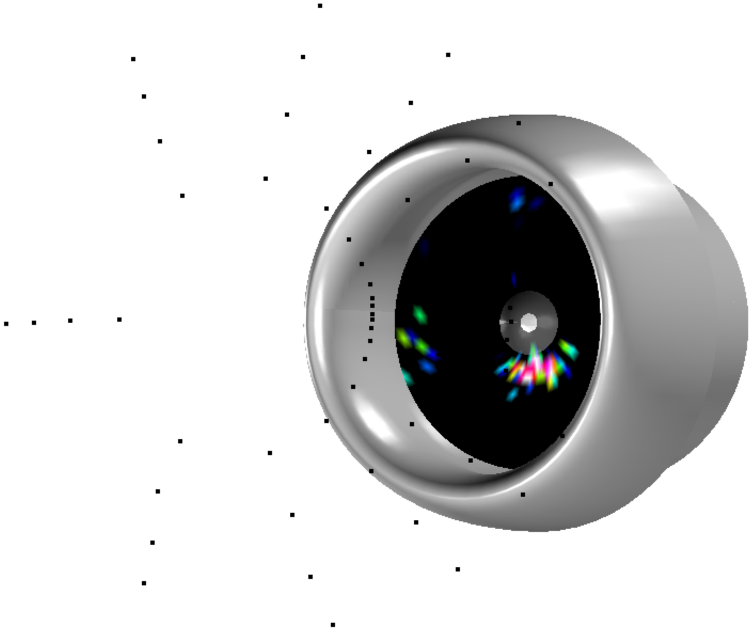
Boeing/Pratt&Whitney ICD Array, 1999

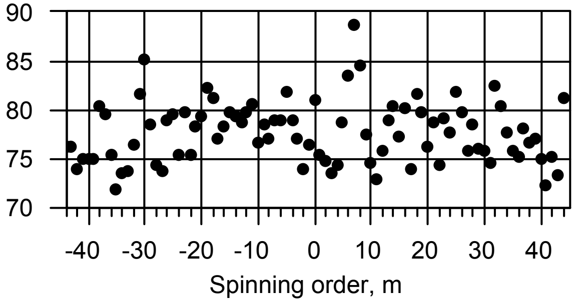


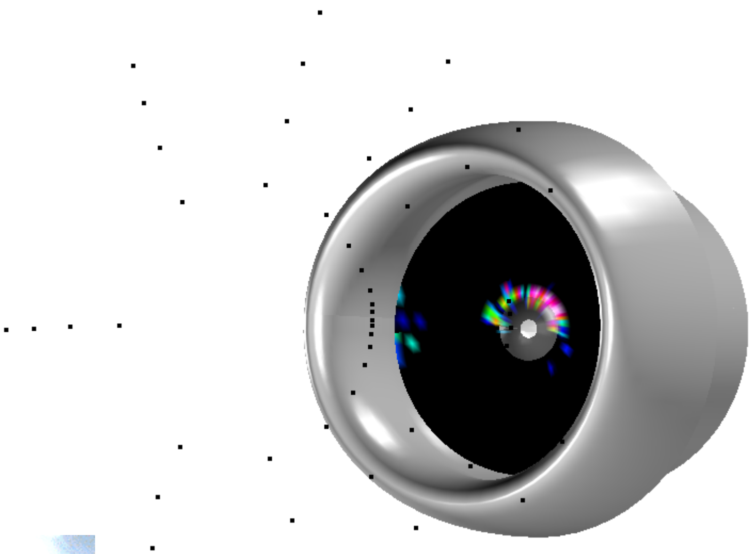


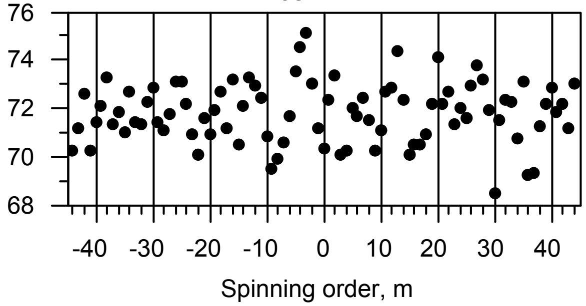
Co-rotating mode

Counter-rotating mode







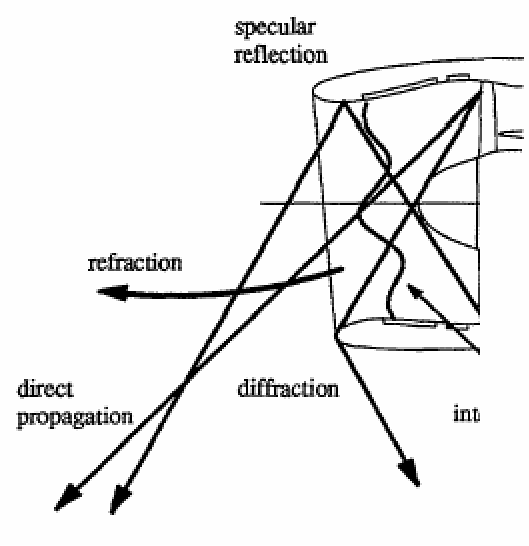


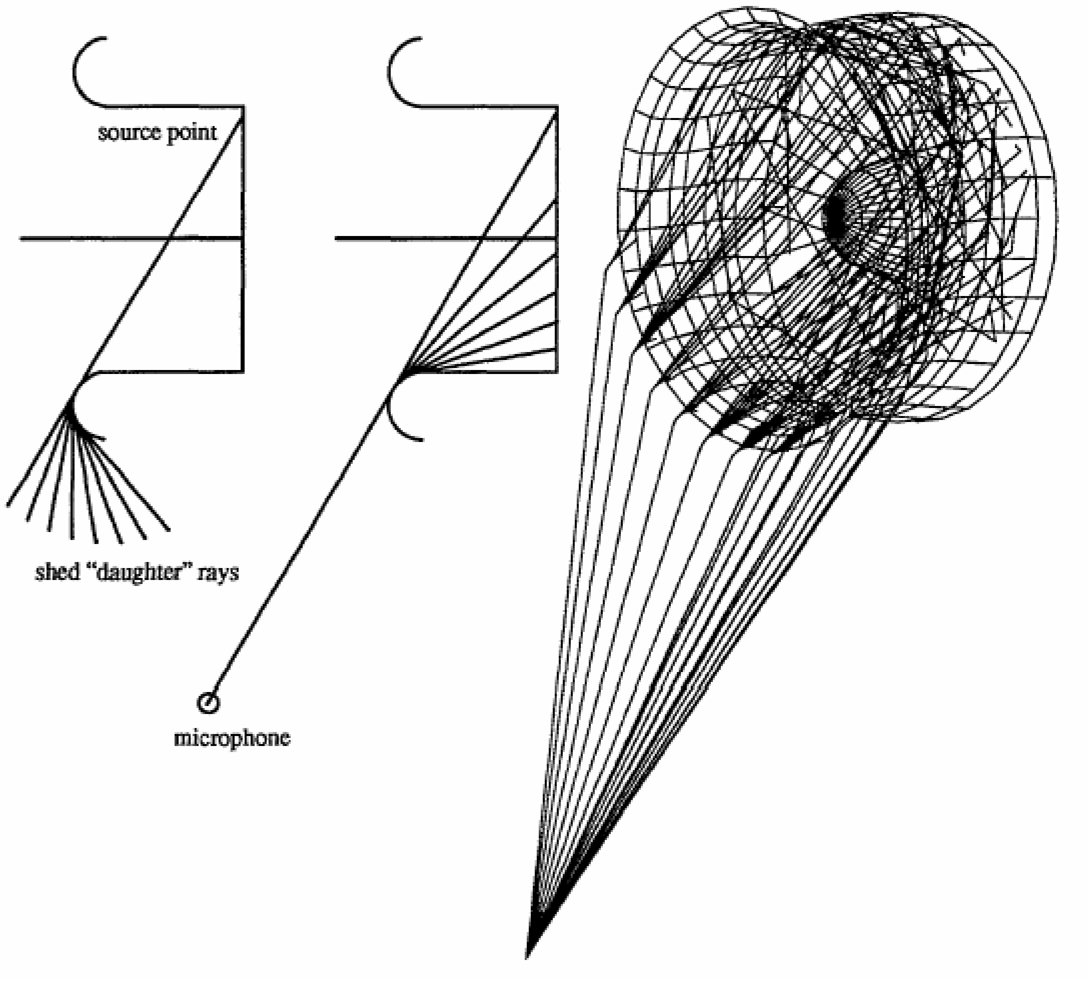
AARC TUBE* 2006

*Thematic Uniaxial Bladeless Environment

Boeing Large Test Chamber
Jan. 10, 2006

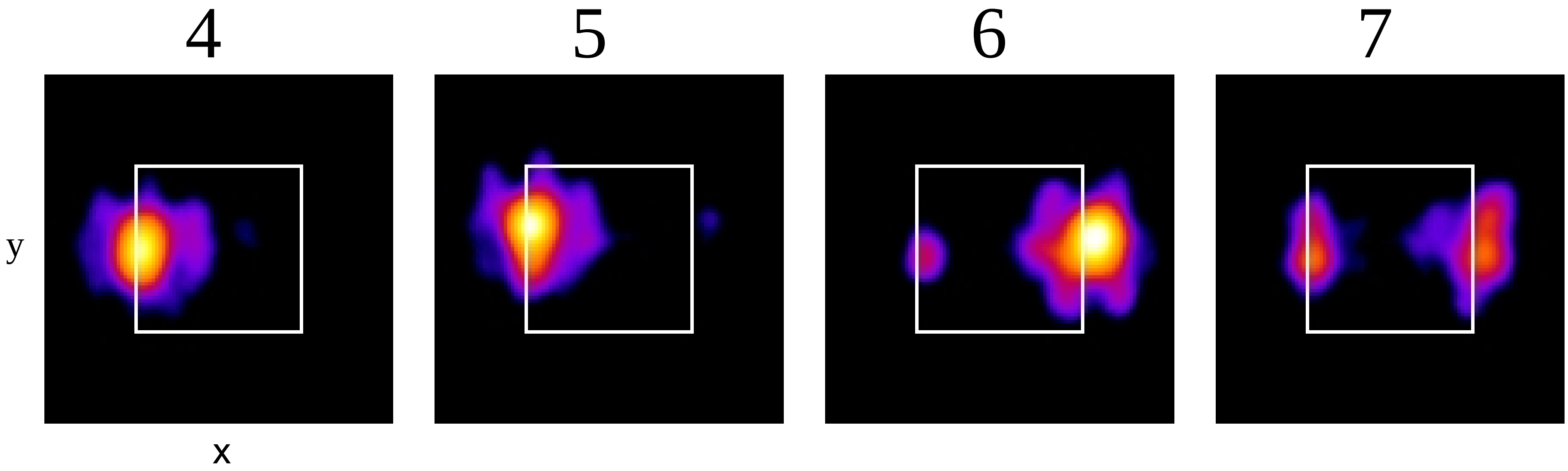
Review of propagation mechanisms





AIAA 1996-1773 (RDIFF)

Regular Beamforming for Broadside Configs.



16 kHz, 1 octave BW, 10 dB color scale, outer array

Beamforming results

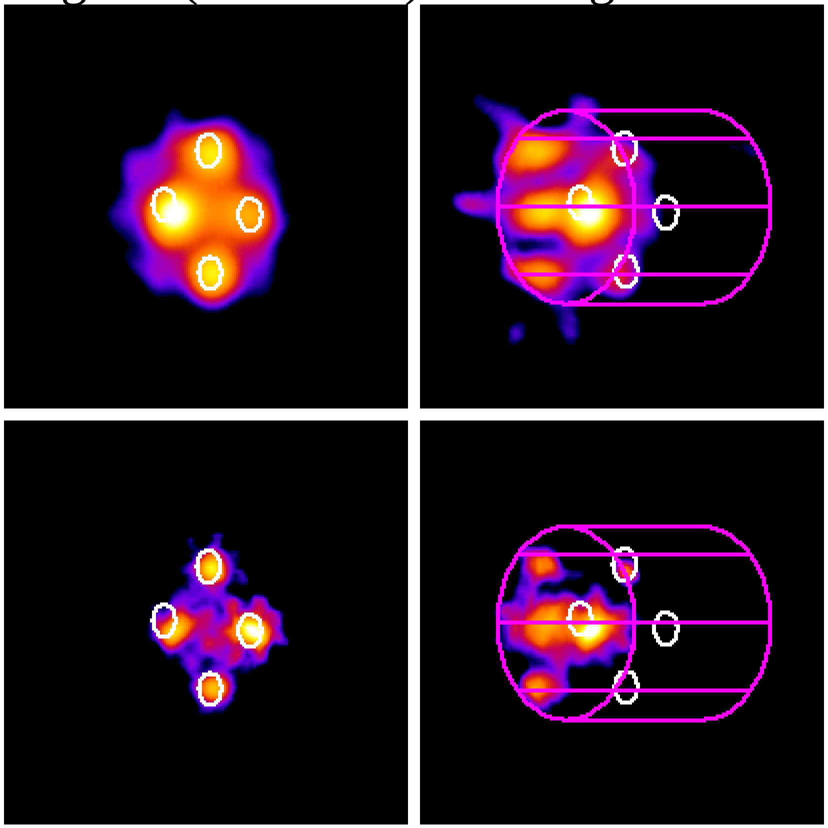
Cfg. 11 (no TUBE)

Cfg. 10

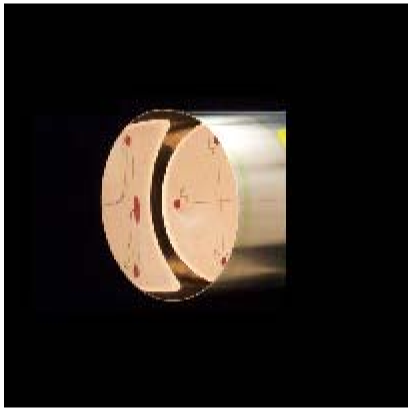
1/3 o.b.

15 kHz

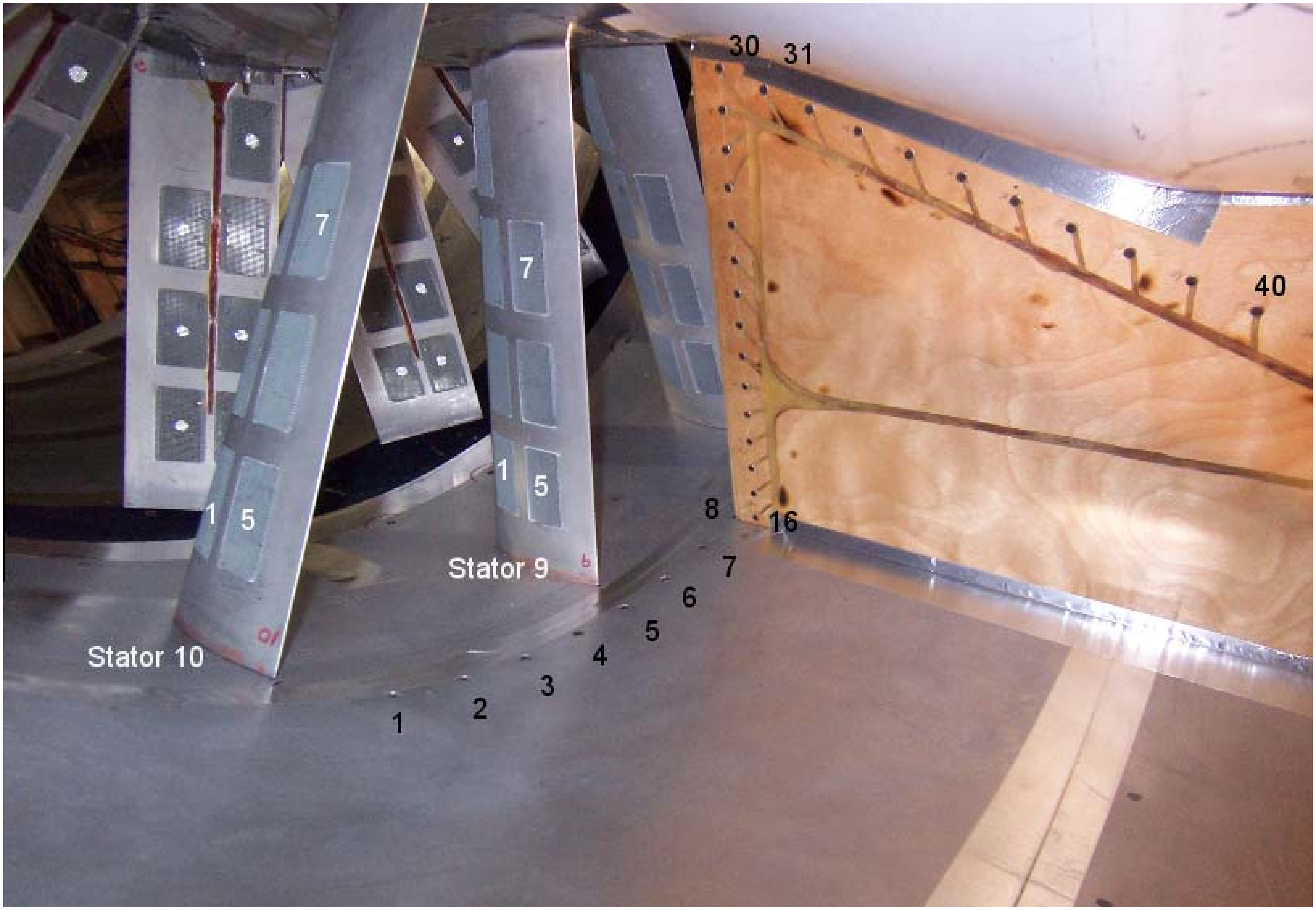
30 kHz



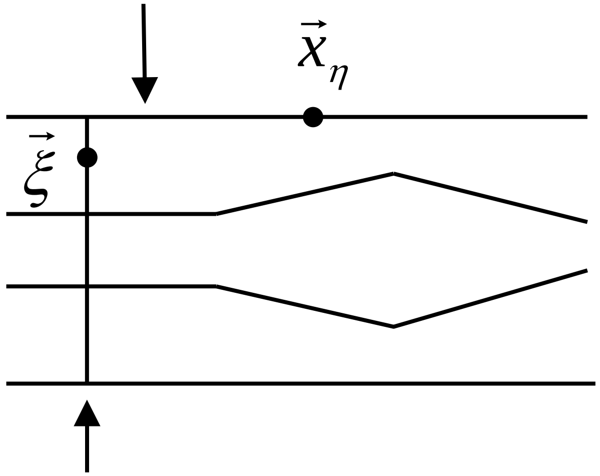
10 inch Optical



AARC, NASA ANCF Testing



Array steering vectors: modal expansions



Uniform annular duct segment

Source plane

Orthonormal modes for the
uniform annular duct

Modes for the
rest of the duct
(incident + scattered)

$$g_\eta\left(\vec{\xi}\right) = \sum_{mn} \varphi^*_{mn}\left(\vec{\xi}\right)\psi_{mn}\left(\vec{x}_\eta\right)$$

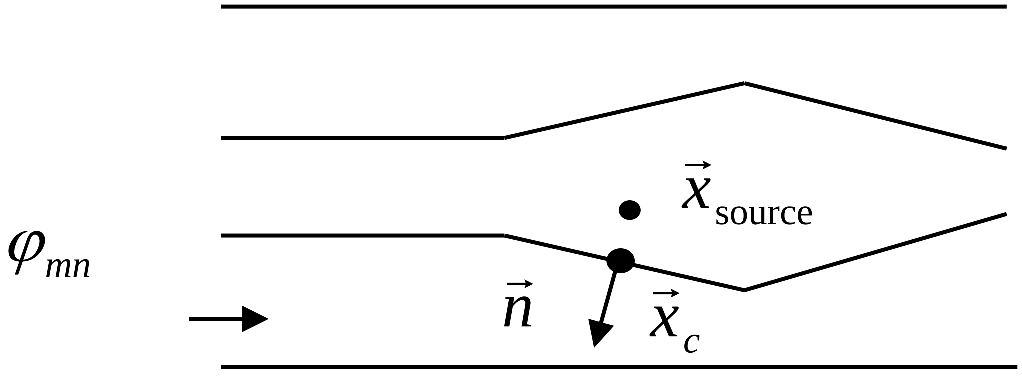
Boundary element code: formulation

Incident mode

Scattering

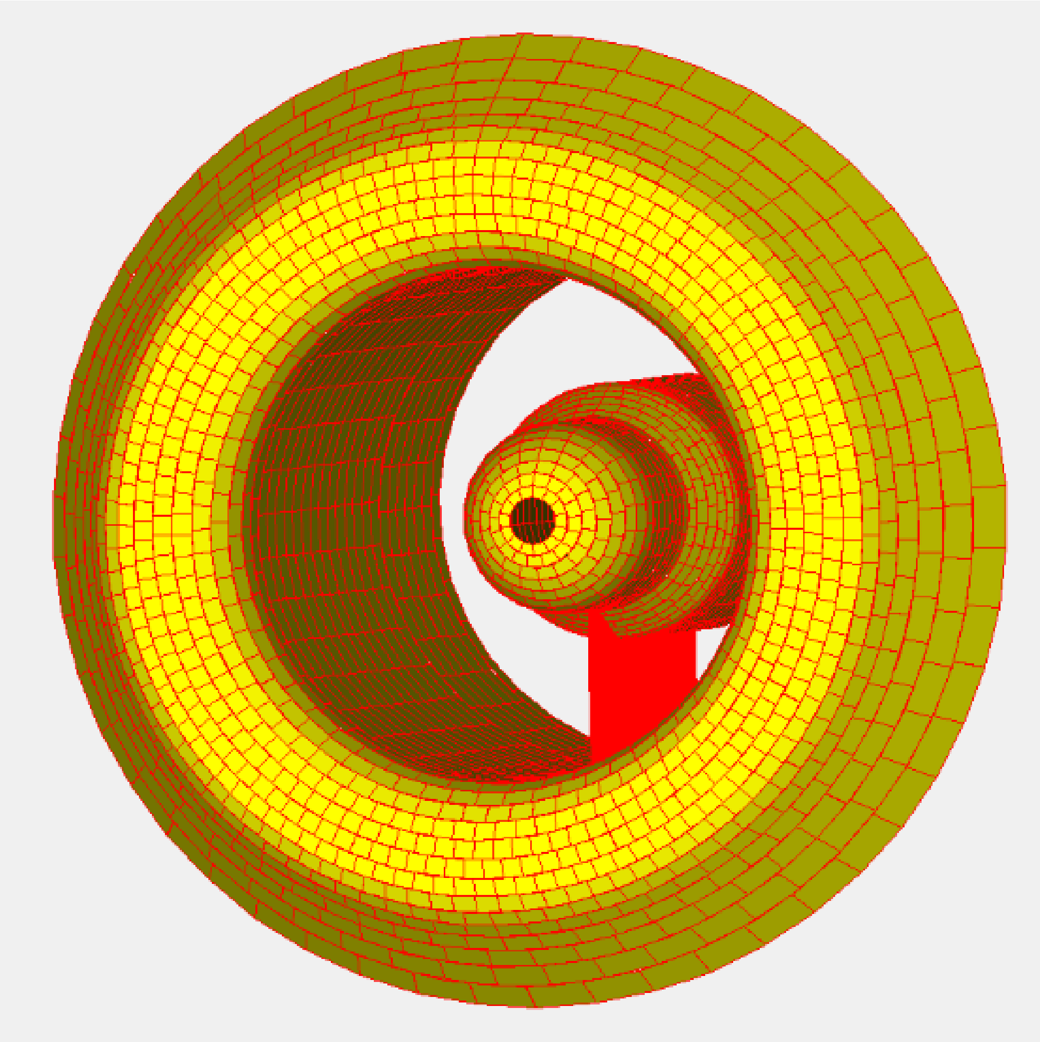
$$\psi_{mn}(\vec{x}_c) = \varphi_{mn}(\vec{x}_c) + \sigma(\vec{x}_c)$$

Collocation point

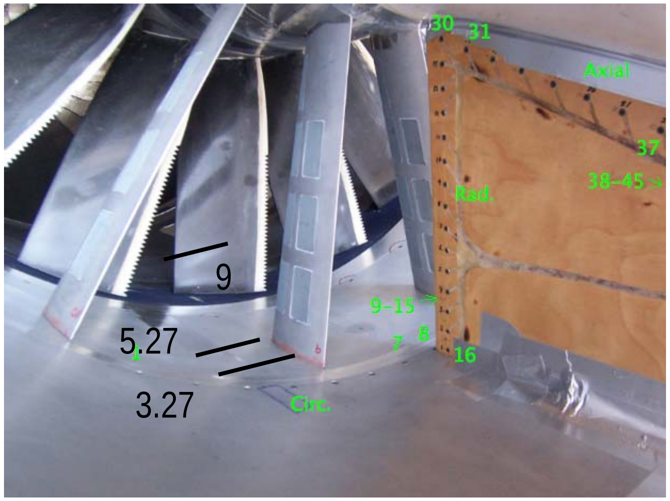


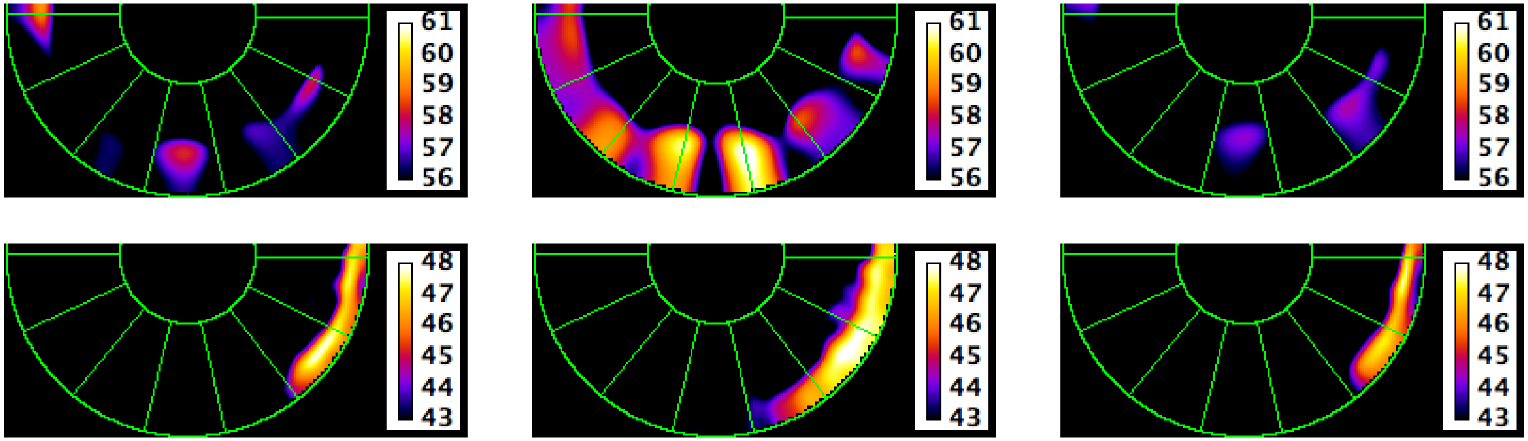
Condition determining σ: $\vec{n} \bullet \vec{v} - \frac{p}{Z} = 0$

Boundary element code: formulation



April Run 11: 444 RPM multipole





z

zφ

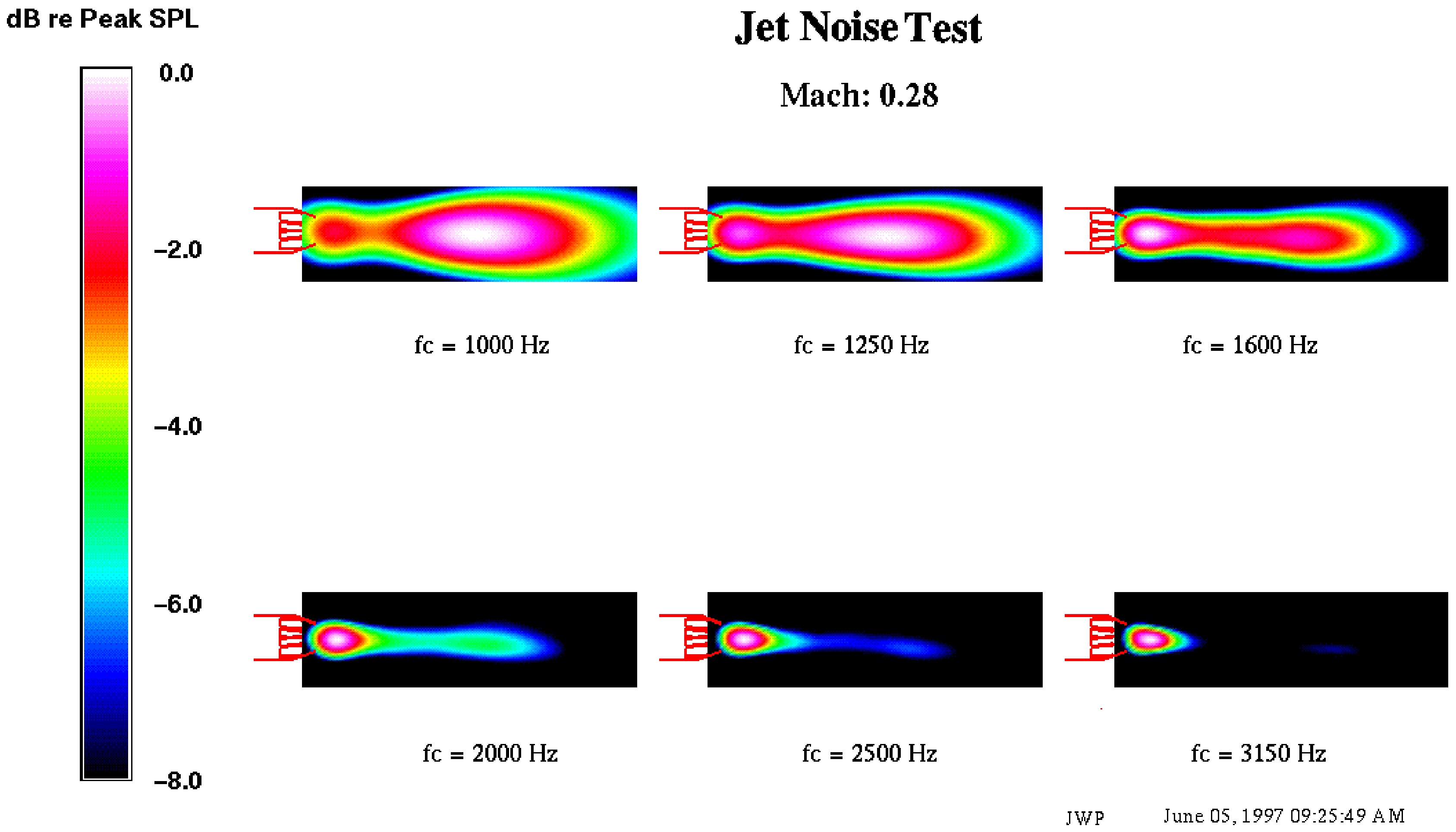
zz

5.27 in.
703 Hz

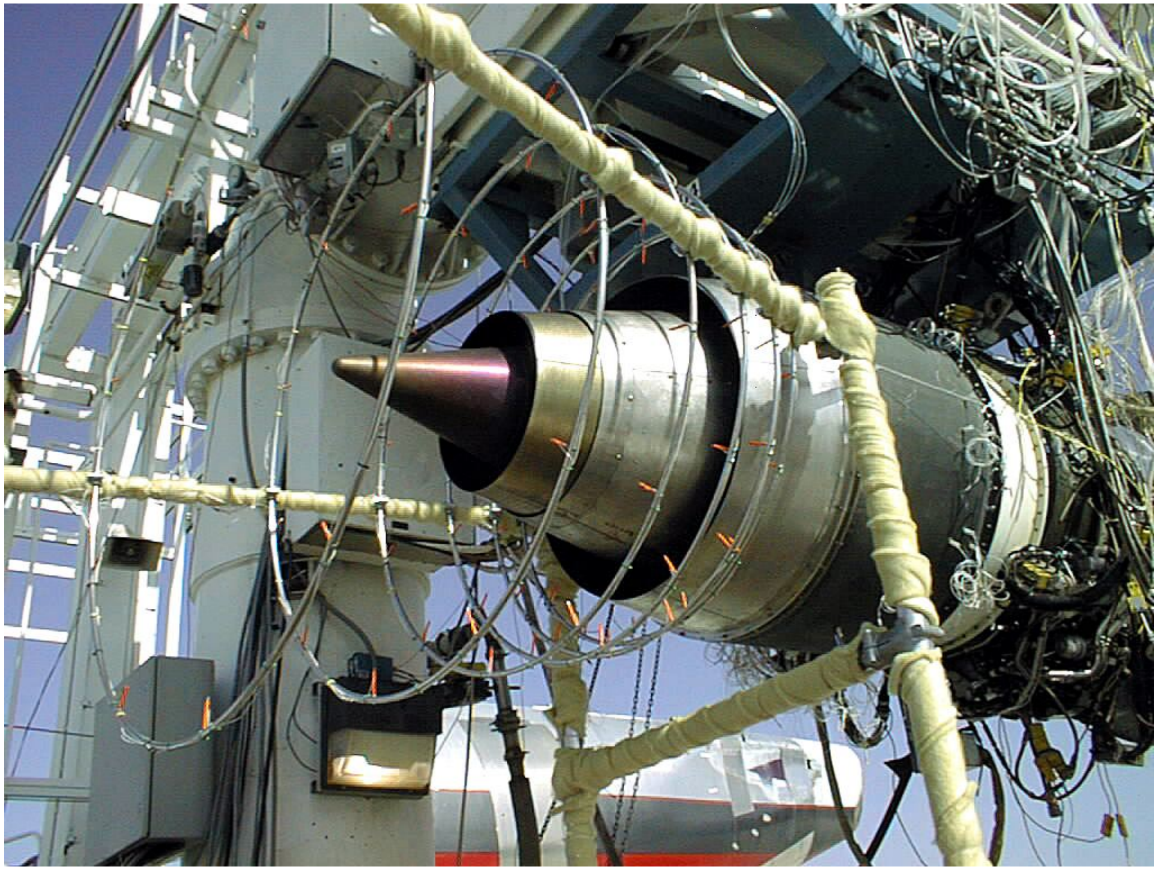
9 in.
2000 Hz

Jet Noise

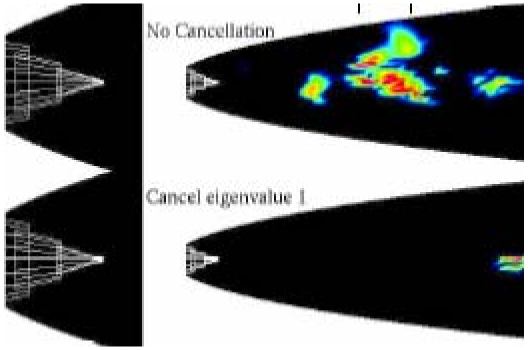
NASA-Glenn/Boeing (Premo) 1997



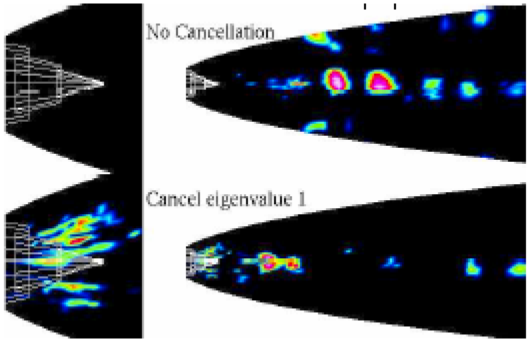
Boeing/Honeywell Cage Array, 1999



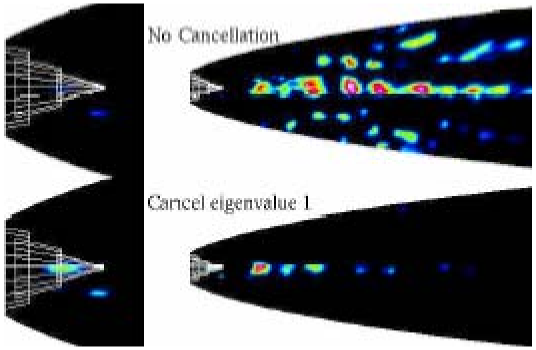
Cage Array, Baseline Configuration



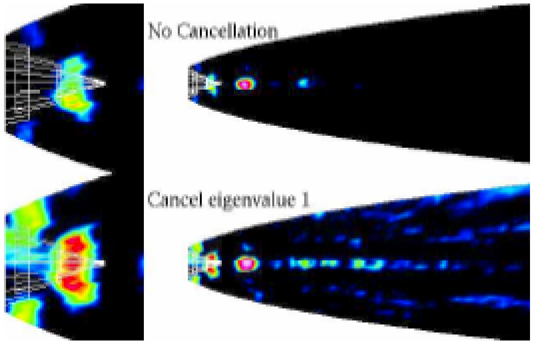
125 Hz



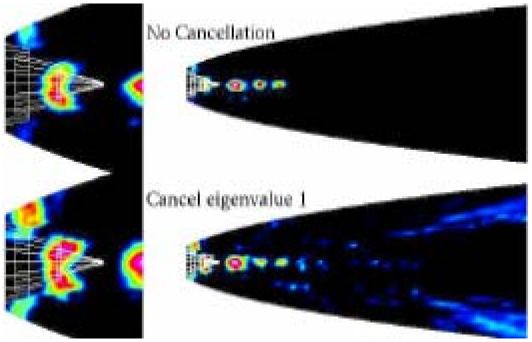
250 Hz



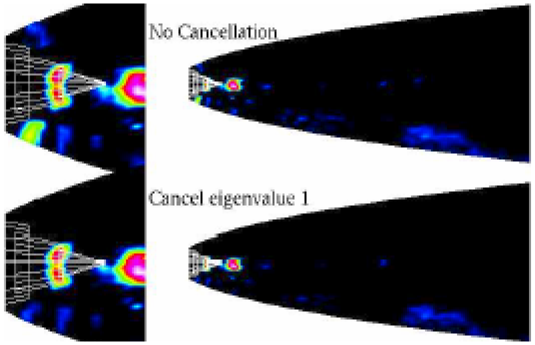
400 Hz



500 Hz

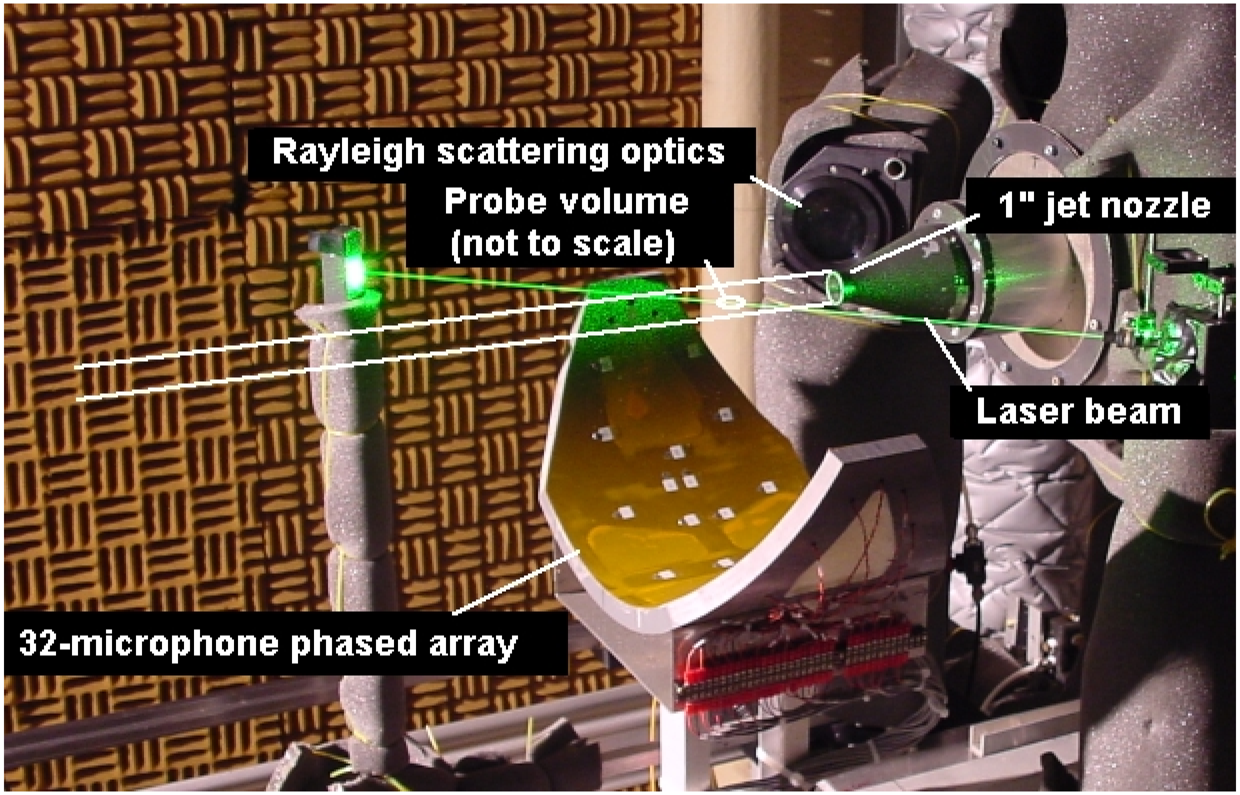


630 Hz

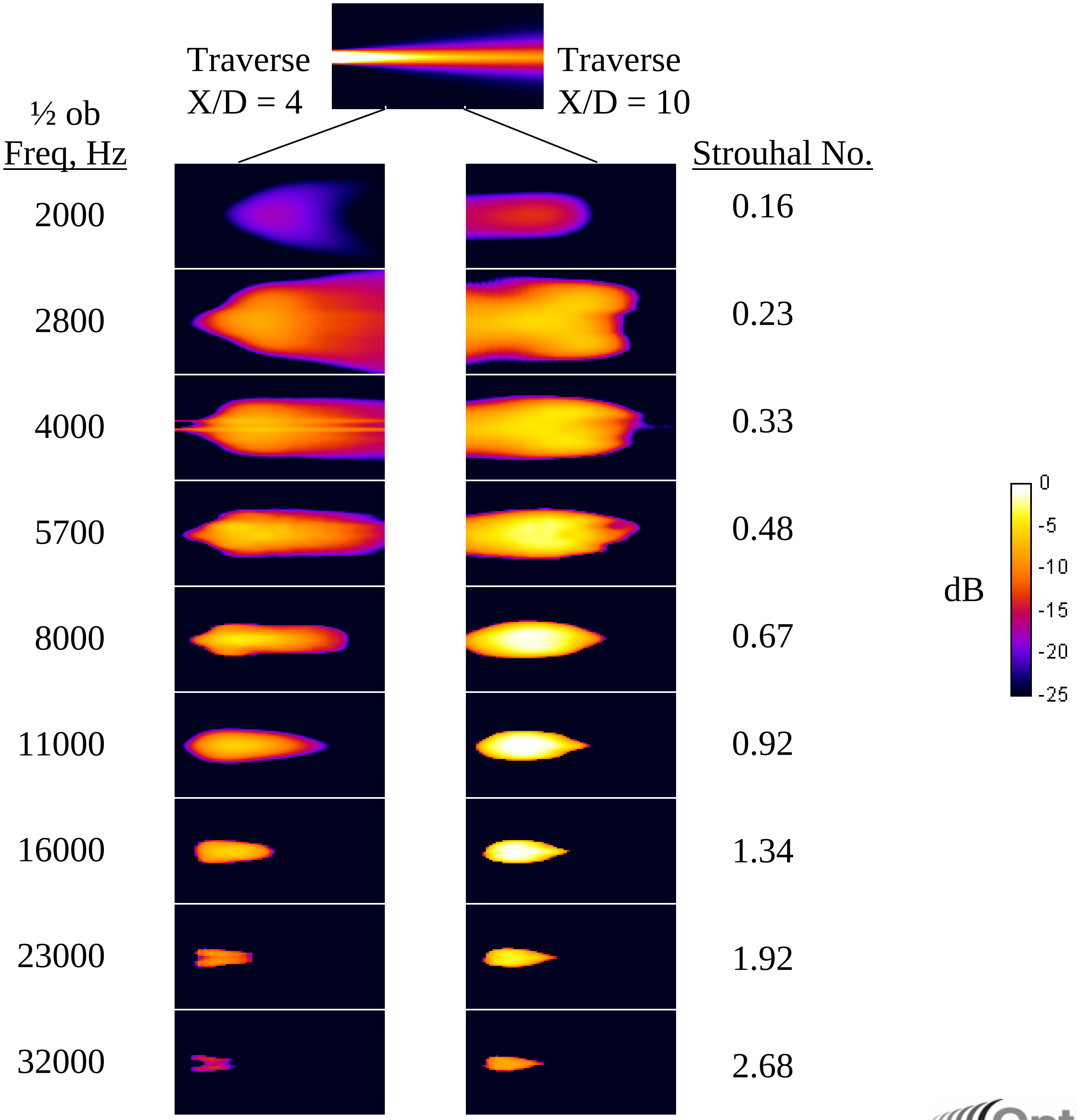


800 Hz

August 2004, NASA Glenn RC, AARC



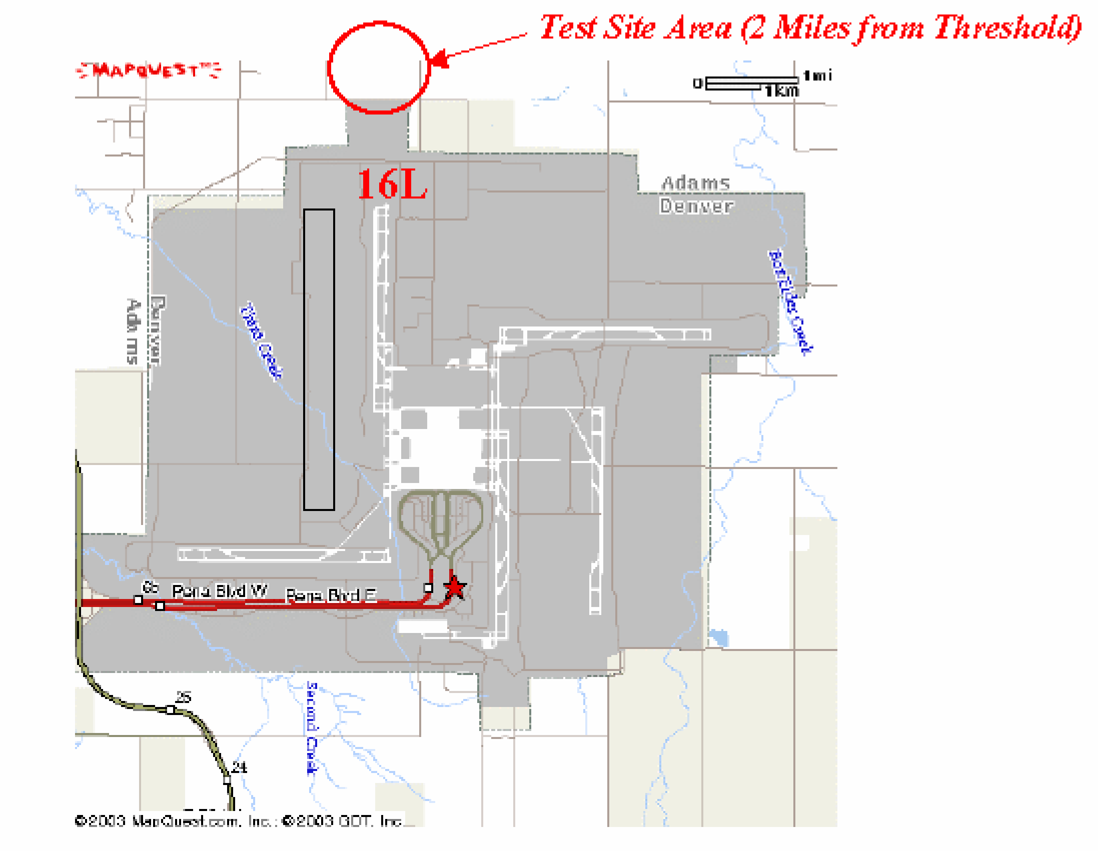
Mach = 0.95
DAMAS2



OptiNav

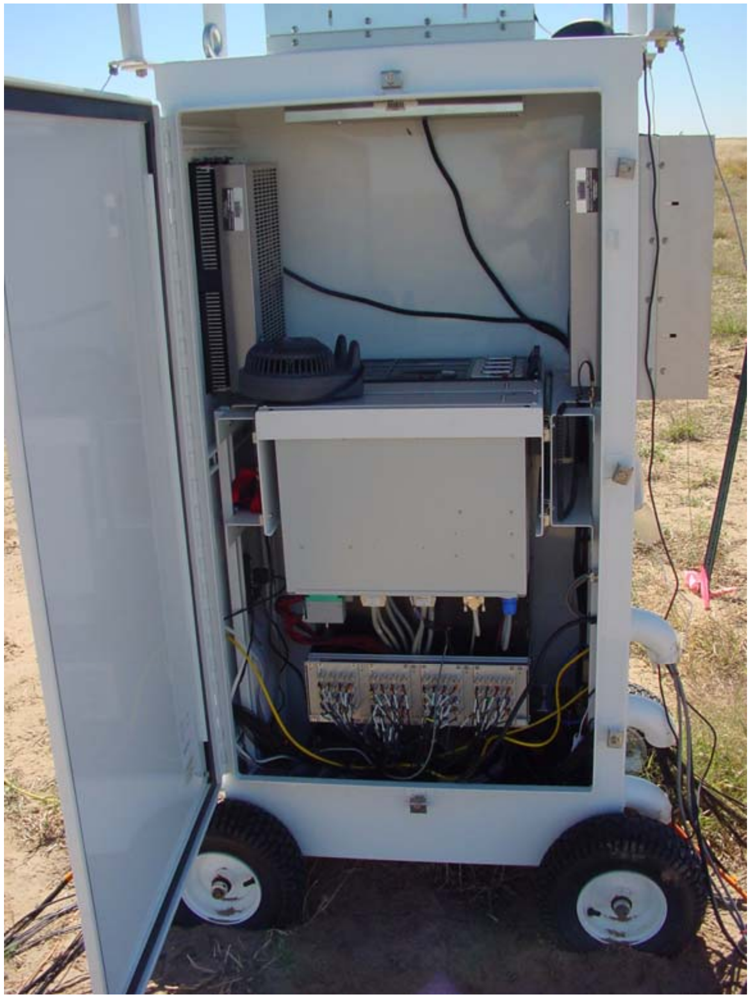
Wake Vortex Test, Denver CO, 2003

Denver Test Aug.-Sept. 2003



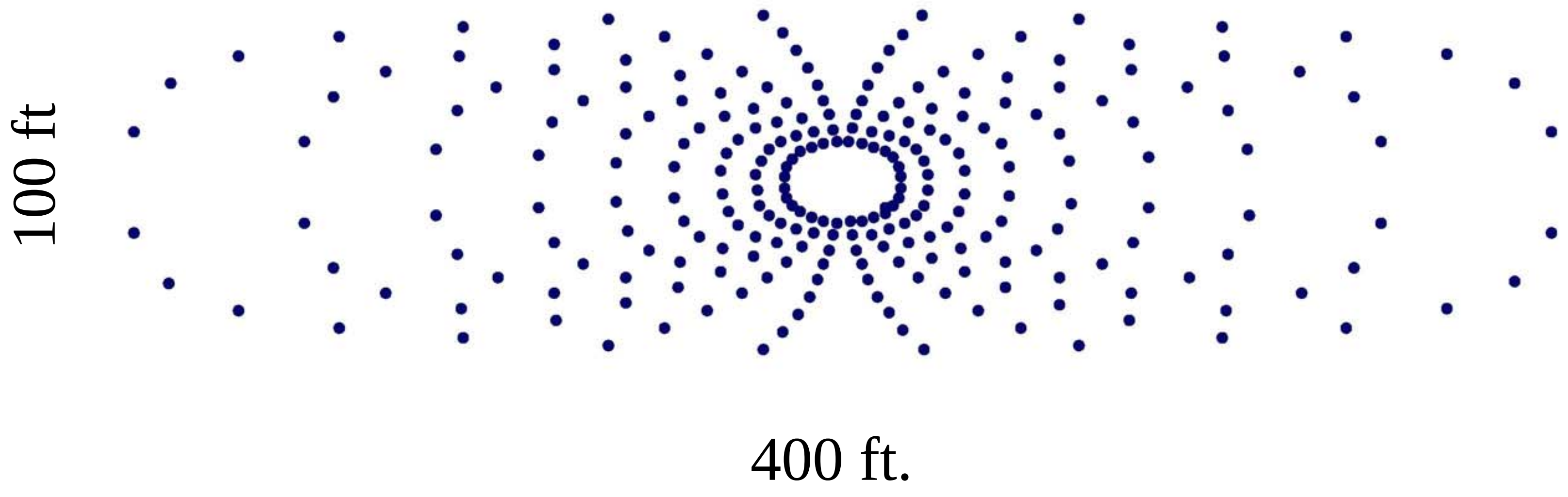
Denver Test Aug.-Sept. 2003
Titan Corp, USDOT

Photograph Curtsey of Jim Elliot

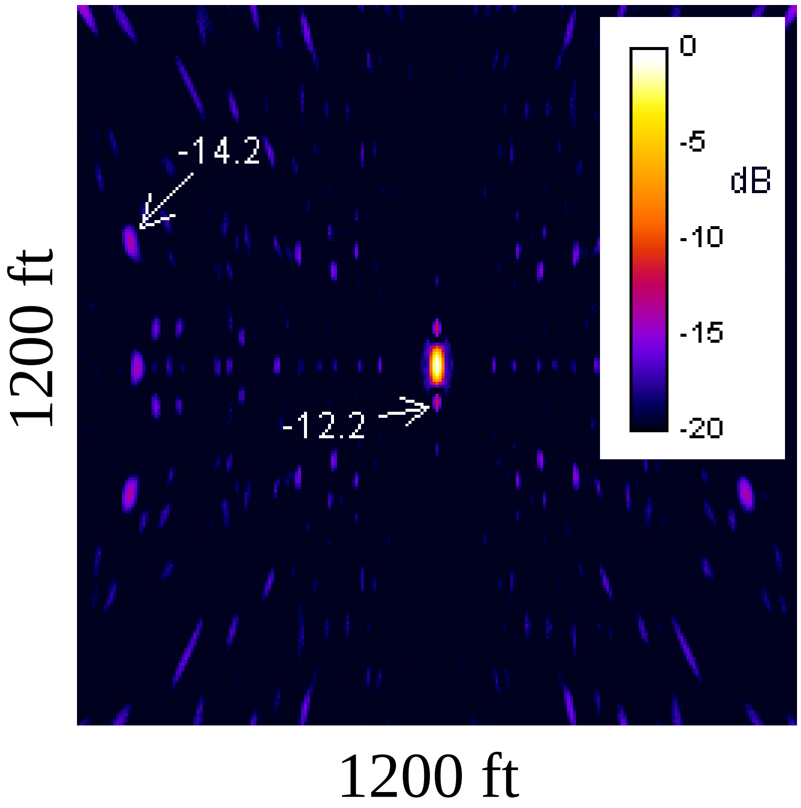


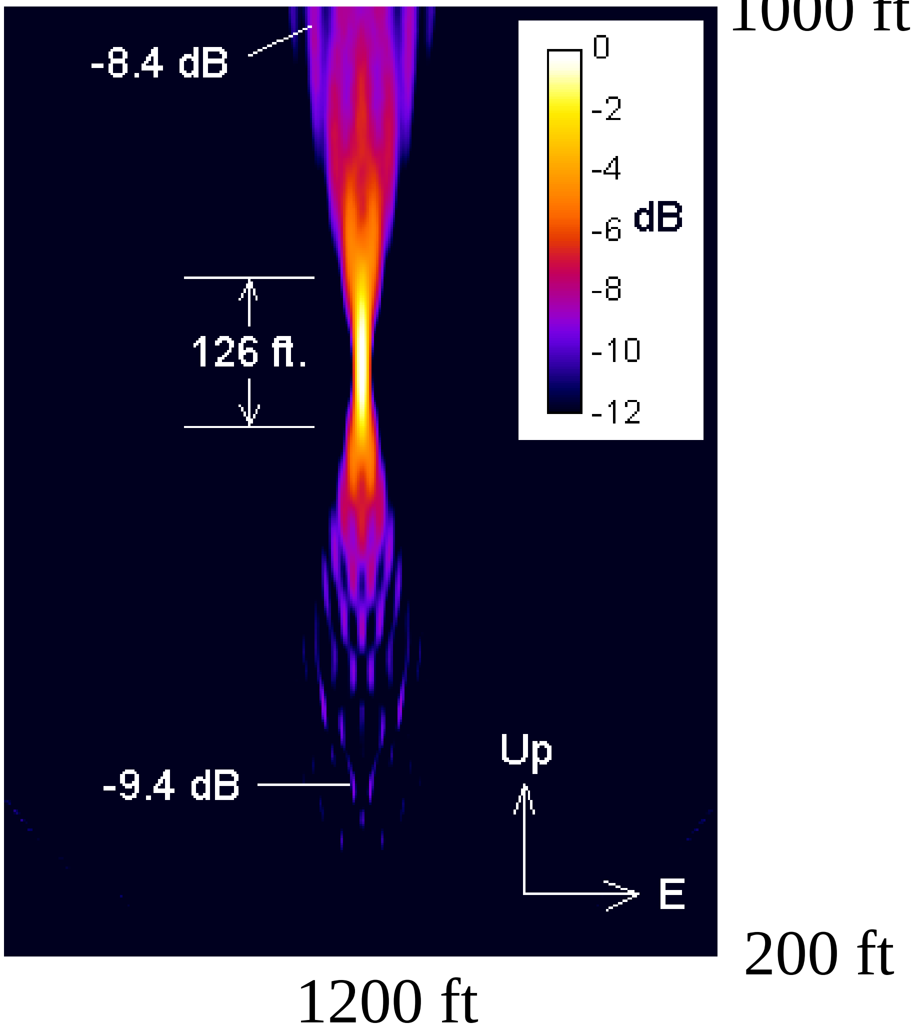

135

Array Design

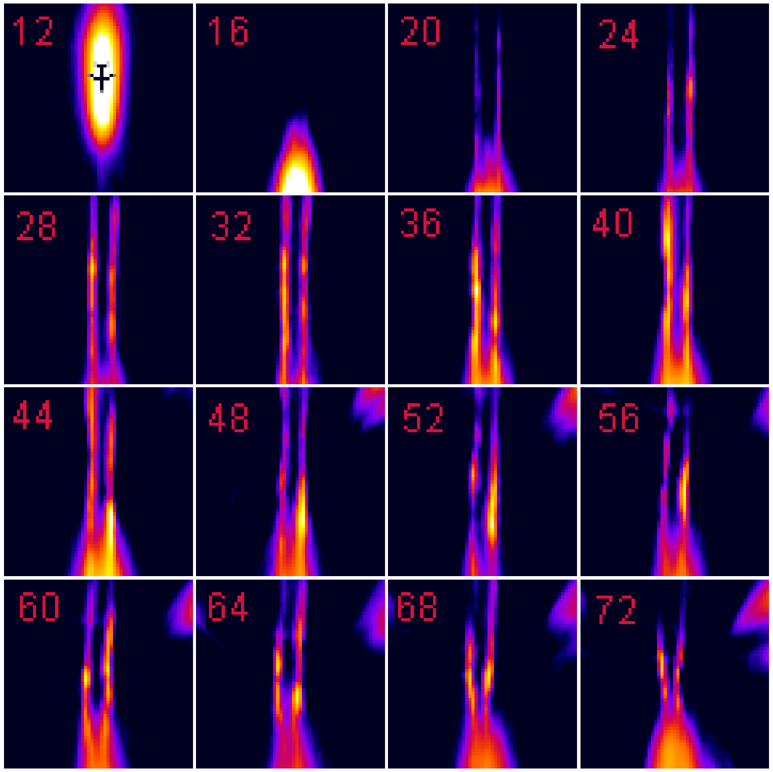


Array Sidelobes, 200 Hz

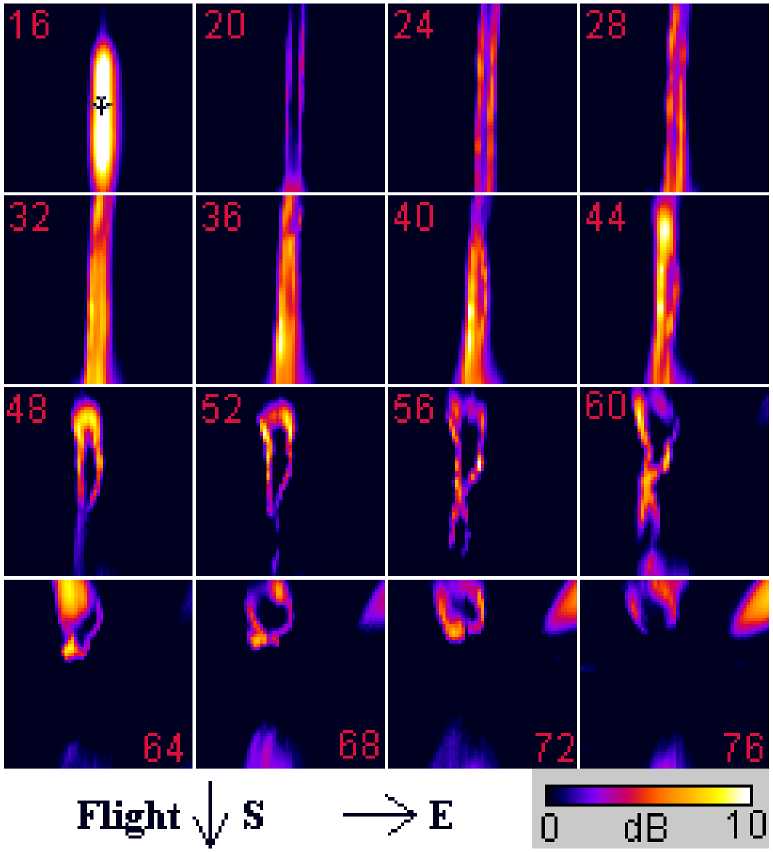

Horizontal Plane (700 ft,)


Vertical Plane

767



737



OptiNav

Open Issues

- systematic way to handle turbulent decorrelation
- determine autospectra after diagonal deletion (CLEAN-SC?)
- multipoles
- nacelle in-duct beamforming
- extended coherent sources (CLEAN-SC?)
- broaden user community

Conclusions

Acoustics beamforming is

- similar to photography
- different from linear algebra
- robust
- an art
- not effective without careful array design
  test technique, and interpretation
- constantly changing for demanding applications
- transformational in aeroacoustics measurements