Phased Microphone Array on Aircraft Fuselage

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Outline

- Introduction
- Effect of refraction and surface curvature
- Effect of smooth-geometry diffraction
- Effect of sharp-edge diffraction
- Application to flight configuration
- Conclusions

NASA/Boeing Flight Test

Czech, M.J., Thomas, R.H., Guo, Y., June, J.C., Clark, I.A., and Shoemaker, C.M.,

"Propulsion Airframe Aeroacoustics and Aircraft System Noise Flight Test on the Boeing 2020 ecoDemonstrator Program,"

AIAA Paper 2022-2994, June 2022

Main Challenge

- Multiple scattering mechanisms
- Arrays on curved surface
- Refraction by nonuniform flow in boundary layer
- Lack of line of sight
- Diffraction by sharp trailing edges and smooth leading edge
- Skewed array look angle

Main Questions

If and how phased array data analysis (beamforming and source deconvolution) can be used to

- Extract source locations and amplitudes?
- Study diffraction by wing leading and trailing edge?

Technical Approach

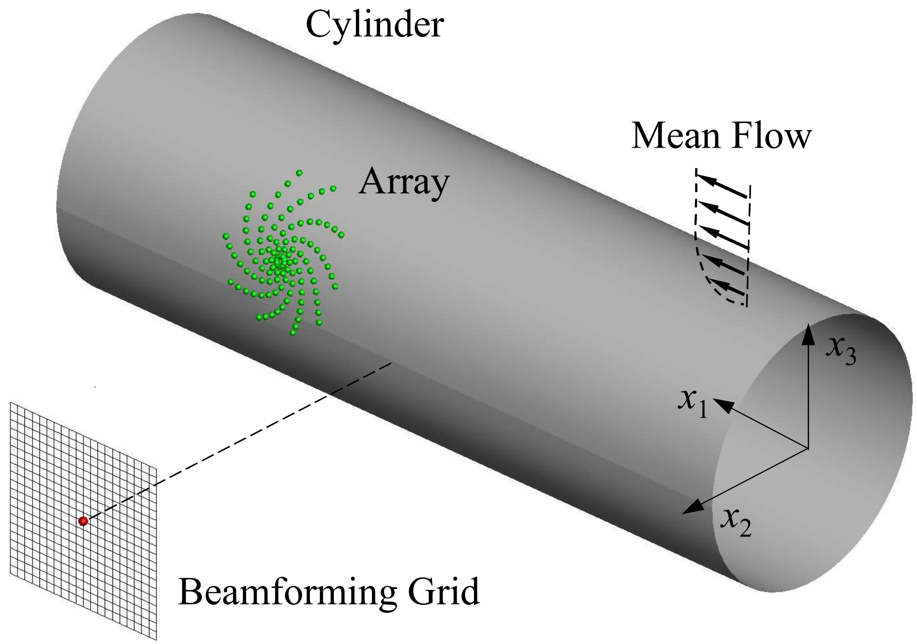
- Canonical problems to separate individual features
  - Cylinder scattering for refraction and reflection with array on cylinder surface
  - Cylinder scattering for smooth-geometry diffraction with array and source on opposite sides of cylinder
  - Semi-infinite plate for sharp-edge diffraction with array and source on opposite sides of plate
- Application to realistic aircraft geometry with multiple scattering mechanisms and multiple sources
  - Under-wing array for source capturing
  - Above-wing array for diffraction detection

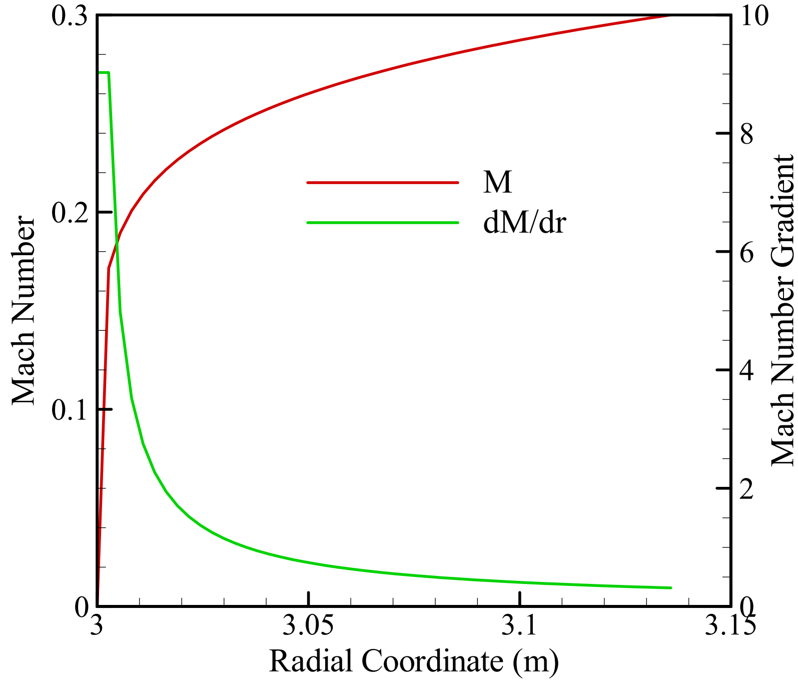
Simulation Process

- All relevant features included in computing acoustic pressure and cross-spectral matrix to simulate physical tests
  - Source coherence
  - Flow refraction
  - Scattering
- Beamforming and source deconvolution
  - Various options of Green’s functions between beamforming grid and array (free space, scattering in uniform flow, refraction by nonuniform flow)
  - Various definitions of steering vector and point spread function

Cylinder Scattering

- Refraction by nonuniform flow in boundary layer
- Reflection by curved surface
- Source at 1000 Hz with 100 dB amplitude, located 3 radii from cylinder surface
- Array on cylinder surface at one radius downstream of source

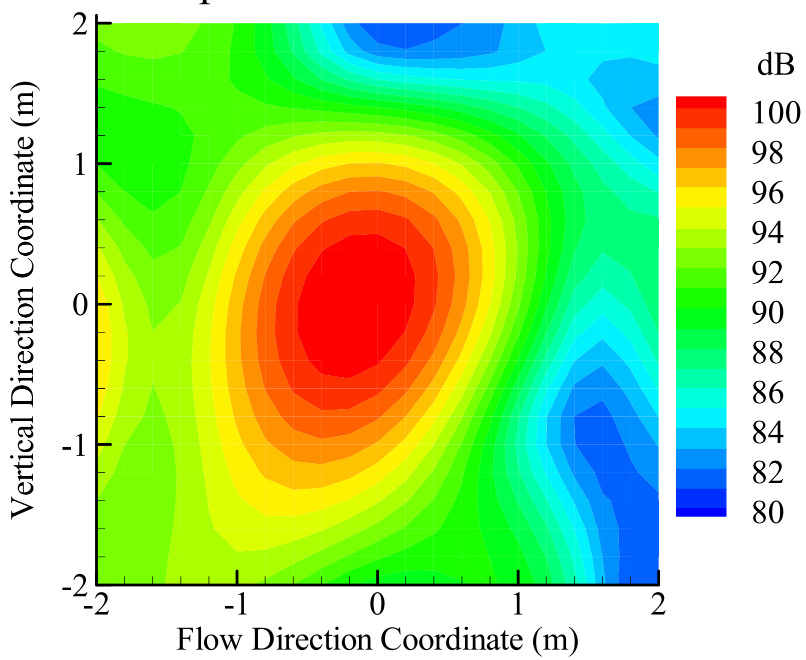




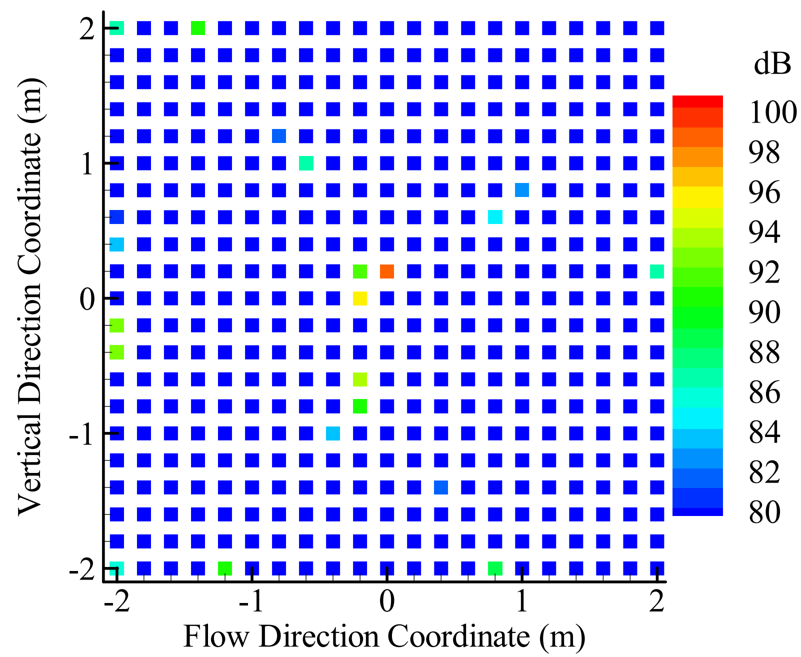
Free Space Green's Function

- Uniform mean flow of M=0.3 (no refraction and no reflection)

Beamforming:
- Max level at source location
- Amplitude error of 1.2 dB



DAMAS:
- Source location missed by one grid element
- 17 erroneous sources
- Amplitude error of 1.9 dB at max source

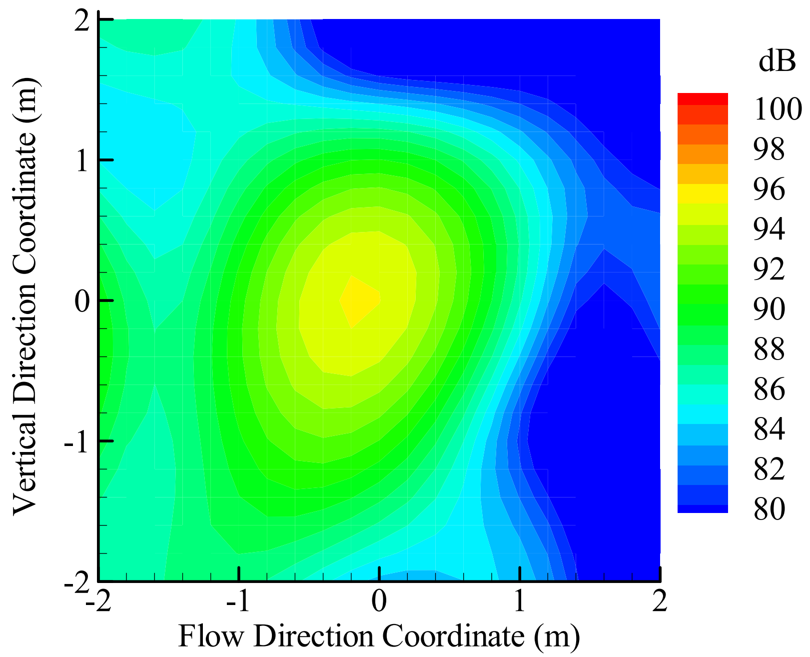


Scattering Green's Function with Uniform Flow

- Uniform mean flow of M=0.3 (no refraction but with reflection)

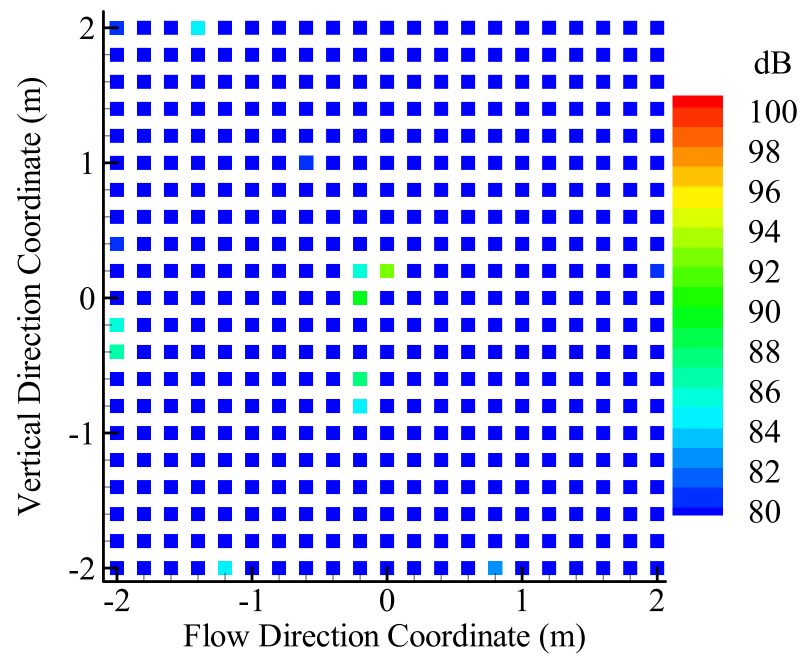
Beamforming:

- Max level at source location
- Amplitude error of 4.8 dB



DAMAS:

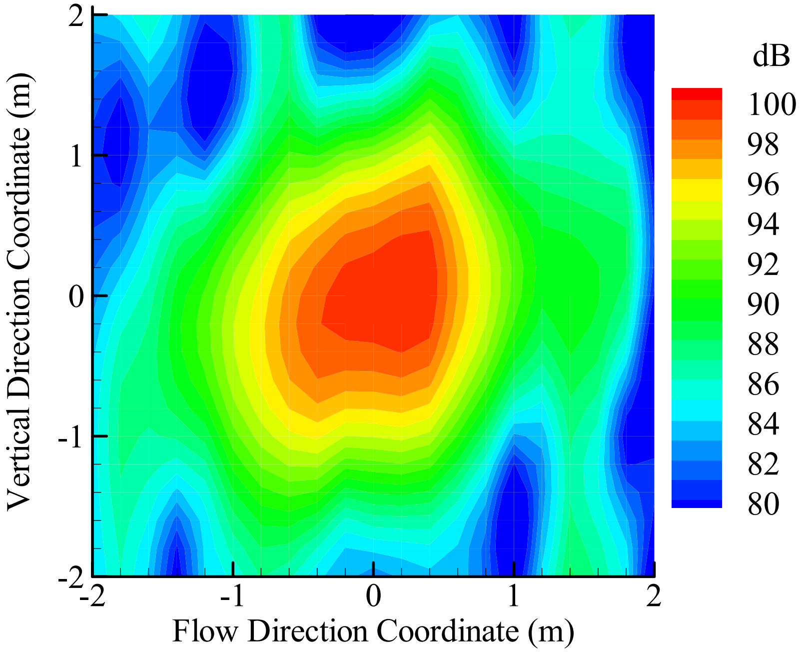
- Source location missed by one grid element
- 8 erroneous sources
- Amplitude error of 7.9 dB at max source



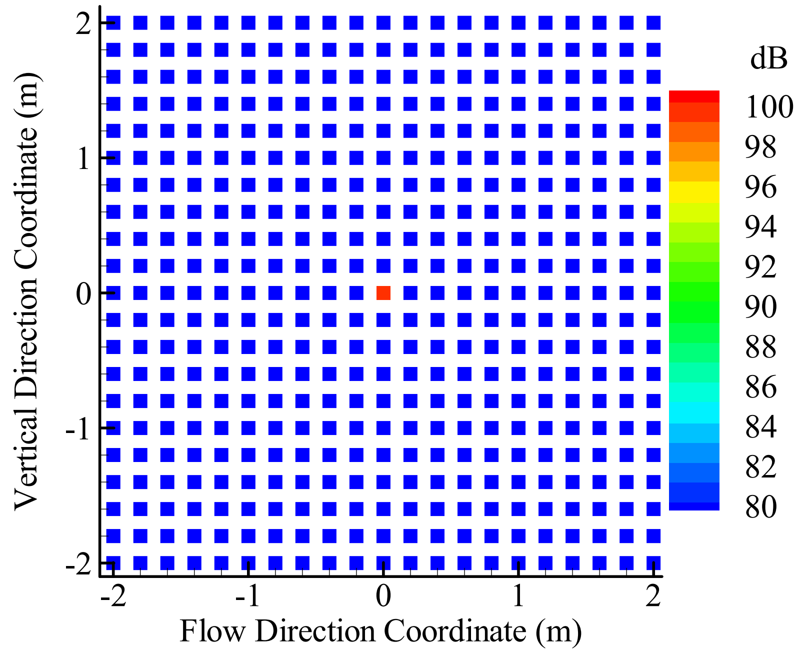
Exact Green's Function

- Fully account for refraction and reflection

Beamforming:
- Max level at source location
- Amplitude error of 0.4 dB



DAMAS:
- Source location captured
- No erroneous source
- Amplitude error of 0.02 dB



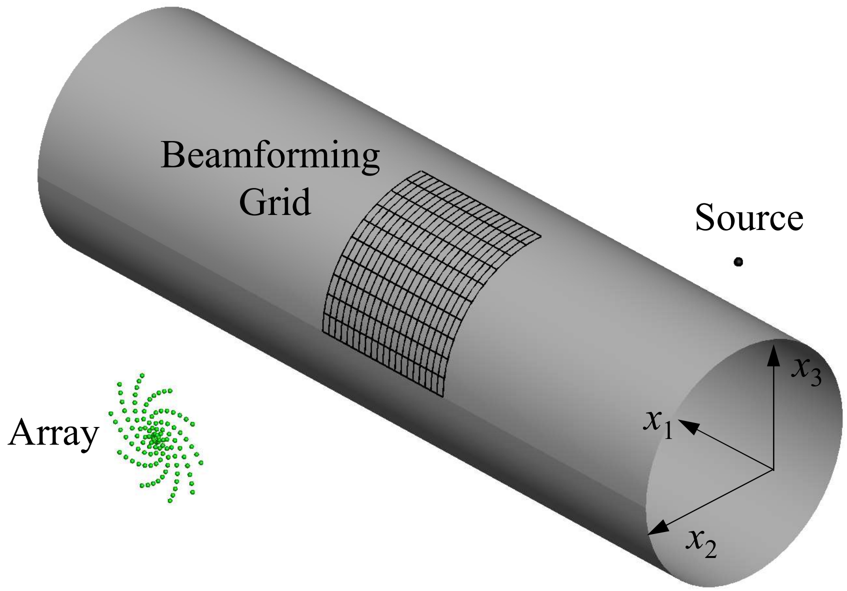
Beamforming and DAMAS Results

- Analytical source
  - 1000 Hz frequency
  - 100 dB amplitude

	Beamforming Contour Maximum (dB)	Source Amplitude from DAMAS (dB)	Number of Erroneous Sources	Source Location Error in Grid Spacing
Exact Green's Function with Nonuniform Flow	100.43	99.98	0	0
Scattering Green's Function with Uniform Flow	95.17	92.11	8	1
Free Space Green's Function with Uniform Flow	101.18	98.12	17	1

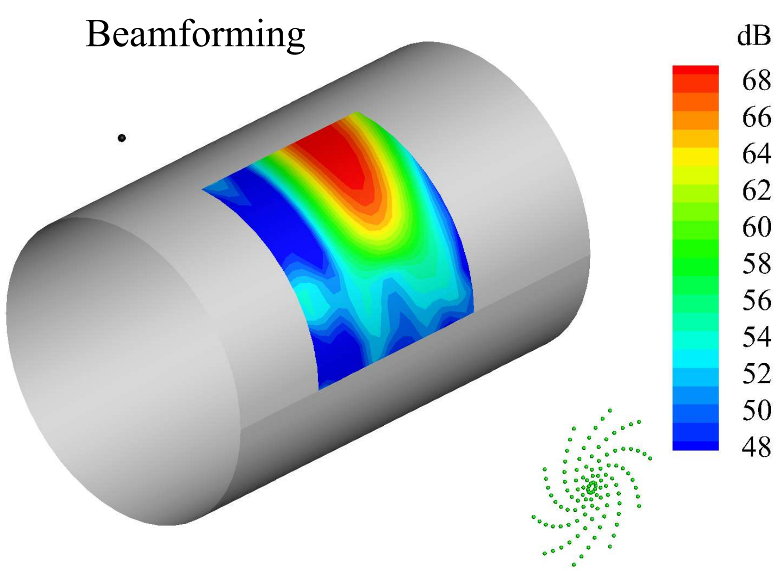
Cylinder Diffraction

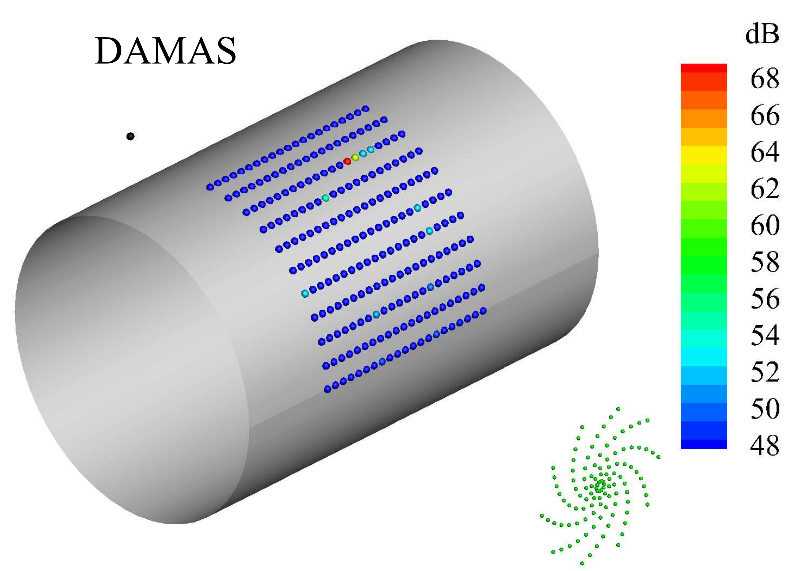
- Source and array on opposite sides of cylinder
- Source at 1000 Hz with 100 dB amplitude, located 1 radius from cylinder surface
- Array located 2 radii from cylinder surface and 1 radius downstream of source
- Beamforming grid on cylinder surface



Detection of Smooth Geometry Diffraction

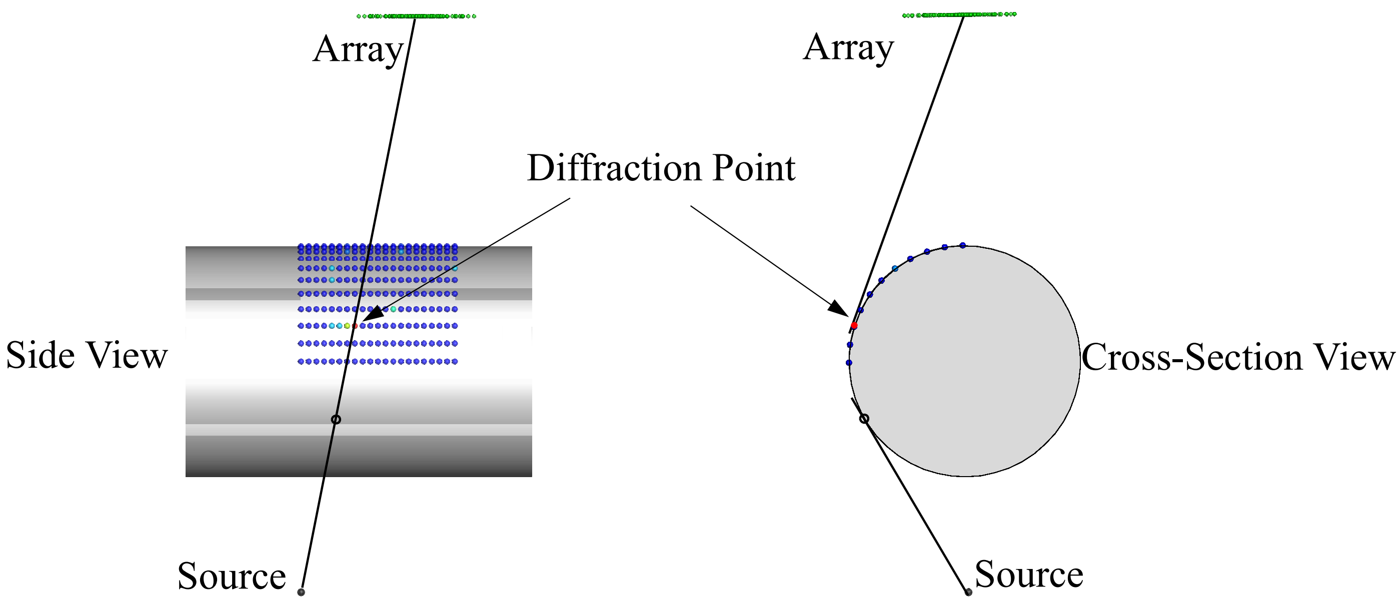
- Beamforming with no maximum within grid but high levels in surface wave radiation area
- Smooth-geometry diffraction captured by DAMAS as apparent source from surface wave radiation
- Real source behind cylinder not seen by array





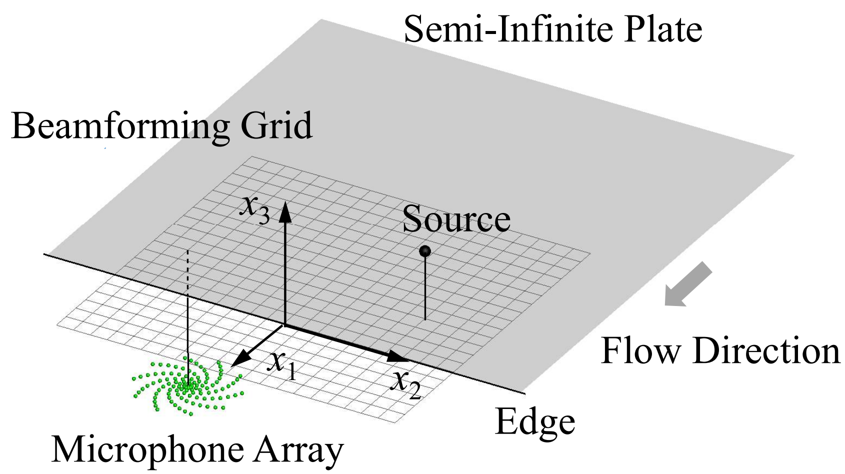
Apparent Source for Smooth-Geometry Diffraction

- Smooth-geometry diffraction by Fermat's principle of propagation along the shortest path
  - Surface waves generated by incident sound at tangential point on source side
  - Creeping wave propagation along helical path on smooth surface
  - Radiation back to acoustic medium at tangential point on opposite side
- Radiation point seen by array as apparent source



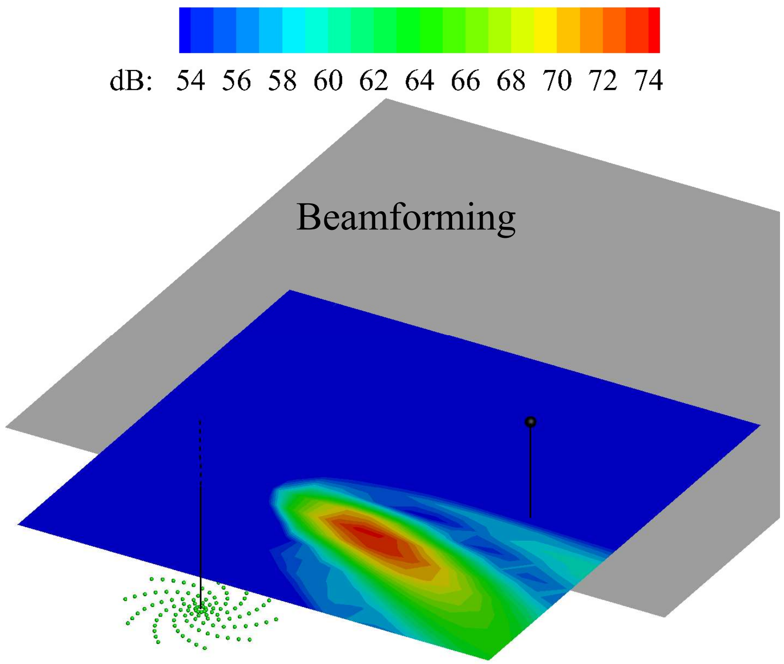
Sharp-Edge Diffraction

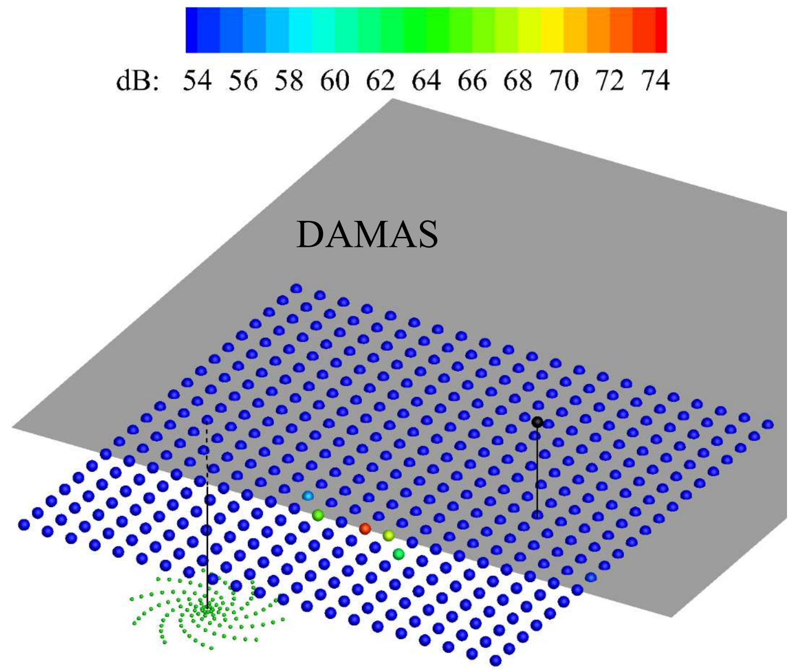
- Source and array on opposite sides of semi-infinite plate
- Source at 1000 Hz with 100 dB amplitude located 2 meters above plate and 2 meters upstream of trailing edge
- Array located 4 meters below plate, 2 meters upstream of trailing edge and 7 meters offset from source in lateral direction
- Beamforming grid on surface of semi-infinite plate



Detection of Sharp-Edge Diffraction

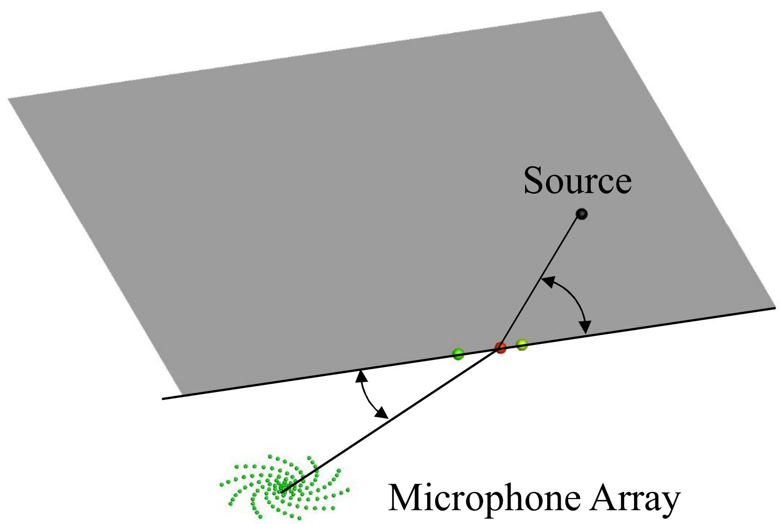
- Beamforming with location of maximum contour levels around diffraction point on sharp edge
- Sharp-edge diffraction captured by DAMAS as apparent source on edge
- Real source on opposite side not seen by array





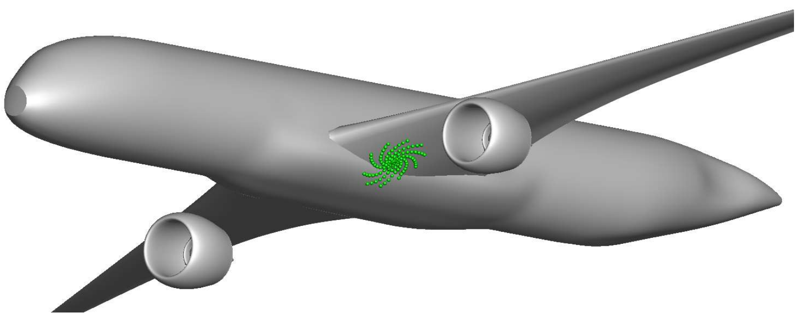
Apparent Source for Sharp-Edge Diffraction

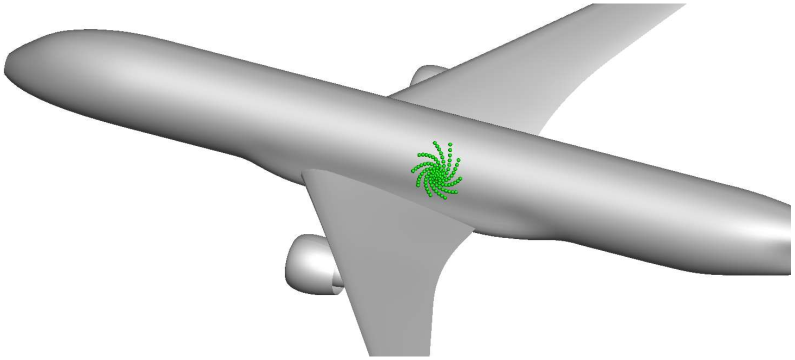
- Sharp-edge diffraction governed by equal-angle rule
  - Angle between incident wave and edge line must equal angle between diffracted wave and edge line
  - Fermat's principle of wave propagation along the shortest path
- Diffraction point on edge captured by array



Application to Aircraft

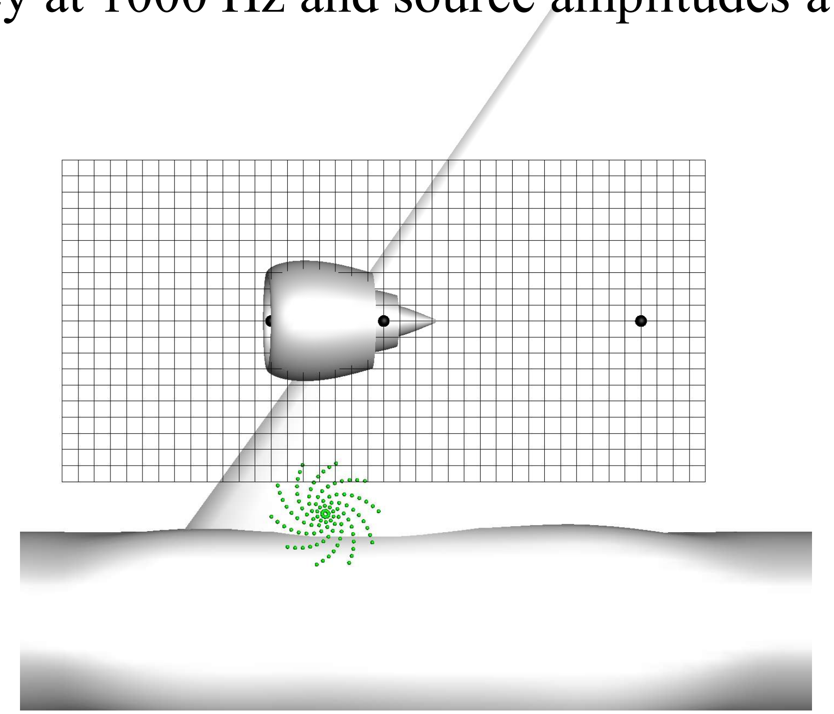
- Generic aircraft with flight Mach number 0.3
- Two on-board arrays
- Three sources at locations representative of inlet, aft fan and jet noise
- Multiple scattering mechanisms
  - Curved-surface reflection by wing and fuselage
  - Sharp-edge diffraction by wing trailing edge
  - Smooth-geometry diffraction by wing leading edge





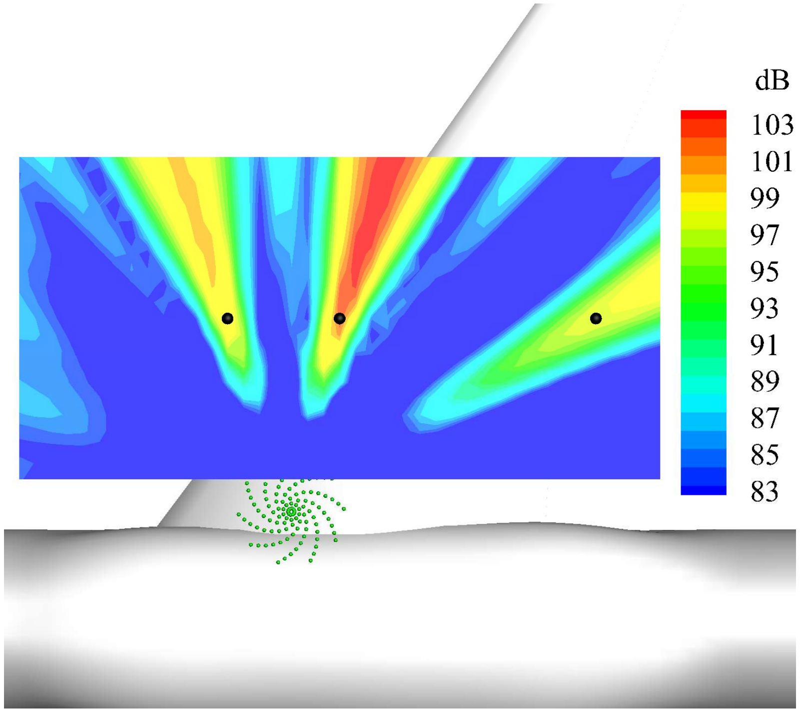
Under-Wing Array

- Partially on fuselage and partially on wing
- Designed for capturing source locations and amplitudes
- Scattering environment with highly skewed array look angle
- Source frequency at 1000 Hz and source amplitudes at 100, 103 and 97 dB

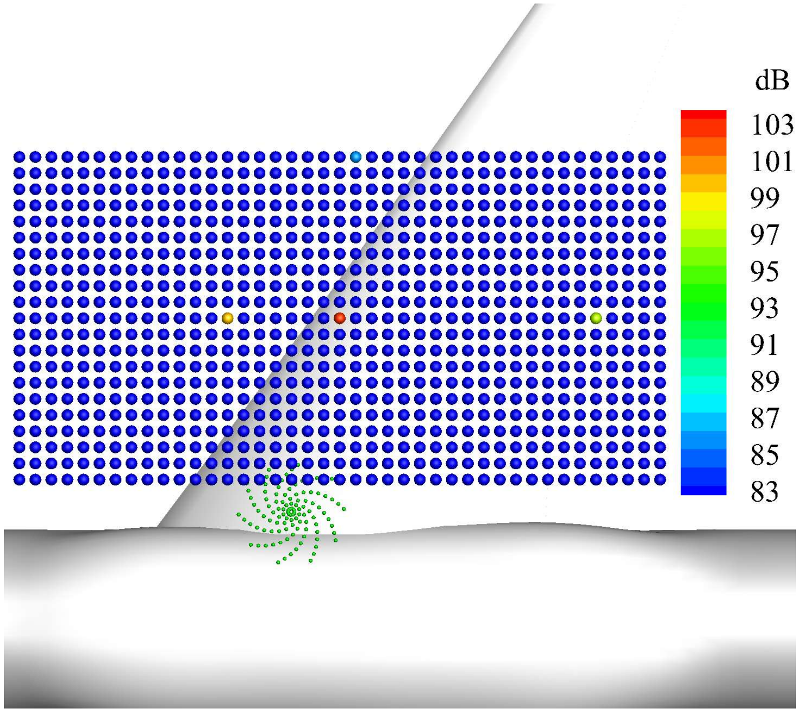


Source Capturing by Array

- Beamforming
  - Highly stretched contour patterns
  - No local maxima within grid
  - Difficult to identify source locations



- DAMAS
  - All three source locations captured
  - Accurate source amplitudes
  - No erroneous sources



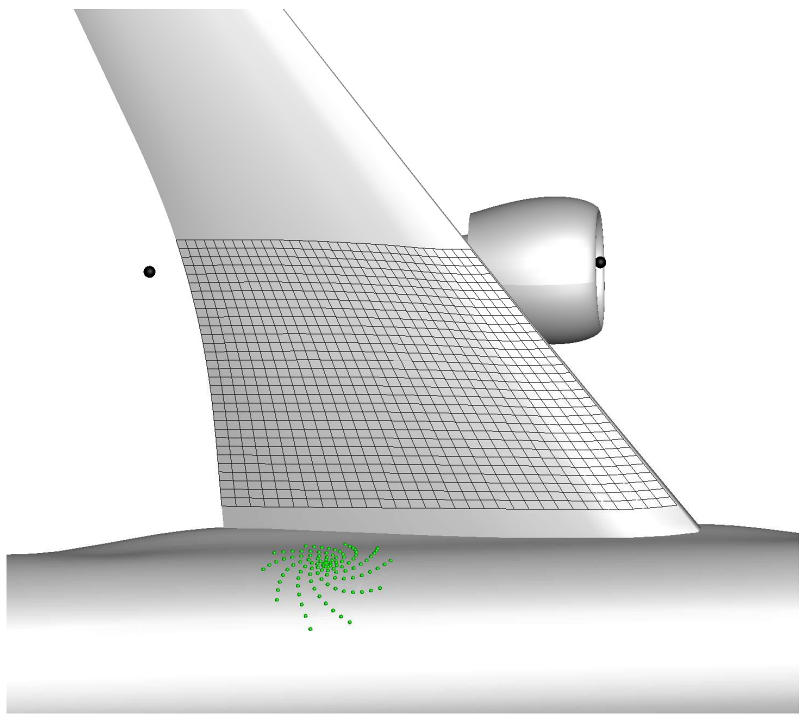
Accuracy of Source Deconvolution

- Analytical sources
  - Frequency at 1000 Hz
  - Amplitudes at 100, 103 and 97 dB
  - Locations respectively at inlet lip, fan duct exit, and downstream locations
  - Named only for convenience of discussion, not meant to represent real engine noise sources

	Inlet Source (dB)	**Aft Fan Source (dB)**	**Jet Source (dB)**
Preset Analytical Value	100	103	97
Source Deconvolution Result	99.86	102.92	96.72
Error	-0.14	-0.08	-0.28

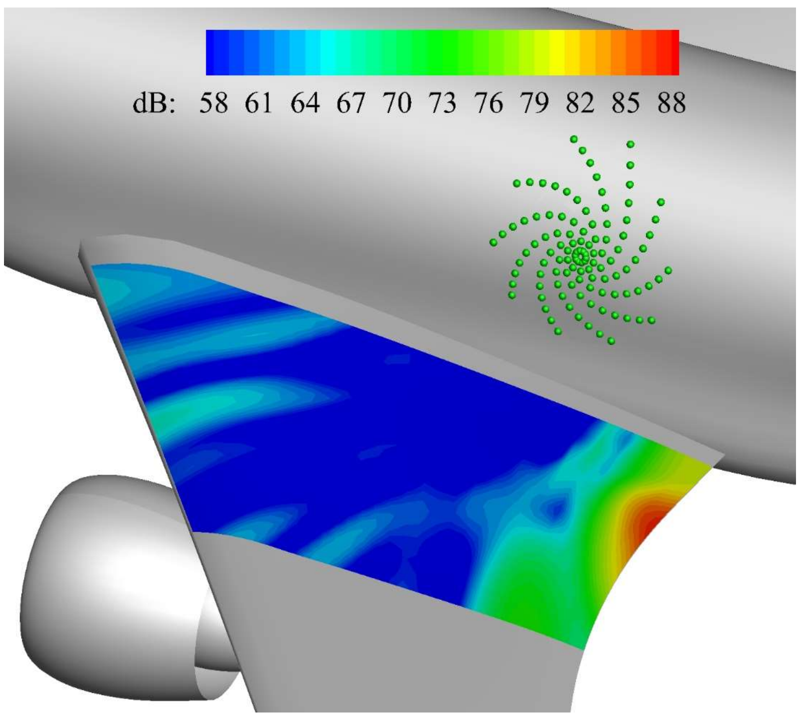
Above-Wing Array

- Entirely on fuselage and designed for capturing diffraction
- Beamforming grid on wing surface
- Source frequency at 1000 Hz and source amplitudes at 100, 103 and 97 dB

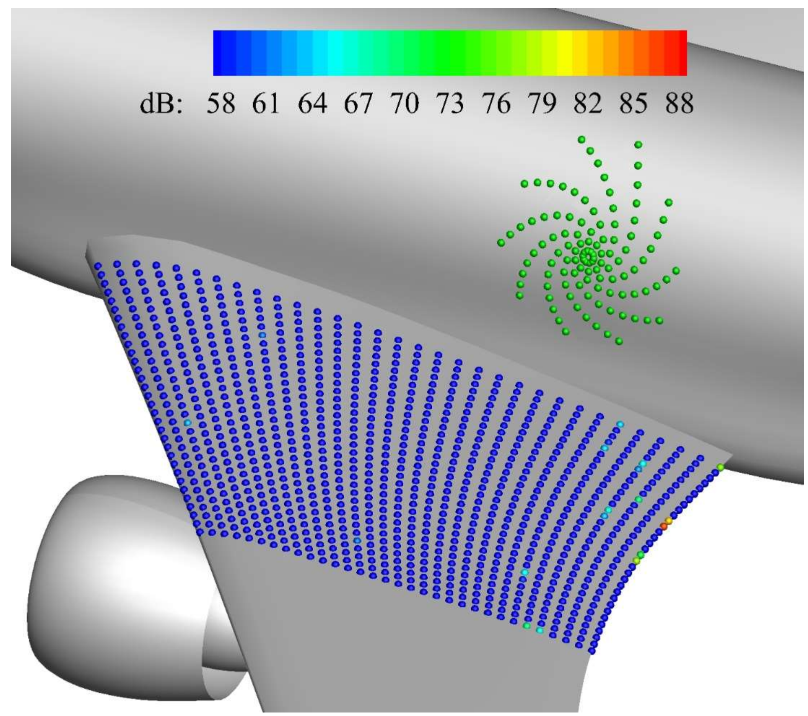


Diffraction Detection by Array

- Beamforming
  - Diffraction patterns captured
  - Local maxima at diffraction points



- DAMAS
  - Diffraction at trailing edge captured on edge line
  - Leading-edge diffraction very weak
  - Erroneous sources on wing surface (more than 20 dB down from maximum)



Conclusions

- Phased arrays mounted on curved surfaces can be used to extract source locations and amplitudes, in the presence of refraction and curved-surface reflection, if exact Green's functions are used in beamforming and source deconvolution.
- Both smooth-geometry and sharp-edge diffraction can be captured by phased arrays as apparent sources at the diffraction points on the diffraction surface.

NASA