Designing shading schemes for microphone phased arrays

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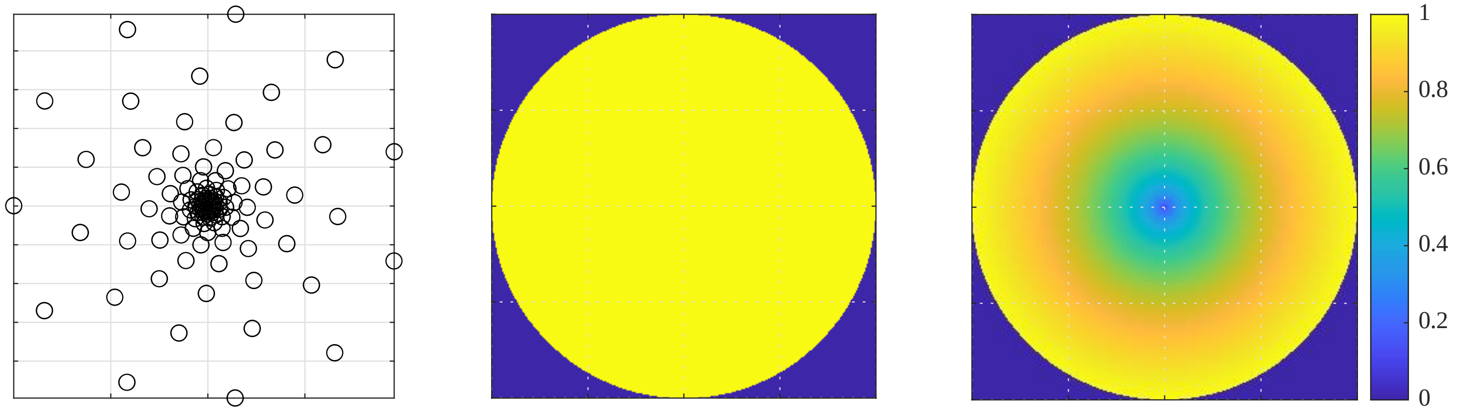
Overview

- Introduction
- Methodology
- Application description
- Metrics and synthetic data
- Experimental data (beamforming/deconvolution)
- Summary and conclusions

Introduction

- Array shading
  - Application of weight values to sensors in an array to emphasize some signals more than others
  - Distinct from steering vector weights
- Aeroacoustic concerns
  - Beamwidth control
  - Compensate for microphone distribution/source directivity
  - Mitigate coherence loss/decorrelation across array face



Shading design

- No standard method… aside from ad-hoc
  - Beamwidth control
    - Analytic for continuous aperture, plane waves
  - Sensor distribution correction
    - Geometry/source models
  - Coherence loss
    - Data-driven
    - Modeling
- This effort
  - Automate beamwidth control for discrete sensor array and point source with varying frequency
  - Monitor characteristics important to geometry correction, coherence loss
  - Propose appropriate cost function, formulate as optimization problem

Methodology

- Addressing axisymmetric shading
- Lit. review dictates that an array designed for broadband application (e.g., full decade span) should emphasize:
  - outer mics at low frequencies (beamwidth control, microphone distribution)
  - inner mics at high frequencies (beamwidth control, source directivity, coherence loss)
- Beamwidth control common – useful parameter for optimization
- Product of two functions often used – first emphasizes outer sensors, second emphasizes inner ones

$$w_n = u(r_n, f)v(r_n, f)$$

Methodology

- Function selection
  - Outer emphasis: radial power laws often used $u(r_n, f) = r_n{}^{\alpha(f)}$
  - Inner emphasis: variety of functions considered, should depend on $r_n, \beta(f)$

- Optimization
  - Maximize array gain at every frequency by varying α, β
    - Data-independent parameter
    - Fast calculation
  - Constraints
    - 3 dB beamwidth equality
    - 10 dB beamwidth inequality
    - $\alpha > 0$

Application

uncovered array plate

Array with screen cover, High-Lift Common Research Model (no nacelle)

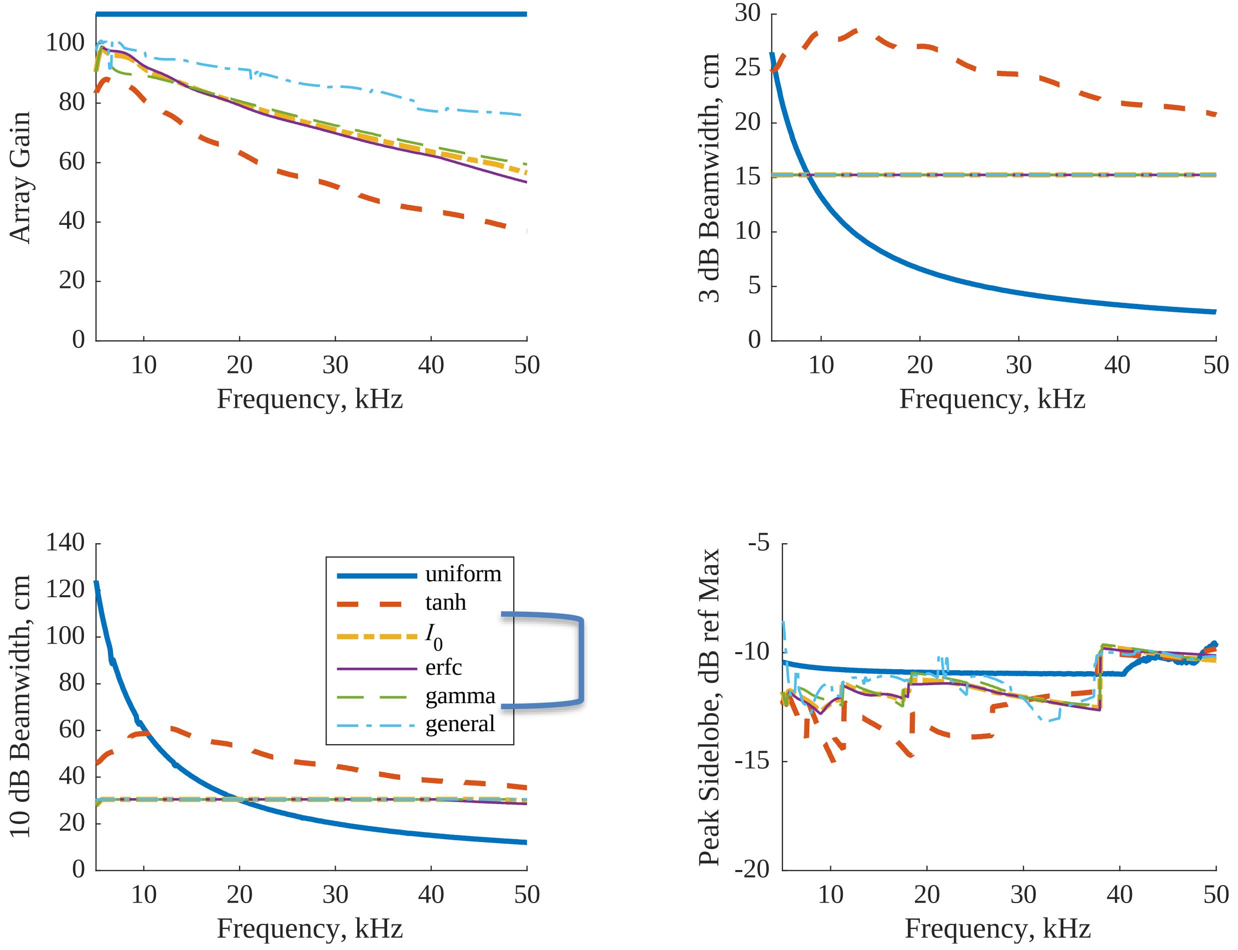
- Airframe noise test in the NASA Langley 14- by 22- Foot Subsonic Tunnel
- 110-element array w/ 36-inch outer ring radius, 1-inch inner ring radius
- Desired beamwidth of 6 inches to separate slat brackets

Application

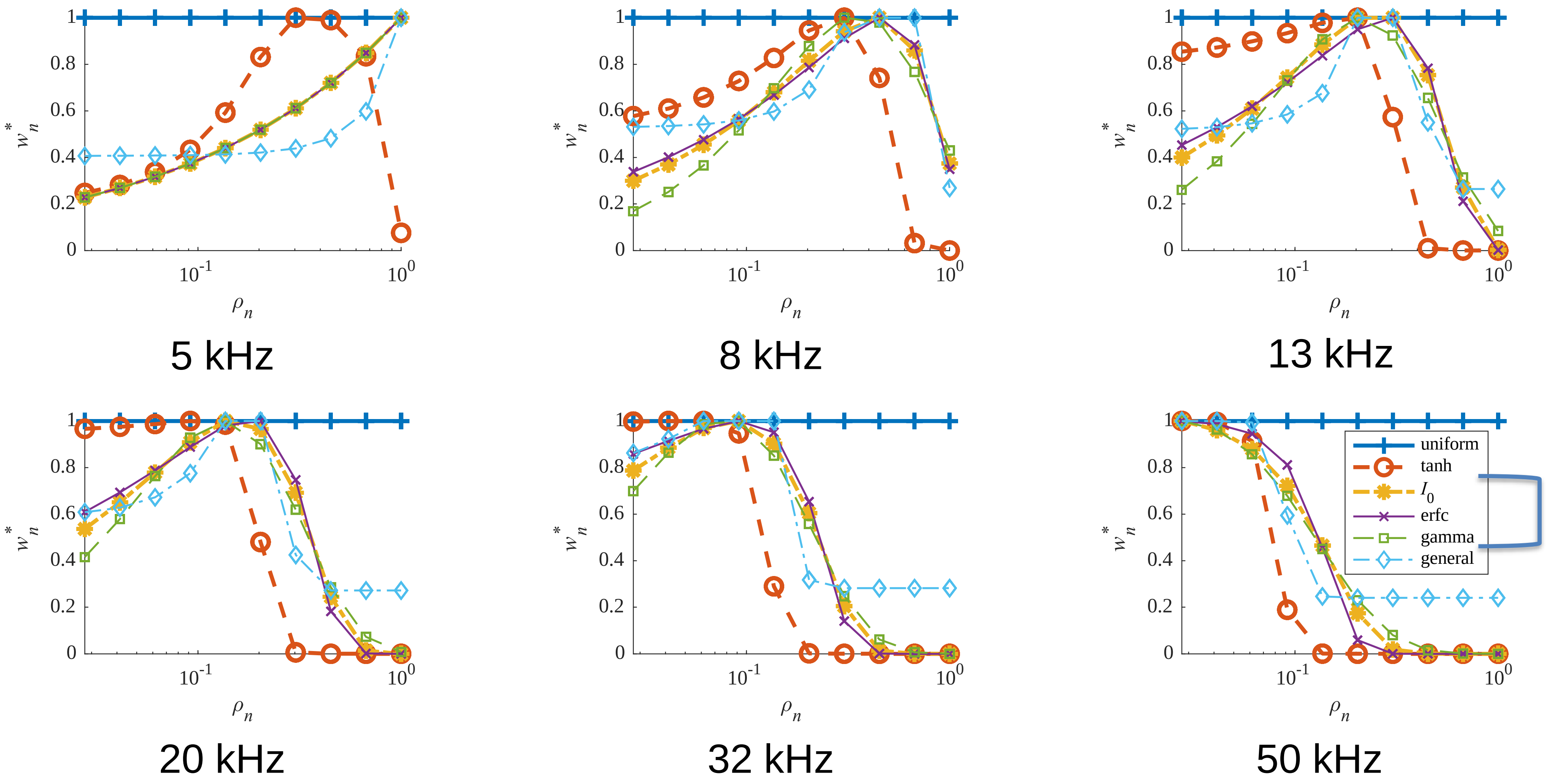
- Candidate functions ($\rho_n = {}^{r_n}/_{r_{max}}$)
  - Modified Bessel function: $w_n(f) = \rho_n{}^{\alpha(f)} I_0\left(\beta(f)\sqrt{1-\rho_n{}^2}\right)$
  - Complimentary error function: $w_n(f) = \rho_n{}^{\alpha(f)}\,\mathrm{erfc}(2[\beta(f)\rho_n - 1])$
  - Decaying exponential (gamma PDF): $w_n(f) = \rho_n{}^{\alpha(f)} e^{-\beta(f)\rho_n}$
- Other comparisons
  - Uniform/no shading
  - Existing, nonoptimized function based on hyperbolic tangent
  - General radial optimization
    - No functional form, but enforce overall shape (only one peak as a function of radius)
    - Poorly constrained, requires further investigation

Shading method metrics

- Array gain
  - Existing method lowest
  - Two-parameter methods similar
  - General method highest
- Beamwidth – optimized methods meet constraints
- Peak sidelobe levels – not directly related to other metrics



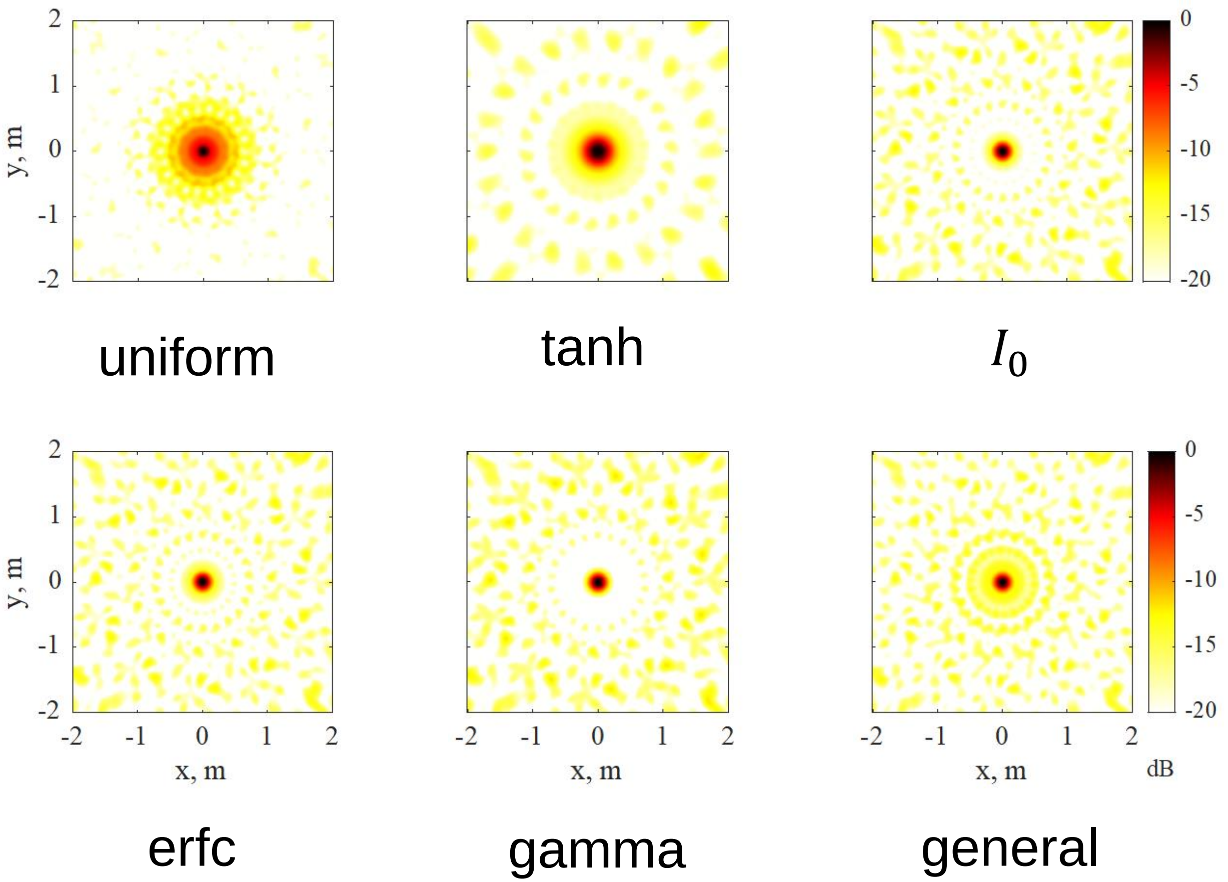
Shading method plots



Two-parameter methods similar, general method does not reject outer mics at high frequencies

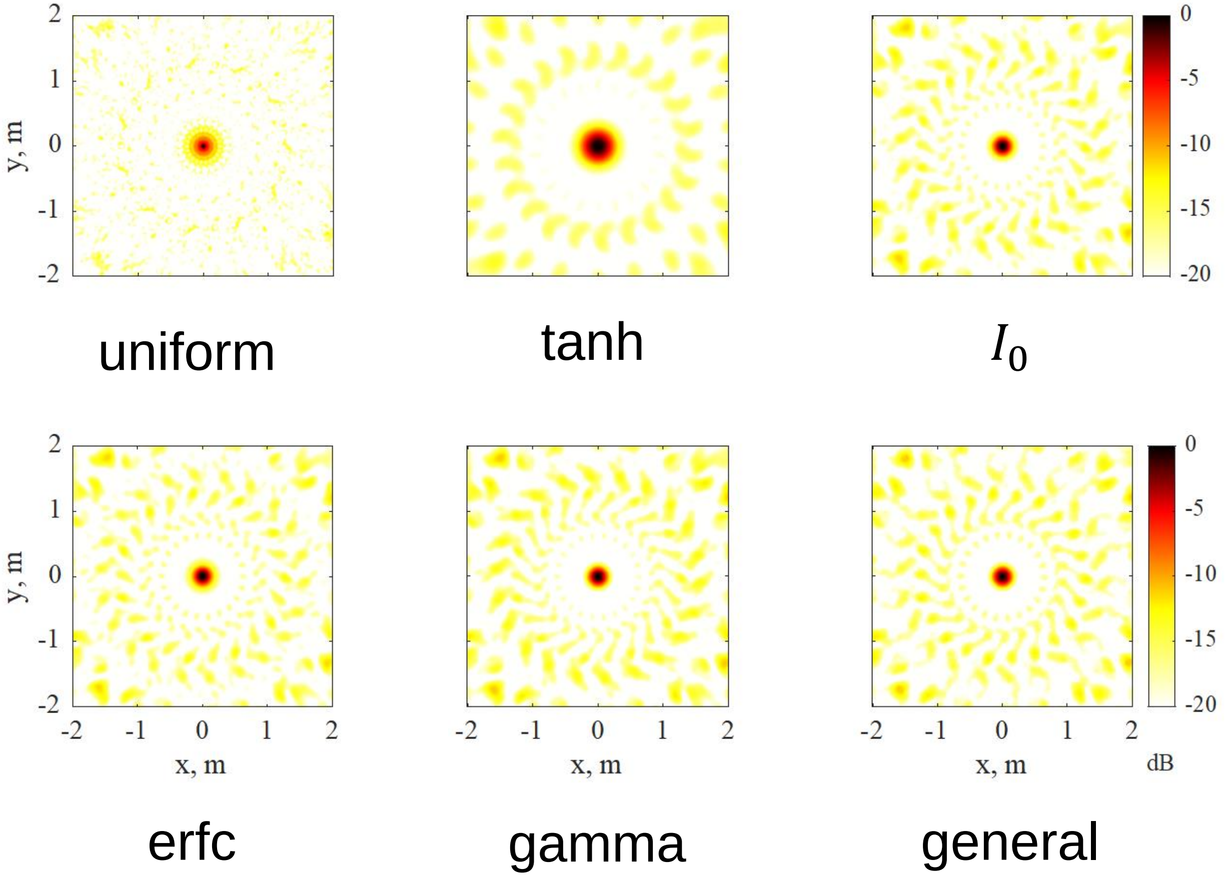
Synthetic data – 8 kHz

- Uniform shading – narrow 3 dB mainlobe, wide 10 dB mainlobe due to inner array mic distribution
- tanh shows this to lesser extent
- General – broad 20 dB mainlobe width
- Two-parameter methods – broadly similar



Synthetic data – 20 kHz

- Uniform shading – 3 dB mainlobe more narrow, fewer, smaller sidelobes of similar magnitude
- tanh – wider 3 dB mainlobe, 10 dB mainlobe width now well-controlled
- All optimized methods similar

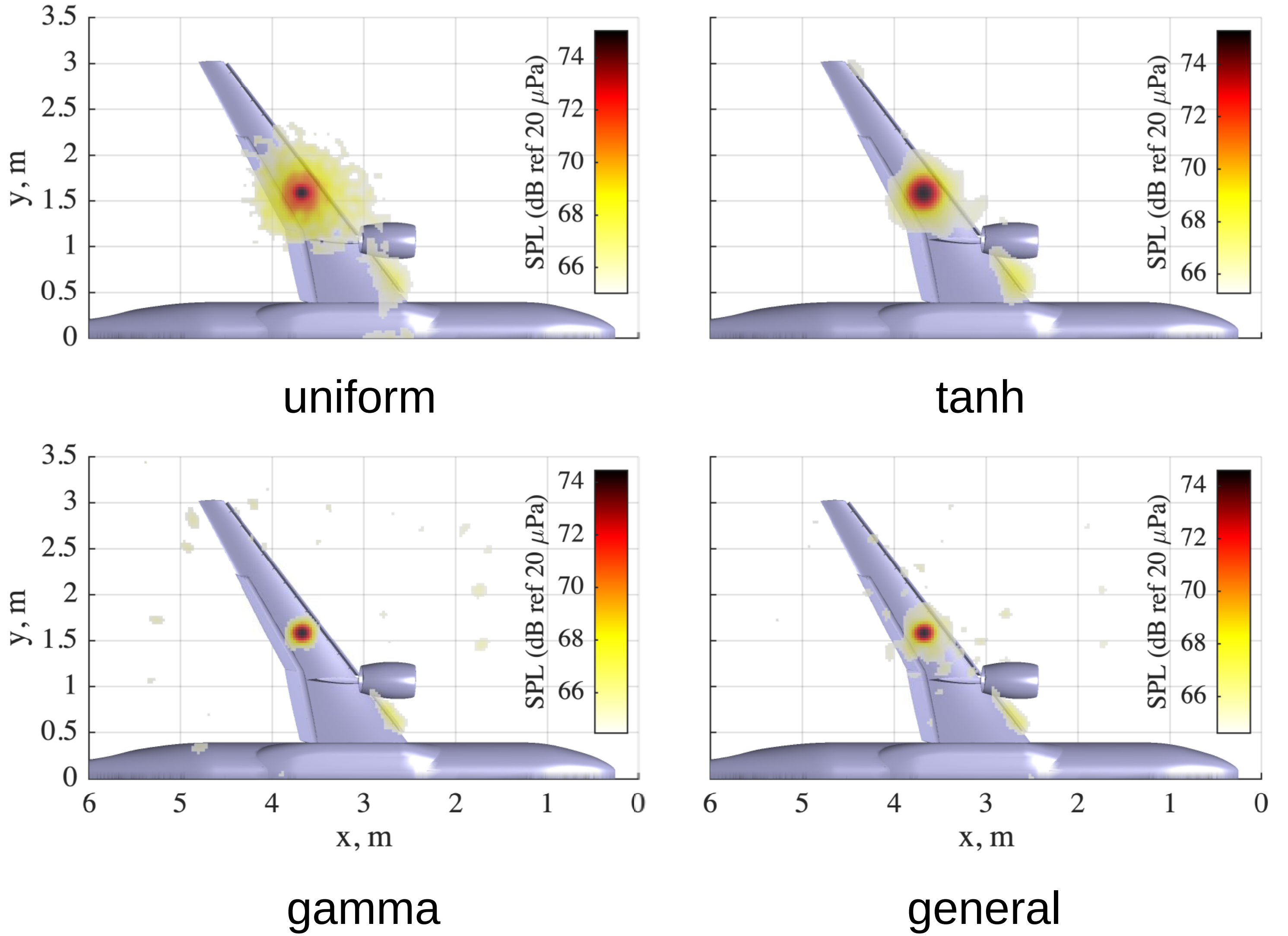


Experimental data – processing parameters

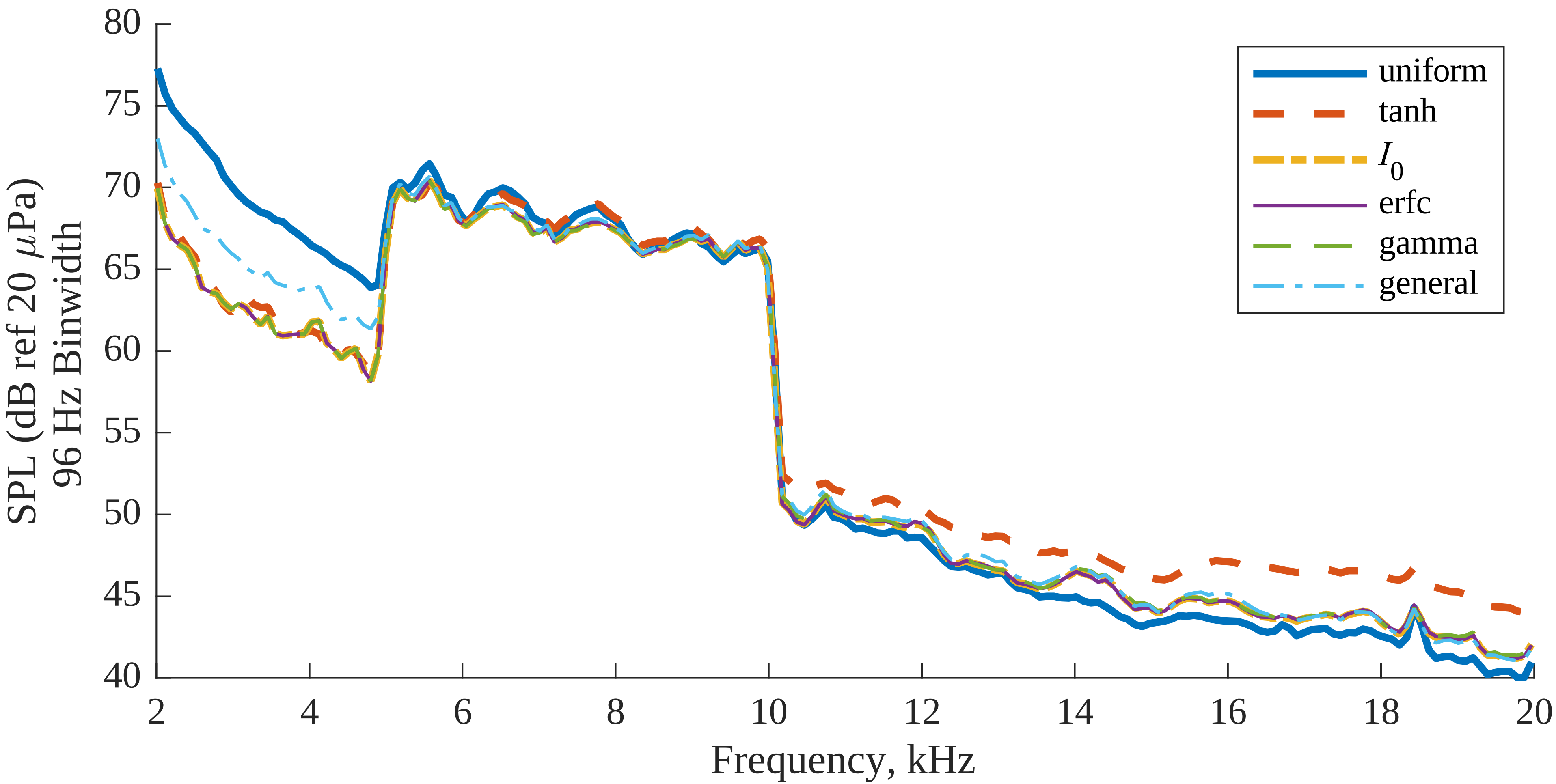
- Model w/ nacelle: 7° AoA, Mach 0.2, embedded speaker operating at 5-10 kHz
- 35 second records processed to 96 Hz binwidth CSM, 75% overlap – ~7000 effective block averages
- Diagonal optimization of CSM – mitigate contamination while keeping CSM positive semidefinite
- Beamforming results computed on ~ 4 m x 3.5 m grid w/ 3 cm spacing, ~15.7k grid points
- 200 DAMAS forward-backward passes of varying direction on the grid
- Images summed to 1/12th-octave bands

Speaker results – 8 kHz beamforming

- Optimized methods extremely similar – only plotting gamma
- Overall behavior matches to synthetic results for a point source
- All methods capture inboard slat/nacelle source
- Fewer sidelobes for uniform/tanh, most for gamma



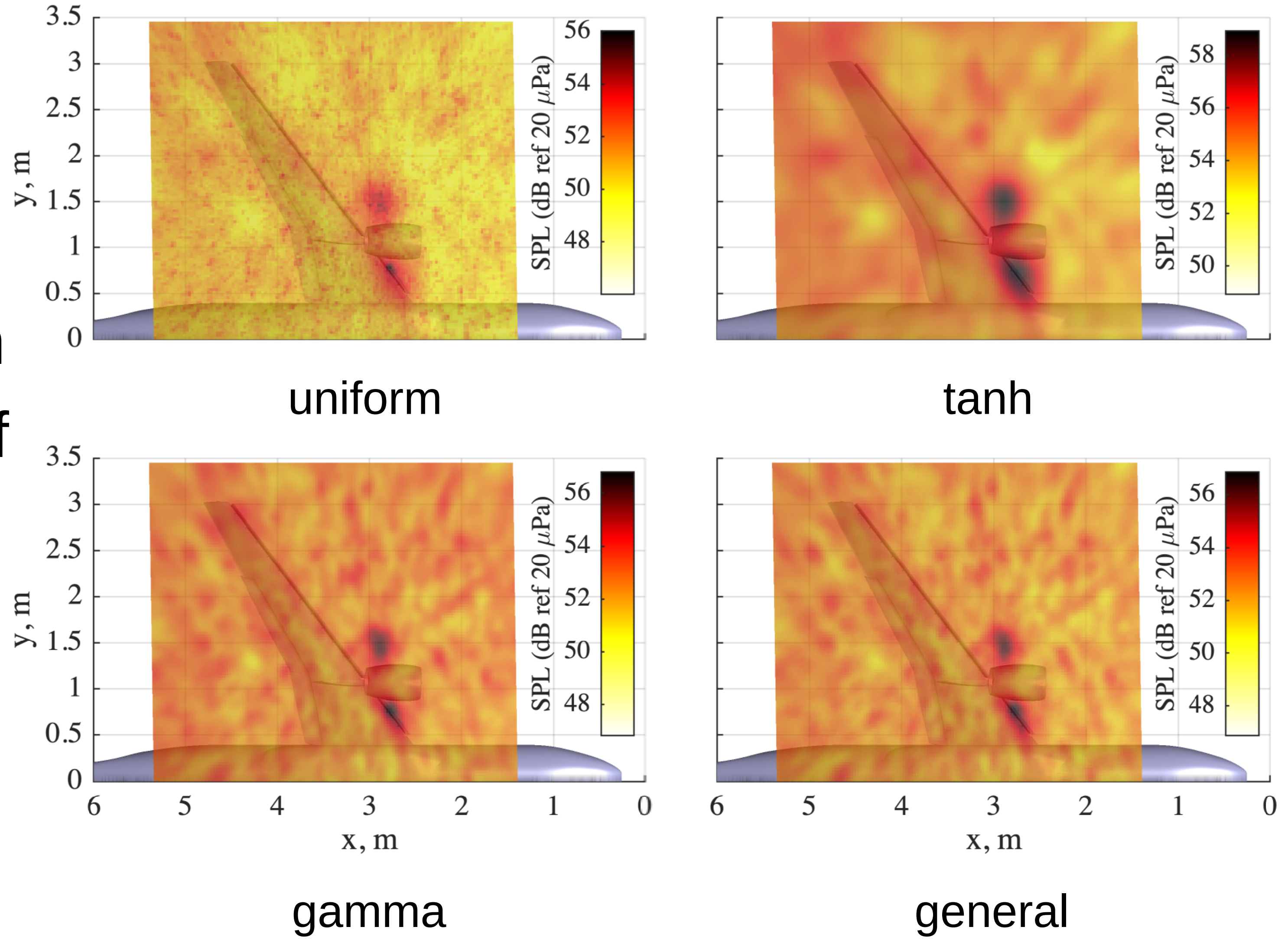
Beamforming spectrum – level at speaker location



- Minor variability across all methods for 5-10 kHz (optimized show agreement)
- Other frequencies – combination of lobe overlap & noise floor

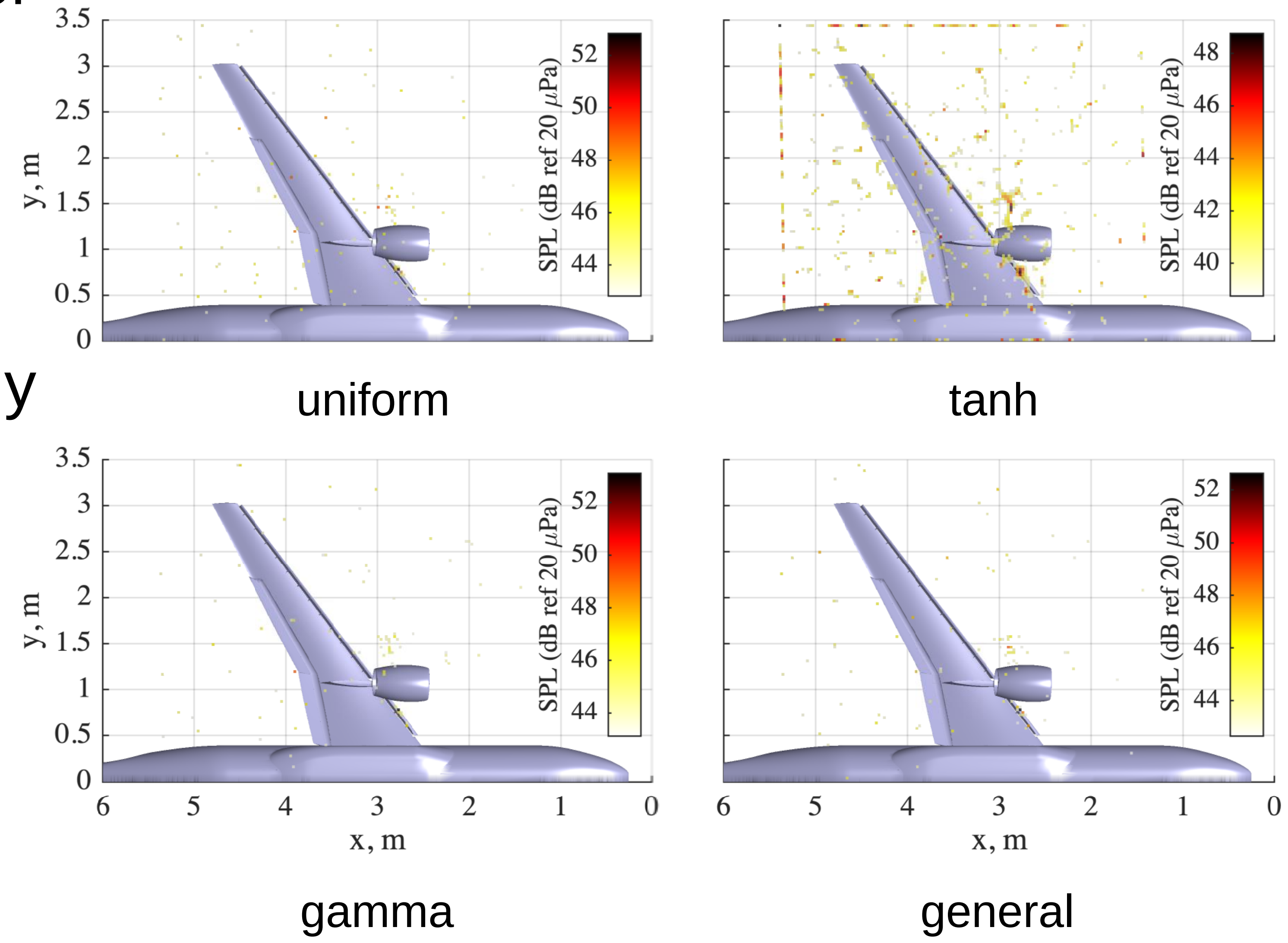
Airframe results – 20 kHz beamforming

- Two sources – inboard slat/nacelle & far wall reflection of unknown source
- uniform – best resolution
- tanh – more emphasis of reflected source, 2 dB higher peak level
- Two-parameter and general methods similar

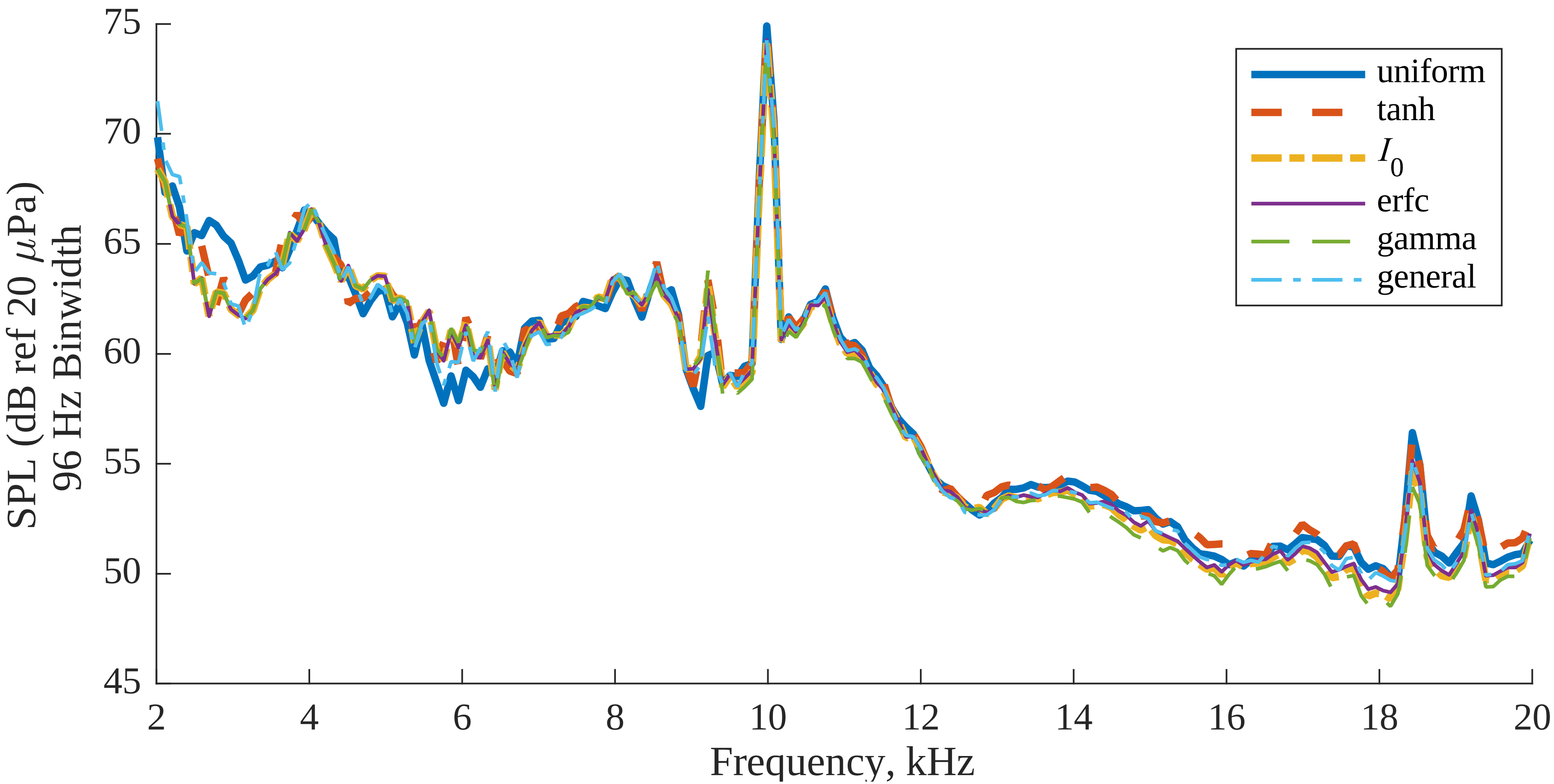


Airframe results – 20 kHz DAMAS

- Broadly similar results for 5 of the 6 methods - sources localized to similar points/clusters
- tanh very different – smeared sources, energy pushed to boundaries
- BeBeC paper blames points/beamwidth; surrogate for A-matrix rank?
  - rank(A_{gamma} = 7565)
  - rank(A_{tanh} = 1995)



Integrated DAMAS – Inboard slat region



- Similar results – some deviation for uniform at low frequencies, tanh at high
- Spectral shapes match, dominant tone level agrees within fraction of dB

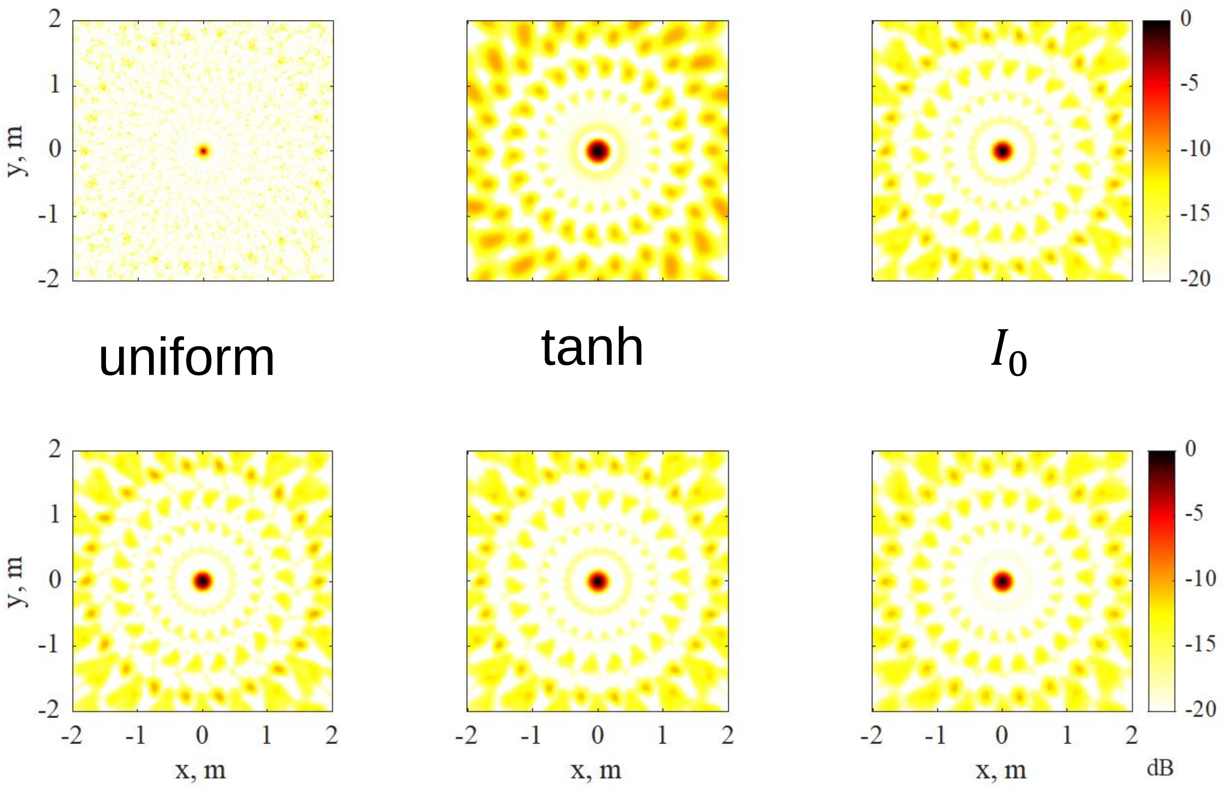
Summary and conclusions

- Shading design method proposed: two-parameter optimization
- Designs compared to no shading, existing shading, and general optimization
- Shading functions show strong influence on visualization of beam maps; DAMAS images sensitive to grid density/A-matrix rank
- Quantitative values less sensitive
  - Minor influence on dominant point source
  - Little influence on integrated deconvolution spectra
- Initial conclusion: shading is important and should be used
  - Major differences between methods matter
  - Minor differences (e.g., erfc vs. gamma) do not

Questions?

Synthetic data – 50 kHz

- Uniform – extremely narrow 3 dB mainlobe
- tanh – wider 3 dB mainlobe than optimized methods, wider sidelobes
- All optimized methods similar



uniform tanh I_0

erfc gamma general