

Acoustic Measurements of Rectangular Nozzles with Bevel

James Bridges*

NASA Glenn Research Center, Cleveland, OH, 44135

A series of convergent rectangular nozzles of aspect ratios 2:1, 4:1, and 8:1 were constructed with uniform exit velocity profiles. Additional nozzles were constructed that extended the wide lip on one side of these nozzles to form beveled nozzles. Far-field acoustic measurements were made and analyzed, and the results presented. The impact of aspect ratio on jet noise was similar to that of enhanced mixing devices: reduction in aft, peak frequency noise with an increase in broadside, high frequency noise. Azimuthally, it was found that rectangular jets produced more noise directed away from their wide sides than from their narrow sides. The azimuthal dependence decreased at aft angles where noise decreased. The effect of temperature, keeping acoustic Mach number constant, was minimal. Since most installations would have the observer on the wide size of the nozzle, the increased high frequency noise has a deleterious impact on the observer. Extending one wide side of the rectangular nozzle, evocative of an aft deck in an installed propulsion system, increased the noise of the jet with increasing length. The impact of both aspect ratio and bevel length were relatively well behaved, allowing a simple bilinear model to be constructed relative to a simple round jet.



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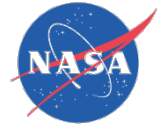
James Bridges

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4–6 June 2012

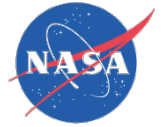
Colorado Springs, CO

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Outline

- Motivation
- Historical Review
- Nozzle Geometries & Flow Conditions
- Facility and Instrumentation
- Results
 - Varying Aspect Ratio
 - Varying Bevel Length
- Modeling Noise Impact
 - Geometric model
 - Flow condition
- Summary



Motivation

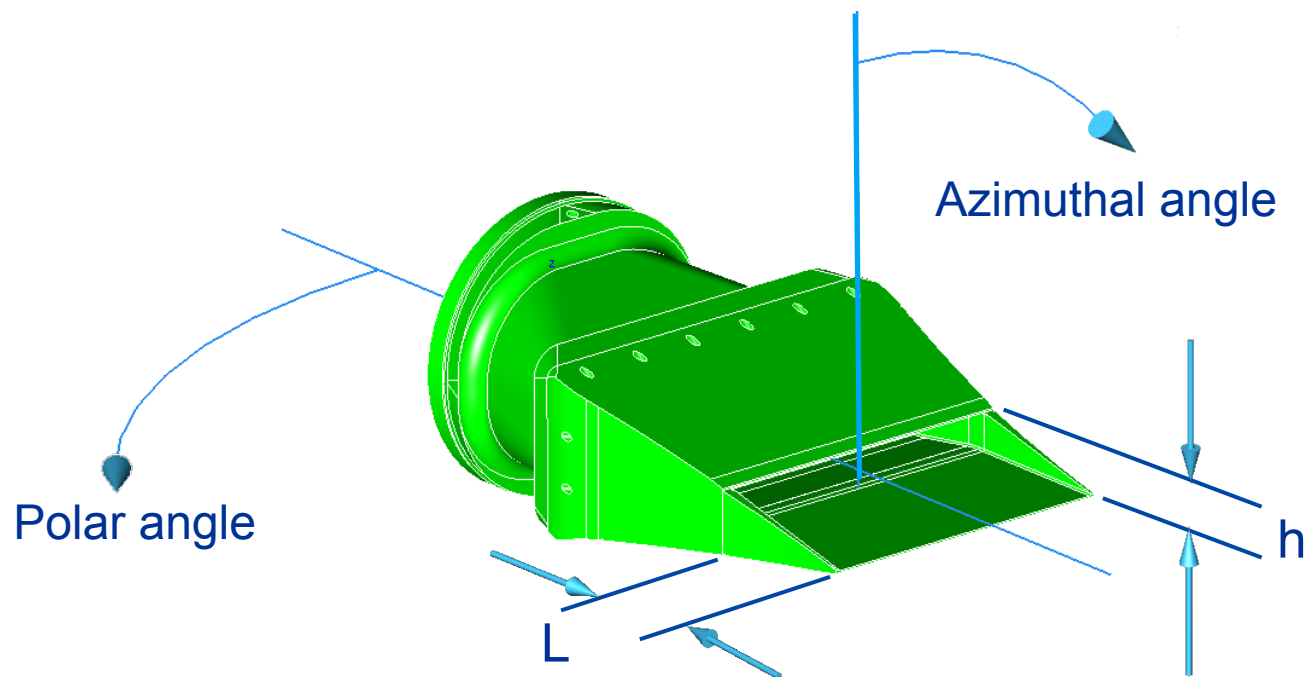
- Highly embedded propulsion systems, such as may be required for low sonic boom, often employ high aspect ratio nozzles and aft decks
 - Highly variable cycle nozzles can be implemented with fewer moving parts in a 2-D geometry
- Database and design tools for rectangular jet noise nonexistent
 - Most jet noise prediction tools assume axisymmetry and no surfaces
- NASA Systems Analysis groups need predictive capability (empirical, RANS-based, LES) for jet noise in ***subsonic plume*** regime.

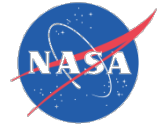




Nomenclature

- Polar angle, fore-to-aft (broadside, aft)
- Azimuthal angle (wide, narrow)





Historical

- Coles NACA (1959)
 - 14:1 and 100:1 slot nozzle on static aircraft
 - Found 10+dB directivity in aft angles for 100:1
- GE CR&D (1970s)
 - 6:1 rectangular nozzle, cold and hot subsonic flows
 - Found suppression relative to round jet
 - Found significant azimuthal dependence, esp. high frequencies
- GTRI (2002-2004)
 - 1.5:1, 4:1, 8:1 rectangular nozzles, subsonic flows
 - Documented variation of noise with aspect ratio, V_j
- None have enough azimuthal angles, flow conditions for modeling
- $O(10)$ of **supersonic** rectangular jet studies

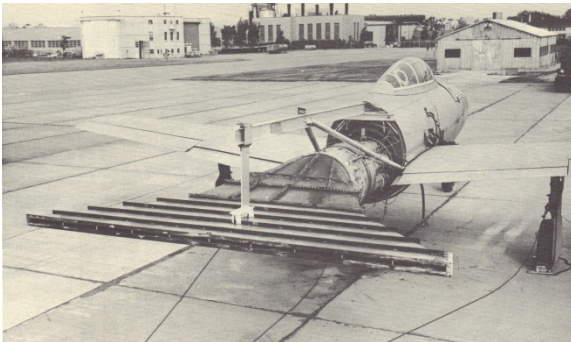


Figure 3-1. C-141 Starliner Facility.

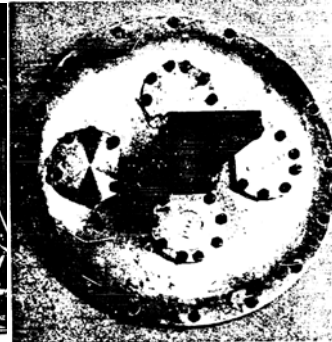
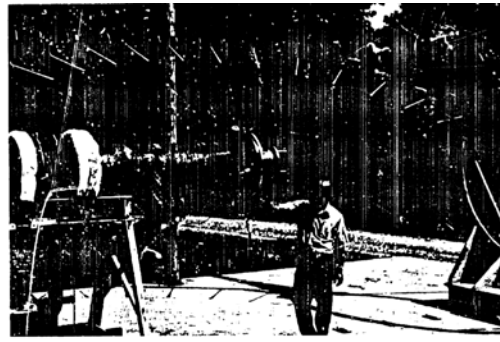


Figure 3-2. Rectangular Jet Engine.





Tam & Zaman (2000)

- “**Subsonic Jet Noise from Nonaxisymmetric and Tabbed Nozzles**” (*AIAA J* 38(4), 2000), Tam & Zaman
- “...the radiated noise fields of the jets under study, including elliptic and large-aspect-ratio rectangular jets, **are found to be quite axisymmetric** and are practically the **same as that of a circular jet** with the same exit area.”

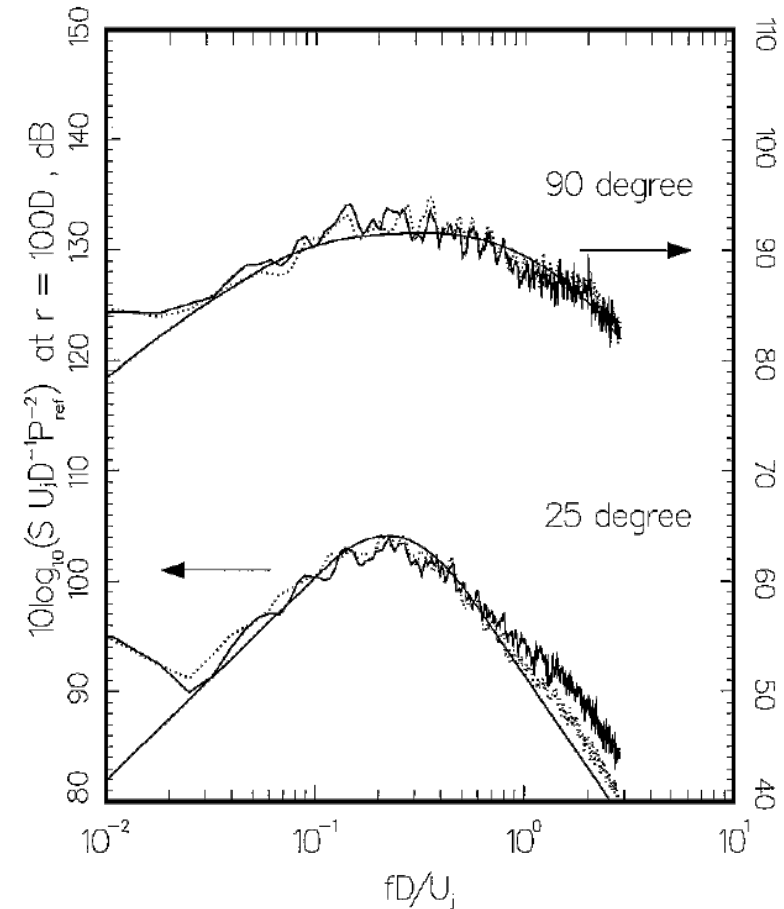
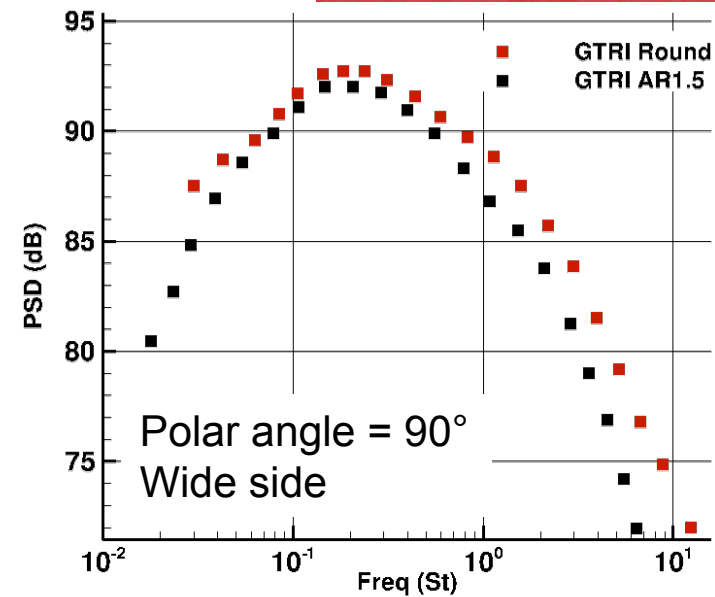
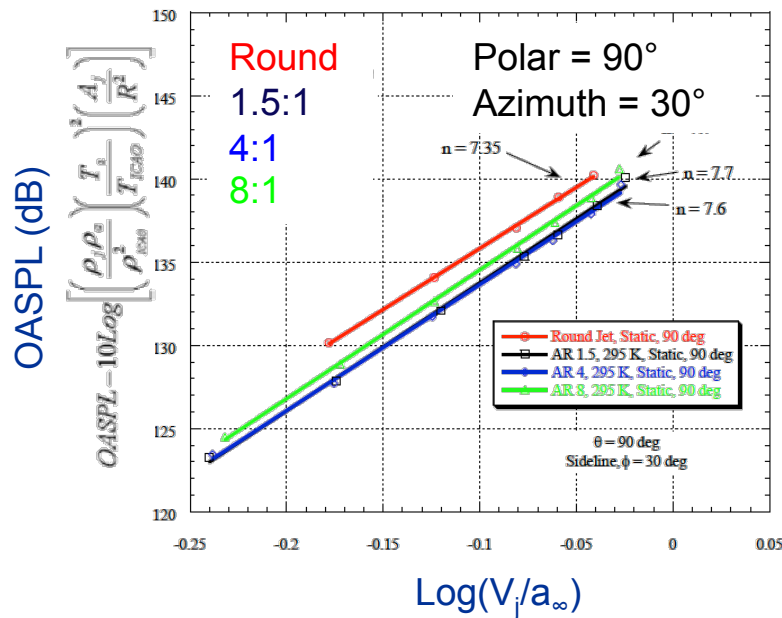


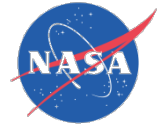
Fig. 4 Noise spectra from aspect ratio 8 rectangular jet, $M_j = 0.82$, $D_{\text{equivalent}} = 0.58$ in.: \cdots , major axis plane; — , minor axis plane; and smooth curves, TGS spectra.



GTRI (2002-2004)

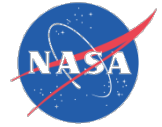
- “Noise Scaling for Unheated Low Aspect Ratio Rectangular Jets” (AIAA-2004-2946), Massey, Ahuja, and Gaeta
- Subsonic, AR=1.5, 4, 8
- Noise data for azimuth = 30°, 90°
- Noise reduction at AR = 1.5; not monotonic in AR





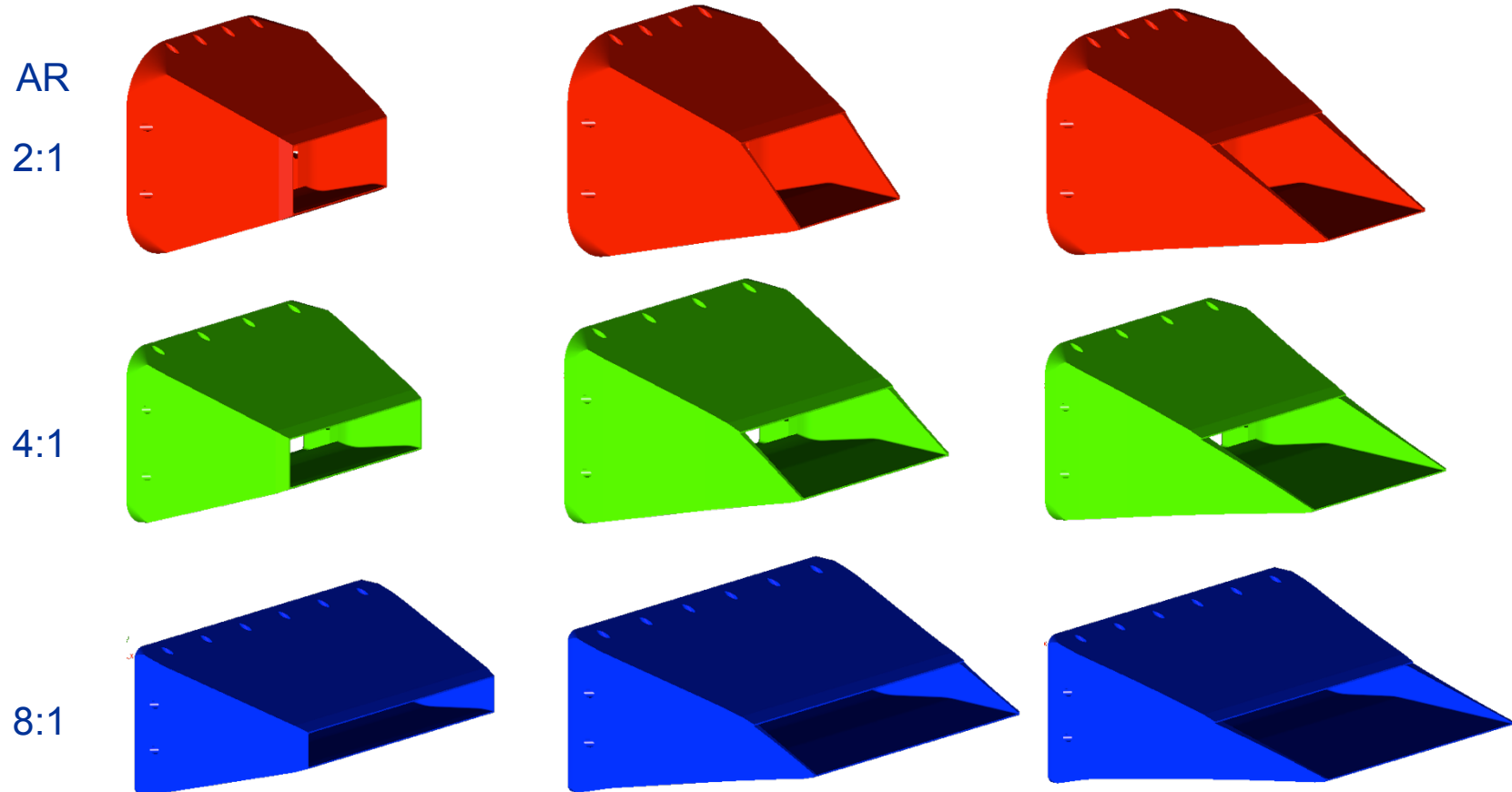
Effect of bevel (aft deck)

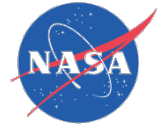
- Attached aft deck is common feature of embedded propulsion concepts
- Extensive work on beveled round nozzles. (Viswanathan ca. 2004)
 - Generally finds noise reduction with bevel
- No open literature found on noise of bevel/scarf/aft deck on high aspect ratio jets except for shock-noise work of Rice & Raman (1993).
- Effect of 'aft deck' or bevel
 - Shielding (reduction)?
 - Shear-surface source (increase)?



Nozzle geometries

- Nozzles designed to minimize velocity distortion at exit (Frate & Bridges AIAA 2011-0975)
- Parametric variation in aspect ratio (AR) and bevel length (L/h)

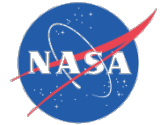




Flow conditions

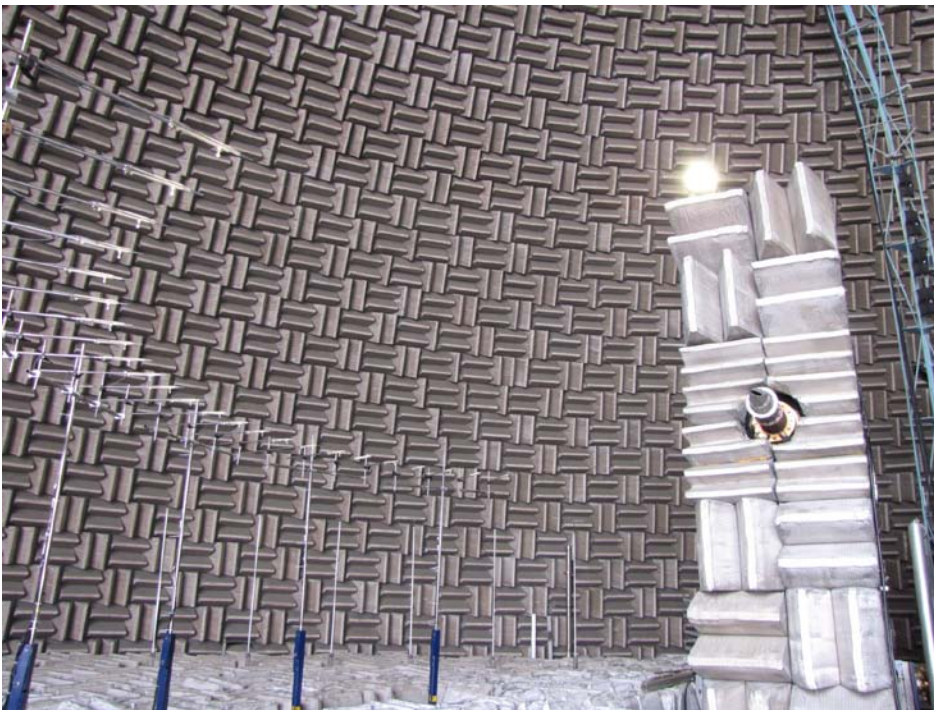
- Subsonic, shock-free

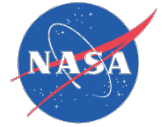
Setpoint	V/a_∞	T_f/T_∞	M
3	0.50	0.95	0.51
5	0.70	0.90	0.74
7	0.90	0.84	0.98
23	0.50	1.76	0.38
27	0.90	1.76	0.68
29	1.33	1.76	1.01
46	0.90	2.70	0.56
48	1.33	2.70	0.82



Facility and Instrumentation

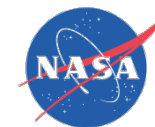
- Small Hot Jet Exhaust Rig (SHJAR) at NASA Glenn
- $D_e = 2.14''$ (54.3mm) (equivalent area)
- $R = 75D_e$ polar arc of 24 $\frac{1}{4}''$ B&K microphones, 5° spacing
- Azimuthal variation by nozzle rotation
- Setpoint accuracy error < 0.5%





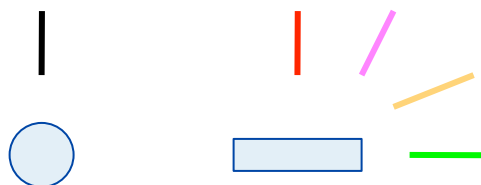
Results

- Far-field acoustic data normalized to $r/D_e = 100$
- Atmospheric attenuation restored
- Power spectral density normalized by U_j and D_e

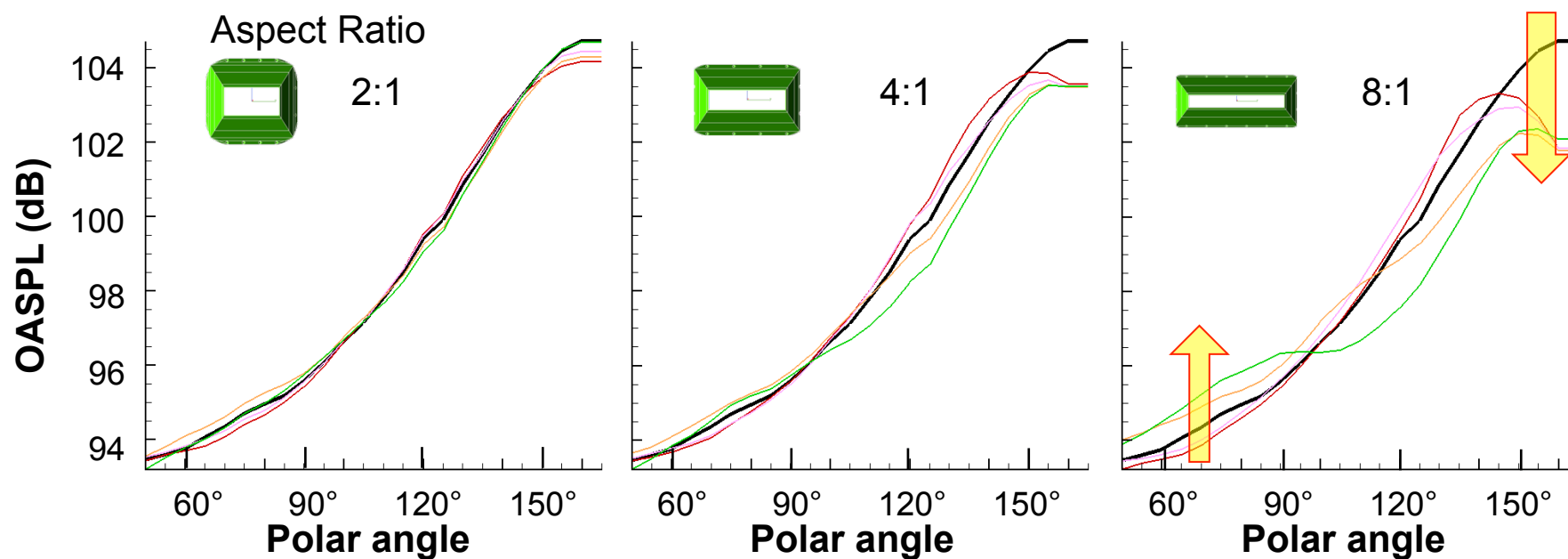


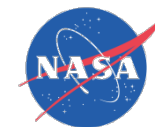
Aspect Ratio—OASPL

$L/h = 0$

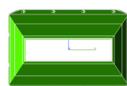


$M=0.96$, cold

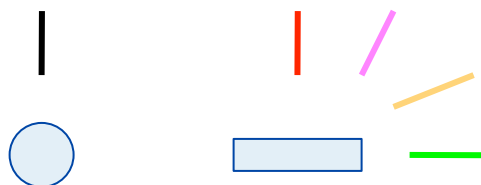




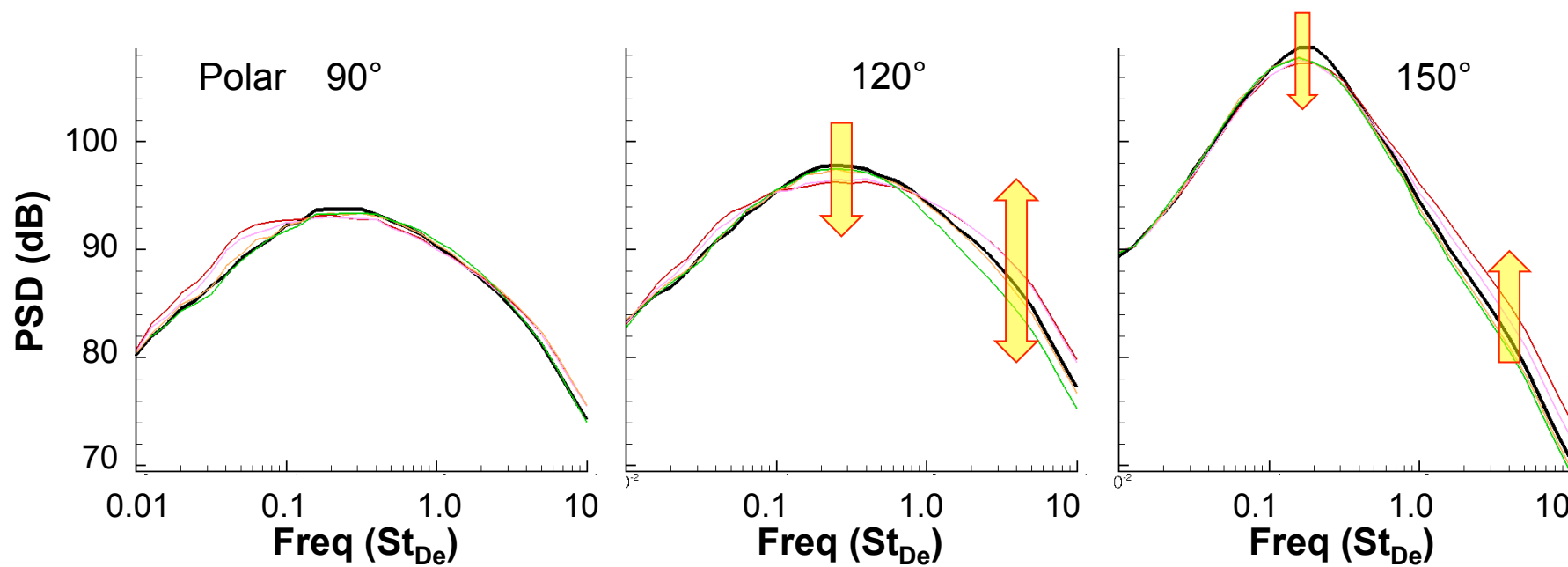
Aspect Ratio—SPL

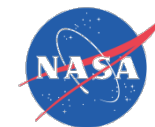


4:1

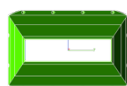


M=0.96, cold

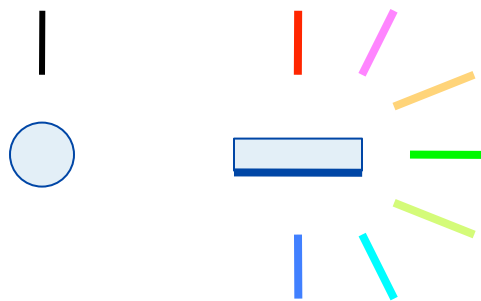
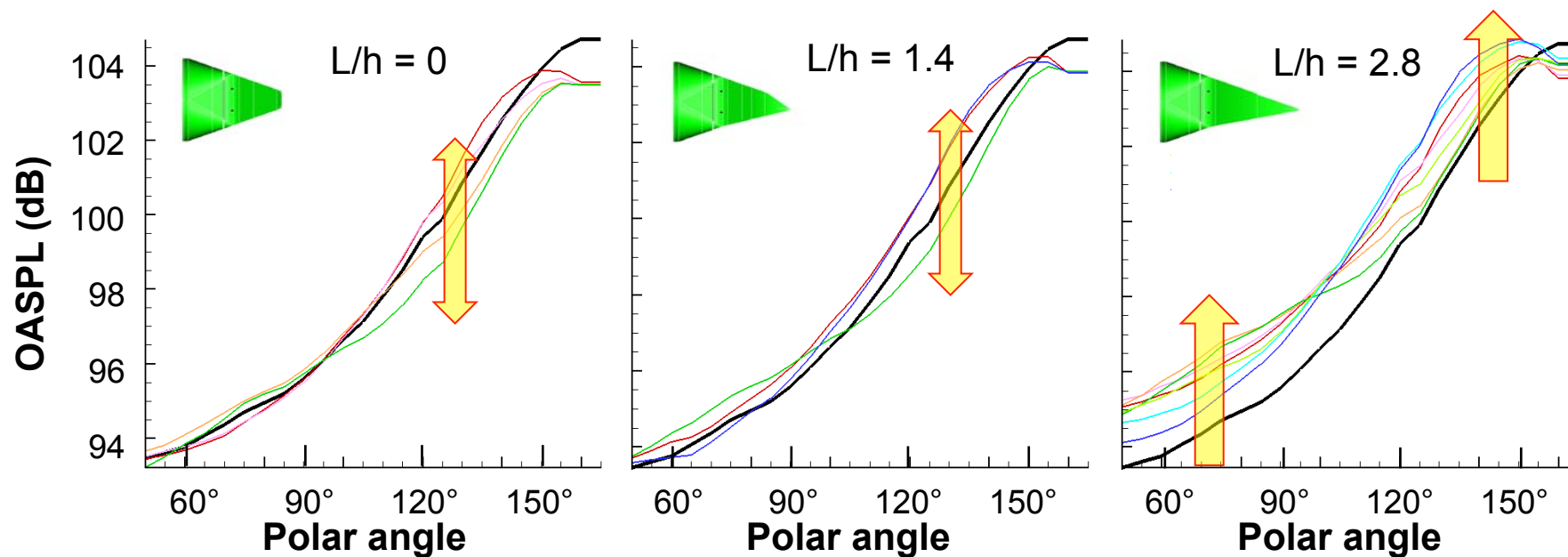


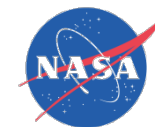


Bevel Length—OASPL

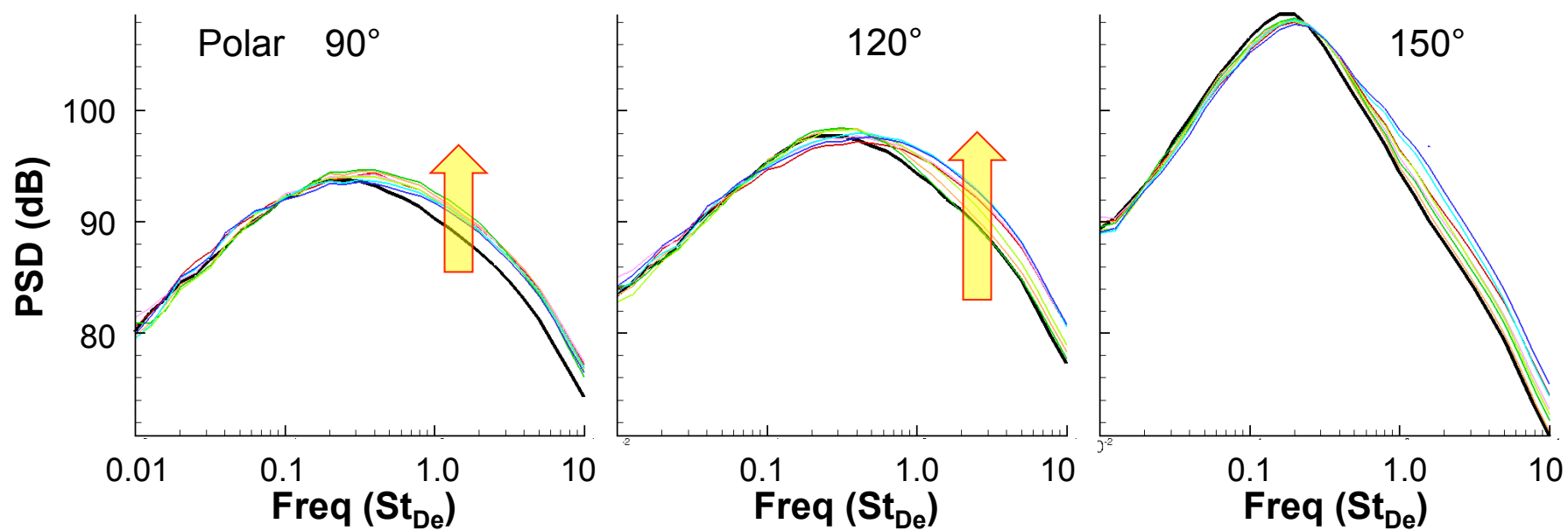
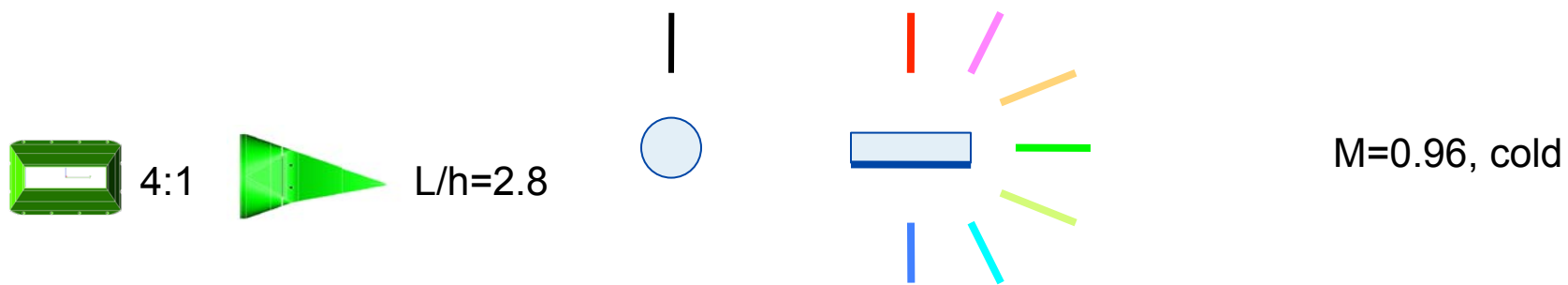


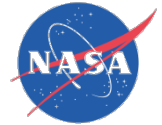
4:1

 $M=0.96$, cold



Bevel Length—SPL





Modeling Noise Impact

- Variation of noise with AR and L/h is very smooth
- Create low-order surrogate model for spectral directivity

$$\begin{aligned} & PSD(AR, L/h; f, \theta, \phi) \\ &= PSD0(f, \phi) \\ &+ AR * a(f, \theta, \phi) \\ &+ L/h * b(f, \theta, \phi) \\ &+ AR * L/h * c(f, \theta, \phi) \end{aligned}$$

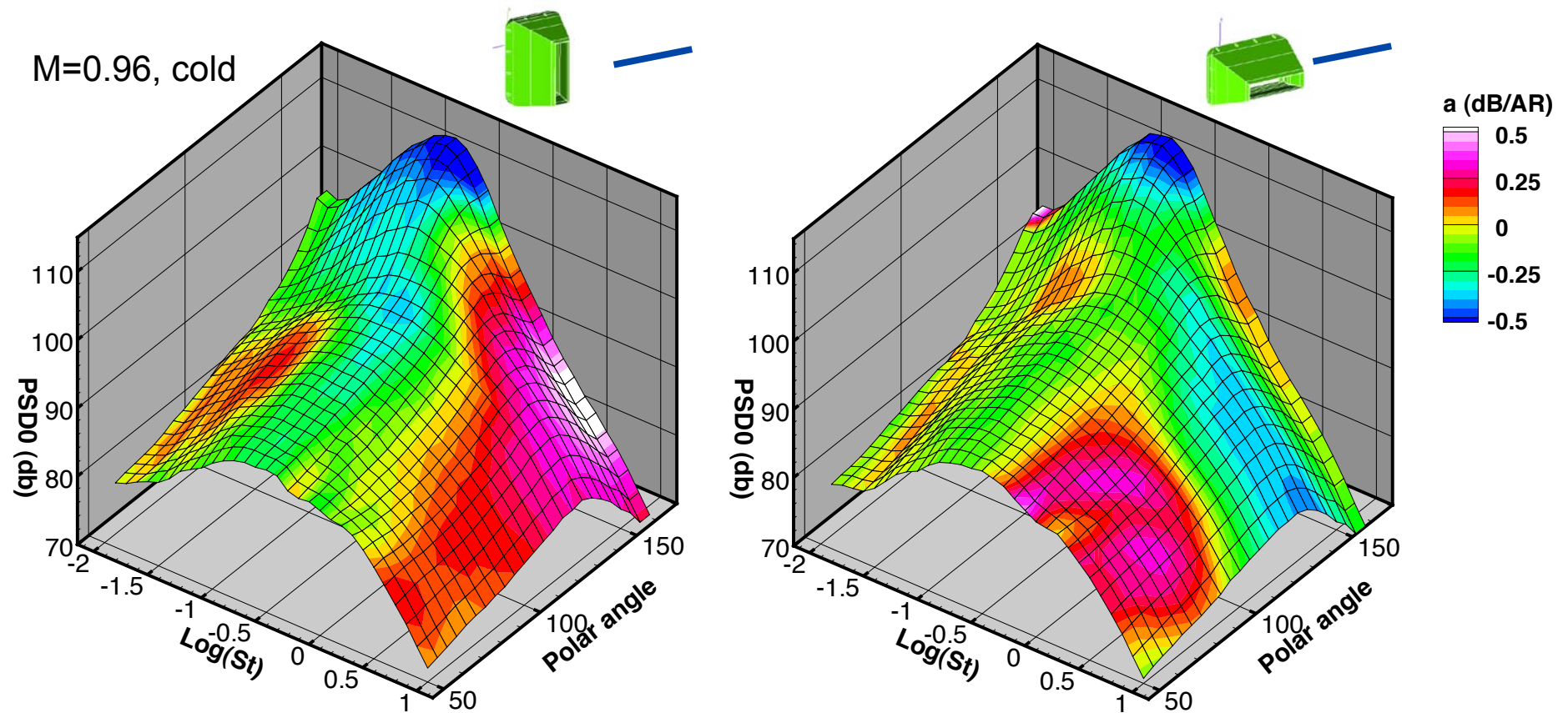
where PSD0 is spectral directivity of round jet at the given flow conditions.

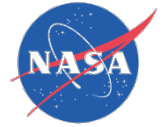
- Hence a is sensitivity of noise to aspect ratio, b to bevel length
- Bilinear model fitted to 3 aspect ratios, 3 bevel lengths each
- Captures trends efficiently if model fits well



Parametric Modeling—Aspect Ratio

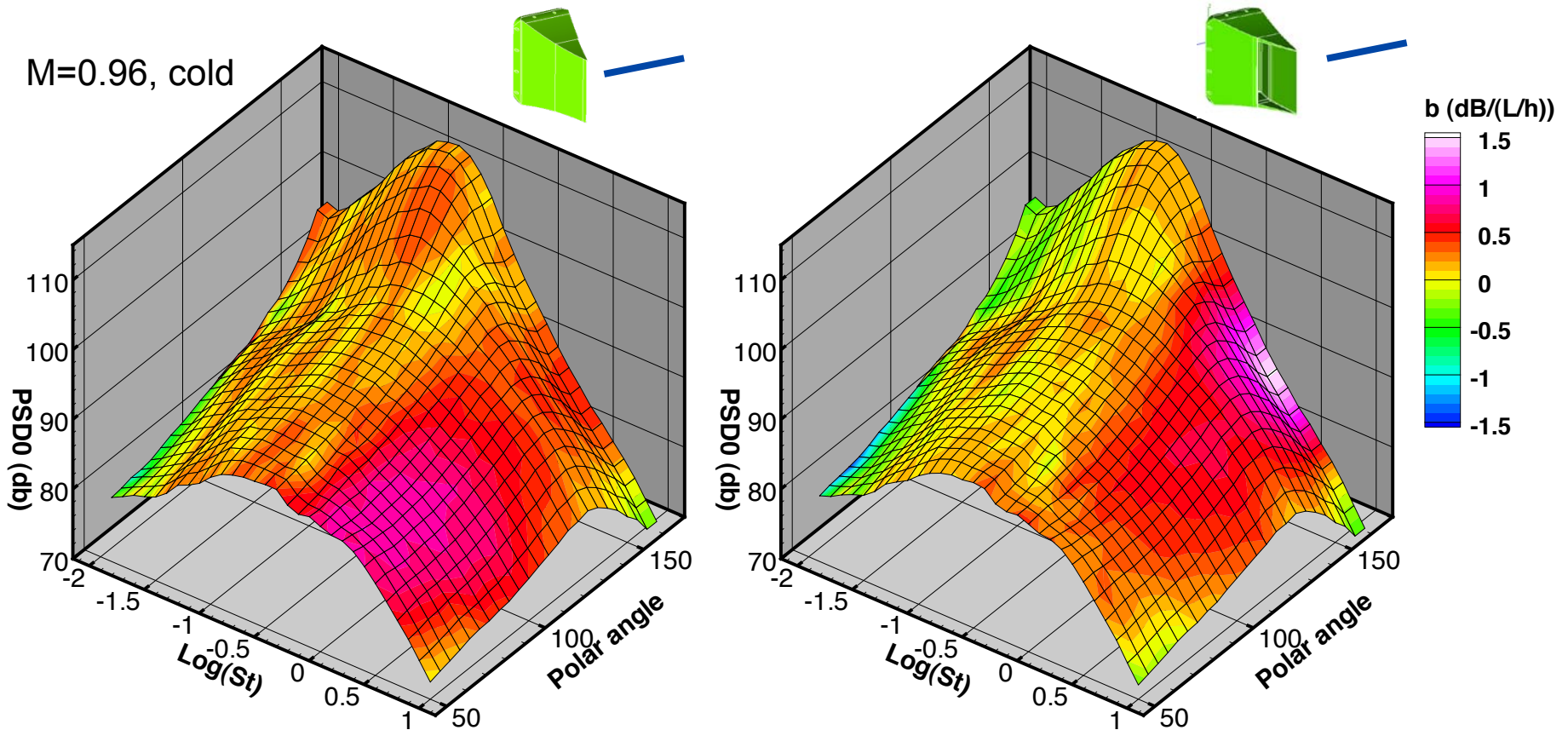
- Surface shape is spectral directivity of round jet, color is aspect ratio coefficient
- Linear coefficient for aspect ratio depicts basic sensitivities
- Noise increases with aspect ratio at high frequencies
- Polar directivity depends on azimuthal angle





Parametric Modeling—Bevel Length

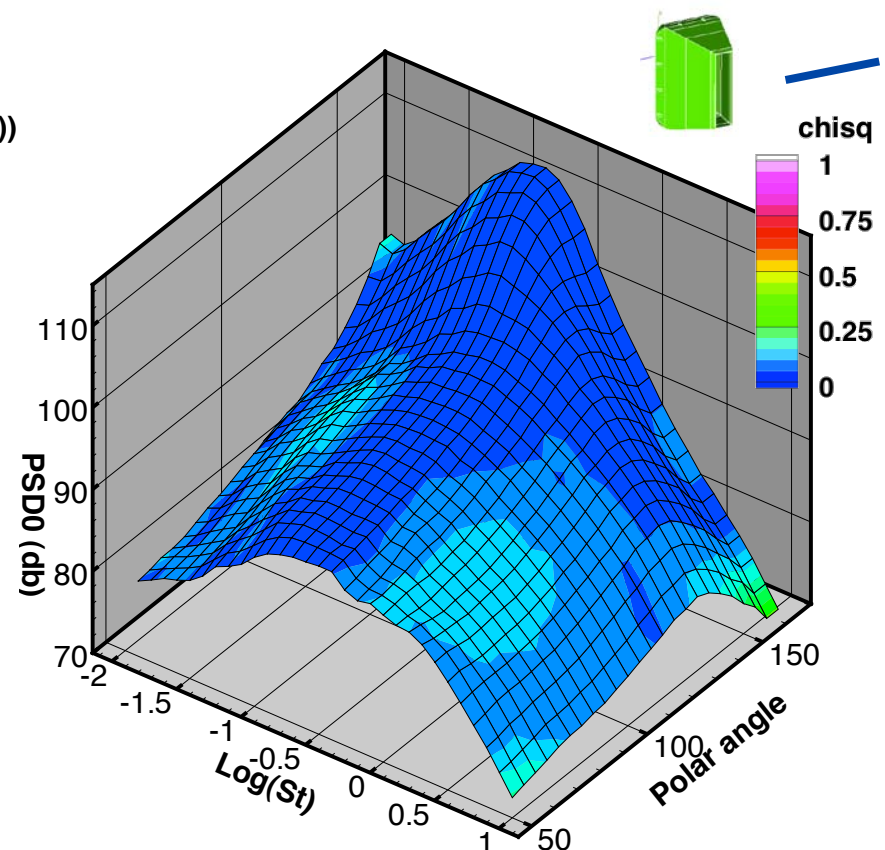
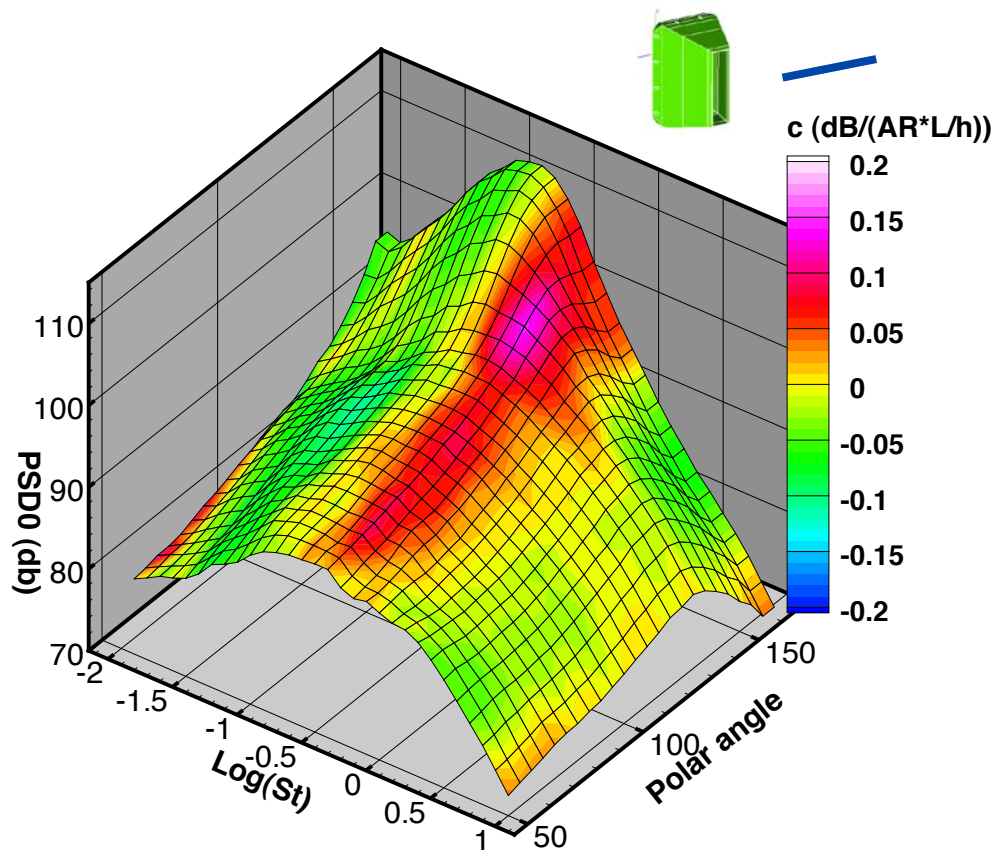
- Linear coefficient for bevel length depicts basic sensitivities
- Positive all angles, almost all frequencies—bevel increases noise.





Parametric Modeling—Cross Sensitivity and Quality of Fit

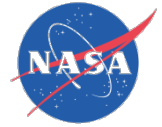
- Coefficient for cross-sensitivities is relatively small—-independent effects?
- Chi-square values very small—very good fit, high confidence model fits data.





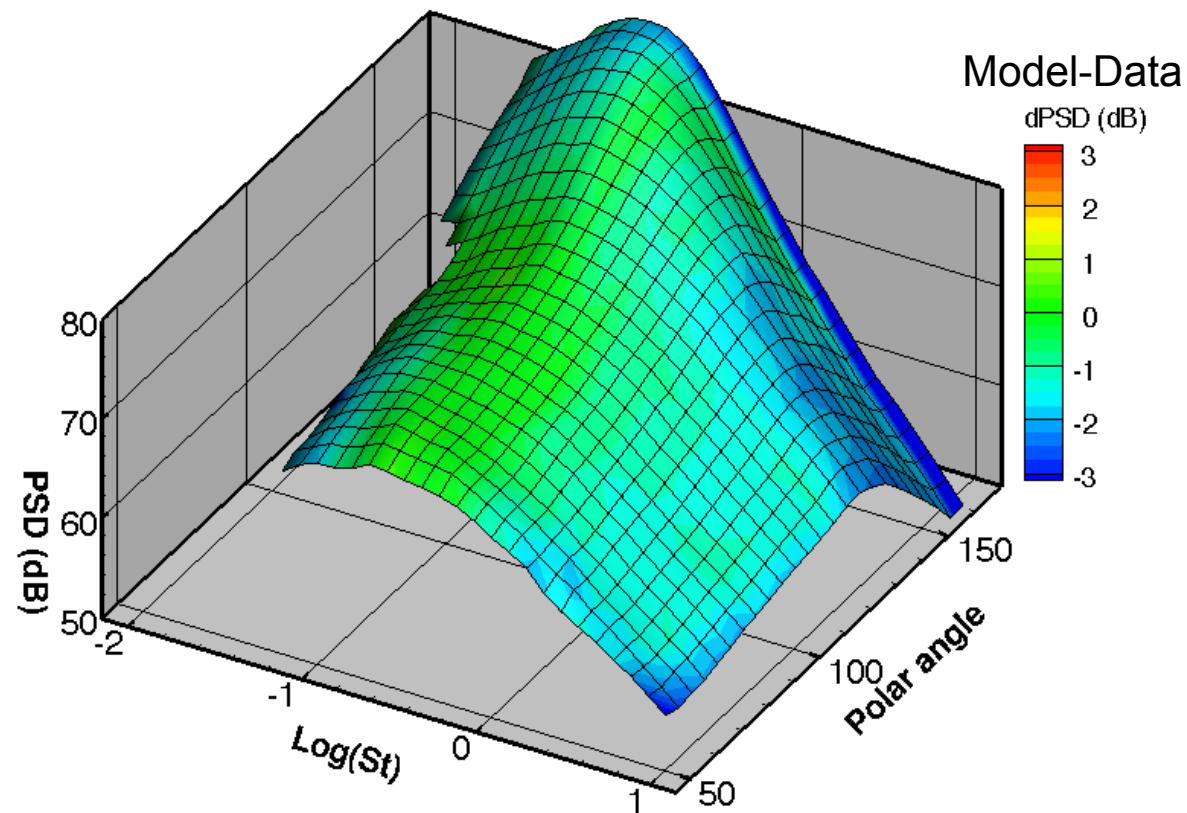
Modeling with Flow Condition

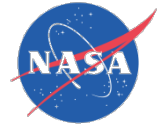
- Model constructed to get first order effect of flow condition PSD0 via round jet model (empirical or other).
- Assumes effect of geometry independent of flow condition.
- Geometric coefficients determined using $Ma = 0.9$, unheated flow data.
- Check model against data at other flow conditions.



$$AR=2, L/h = 0; Ma = 0.5, T_j/T_\infty = 1.76$$

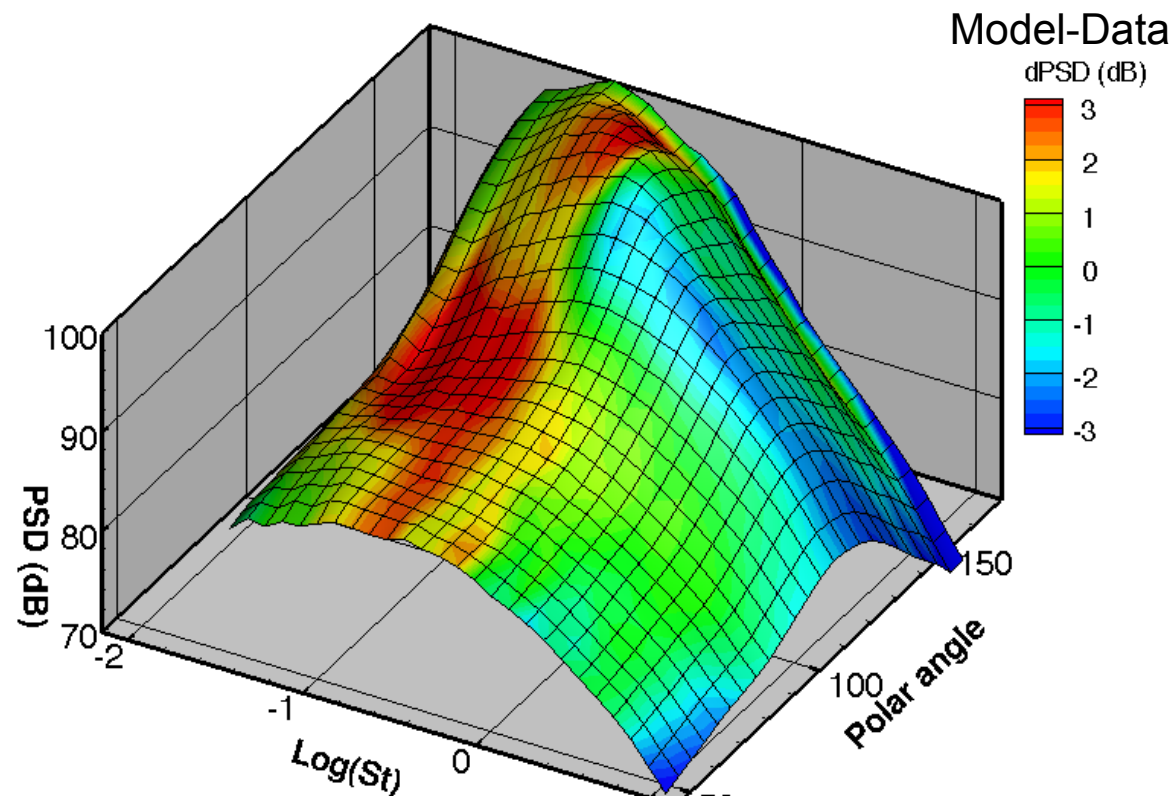
- Color scale indicates errors are within than 1dB
- May underpredict at high frequencies important to human annoyance.

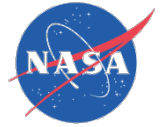




$$AR=8, L/h = 0; Ma = 0.9, T_j/T_\infty = 2.7$$

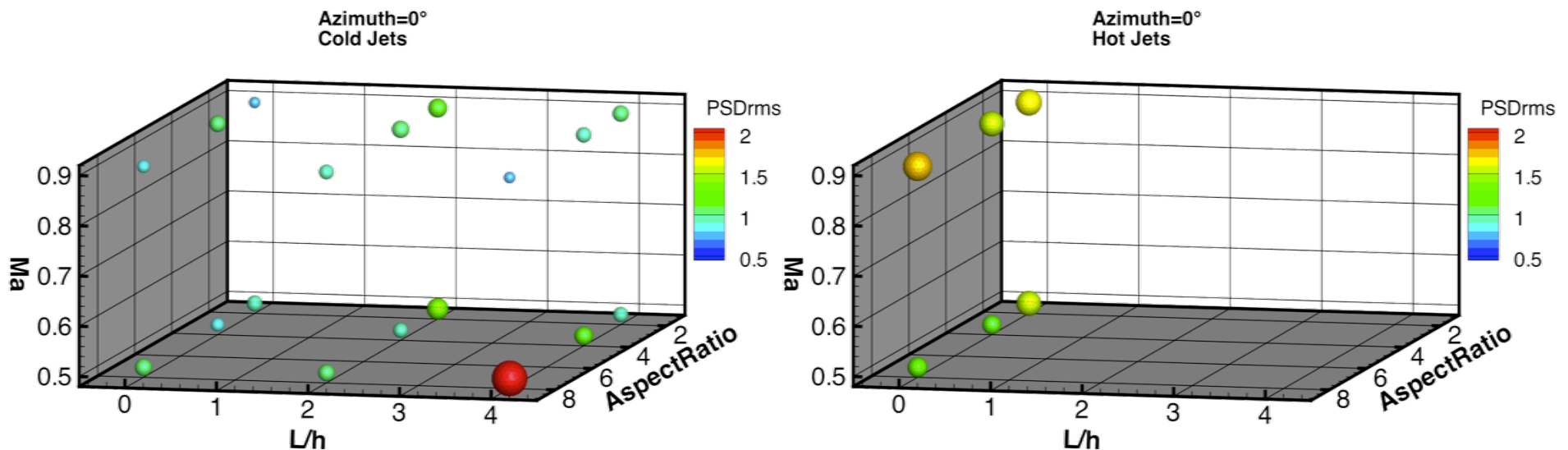
- Colorscale indicates errors of nearly 3dB at broadside polar angles
- Error very small for high frequencies at broadside polar angles





Overall Error of Model

- Integrate variance of error over polar angle and frequency to create overall measure of model accuracy, PSDrms
- Size of sphere and color indicate this error for the measured flow conditions and aspect ratios
- PSDrms less than 1dB for nearly all cold jets
- PSDrms closer to 1.5dB for hot jets (no bevel nozzle data available)





Summary

- Rectangular nozzles important in advanced aircraft applications
- Previous work showed either (a) no effect, or (b) noise reduction from low aspect ratio rectangular nozzles
- Test hardware devised to carefully remove impact of round-to-rectangular transition, assure uniform exit profile
- Tests did not find significant noise reduction at low aspect ratios for subsonic flow conditions
- Data were smoothly varying in aspect ratio and bevel length
- Increasing aspect ratio increased high frequency noise to the wide side, decreased peak noise to all azimuthal angles.
- Increasing bevel length always increased noise at all angles and frequencies
- Simple empirical model for geometric impact on spectral directivity fitted to data
- Geometric impact relatively independent of flow condition
- More physics-based approach would likely improve model