ACOUSTIC PREDICTION STATE OF THE ART ASSESSMENT

Milo D. Dahl

Presentation for the NASA
Fundamental Aeronautics 2007 Annual Meeting

Abstract:
The acoustic assessment task for both the Subsonic Fixed Wing and the Supersonic projects under NASA's Fundamental Aeronautics Program was designed to assess the current state-of-the-art in noise prediction capability and to establish baselines for gauging future progress. The documentation of our current capabilities included quantifying the differences between predictions of noise from computer codes and measurements of noise from experimental tests. Quantifying the accuracy of both the computed and experimental results further enhanced the credibility of the assessment. This presentation gives sample results from codes representative of NASA's capabilities in aircraft noise prediction both for systems and components. These include semi-empirical, statistical, analytical, and numerical codes. System level results are shown for both aircraft and engines. Component level results are shown for a landing gear prototype, for fan broadband noise, for jet noise from a subsonic round nozzle, and for propulsion airframe aeroacoustic interactions. Additional results are shown for modeling of the acoustic behavior of duct acoustic lining and the attenuation of sound in lined ducts with flow.

Acoustic Prediction State of the Art Assessment

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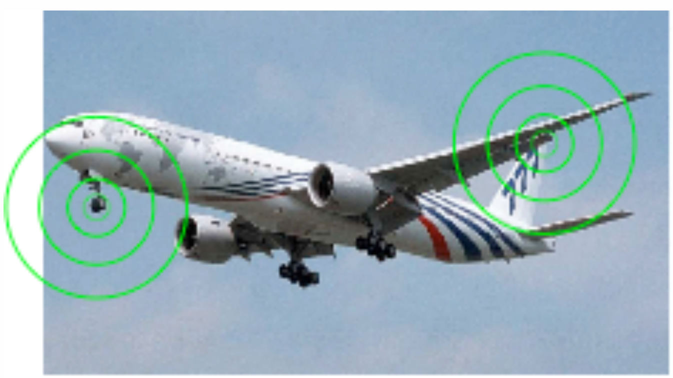
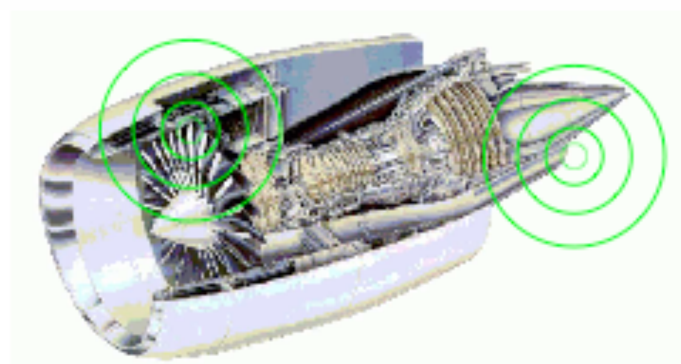
Fundamental Aeronautics
Annual Meeting

October 30, 2007



Airframe Noise



Engine Noise

Fundamental Aeronautics Program Plan

NASA needs robust, highly accurate tools and methods for performance prediction, experimental testing, and finally a verification and validation strategy that will create the opportunities to corroborate our prediction capabilities.

Goal is to develop physics based multi-disciplinary analysis and optimization (MDAO) tools with quantified levels of uncertainty.

Fundamental Aeronautics Program Plan
Current NASA Capability

Specific milestones in:
Subsonic Fixed Wing and Supersonic
Require assessment of noise prediction capability

- Document current capabilities for noise prediction versus validated data bases

  Assess state-of-the-art capability to predict noise

- Quantify our ‘error bars’ or *levels of uncertainty*

Establish Baselines

- Identify where to improve our tools (predictive and diagnostic)
- Identify needed experimental data

Outline

- Process of Assessment
- Topic Areas and Codes
- Sample Results
  - Aircraft Systems
  - Engine Systems
  - Airframe, Landing Gear Prototype
  - PAA and Jet, Subsonic Round Nozzle
  - Fan, Broadband
  - Liner and Duct
- Concluding Remarks

Definition of Assessment

Assessment: Act of documenting the degree to which computer models and codes meet the specified requirements following a verification and validation process.

- Ideally, assessment is part of the V & V process
  Quantified data available:
  - Verification that the code is right
  - Validation comparing predictions to measurements

- Assessment difficult when V & V practices not followed

Following V & V Practices Gives Confidence in Prediction

Confidence in prediction as error gets smaller

$$E = E_1 + E_2 + E_3$$

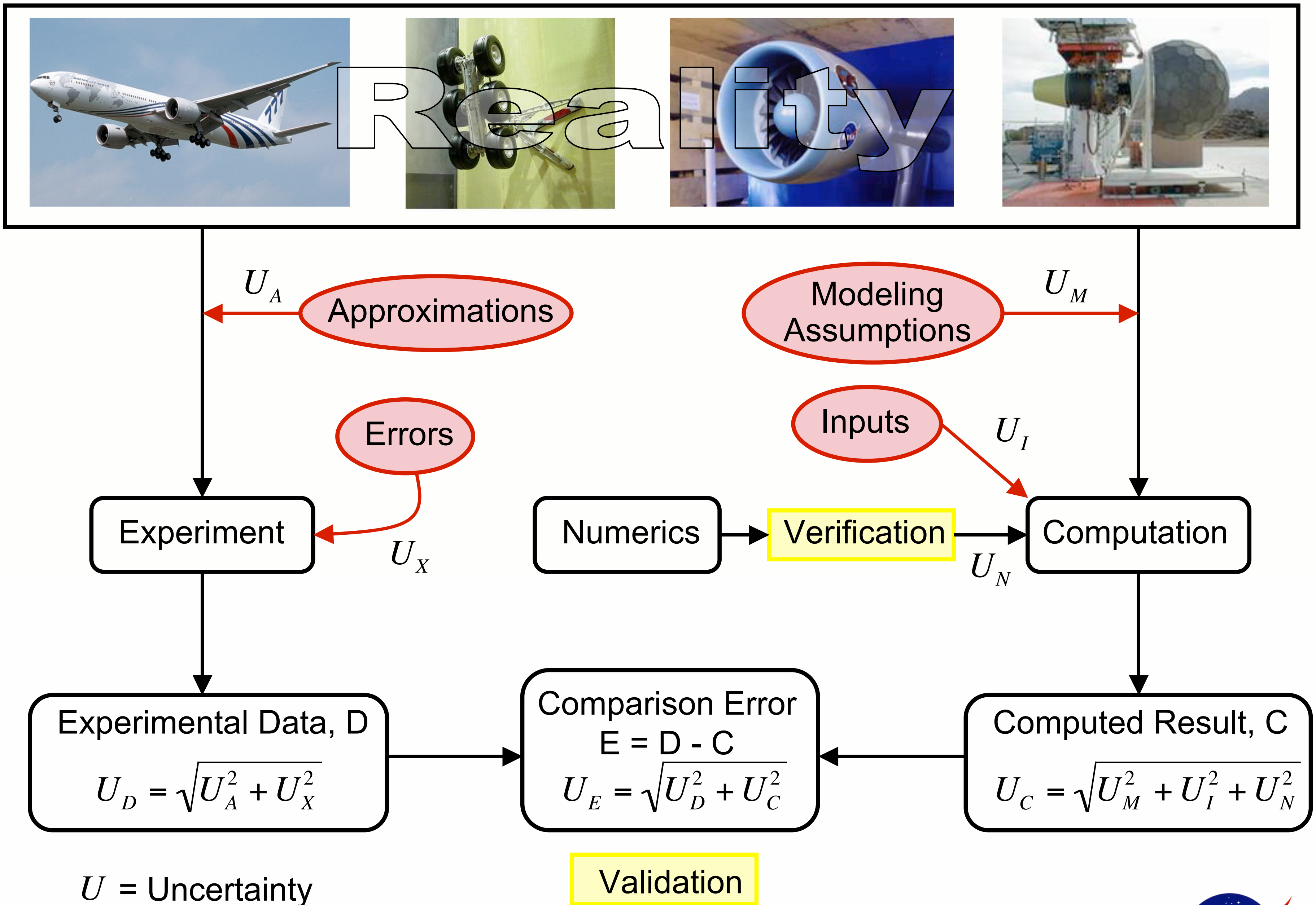
E_1 = Calculation - Exact

E_2 = Experiment - Calculation

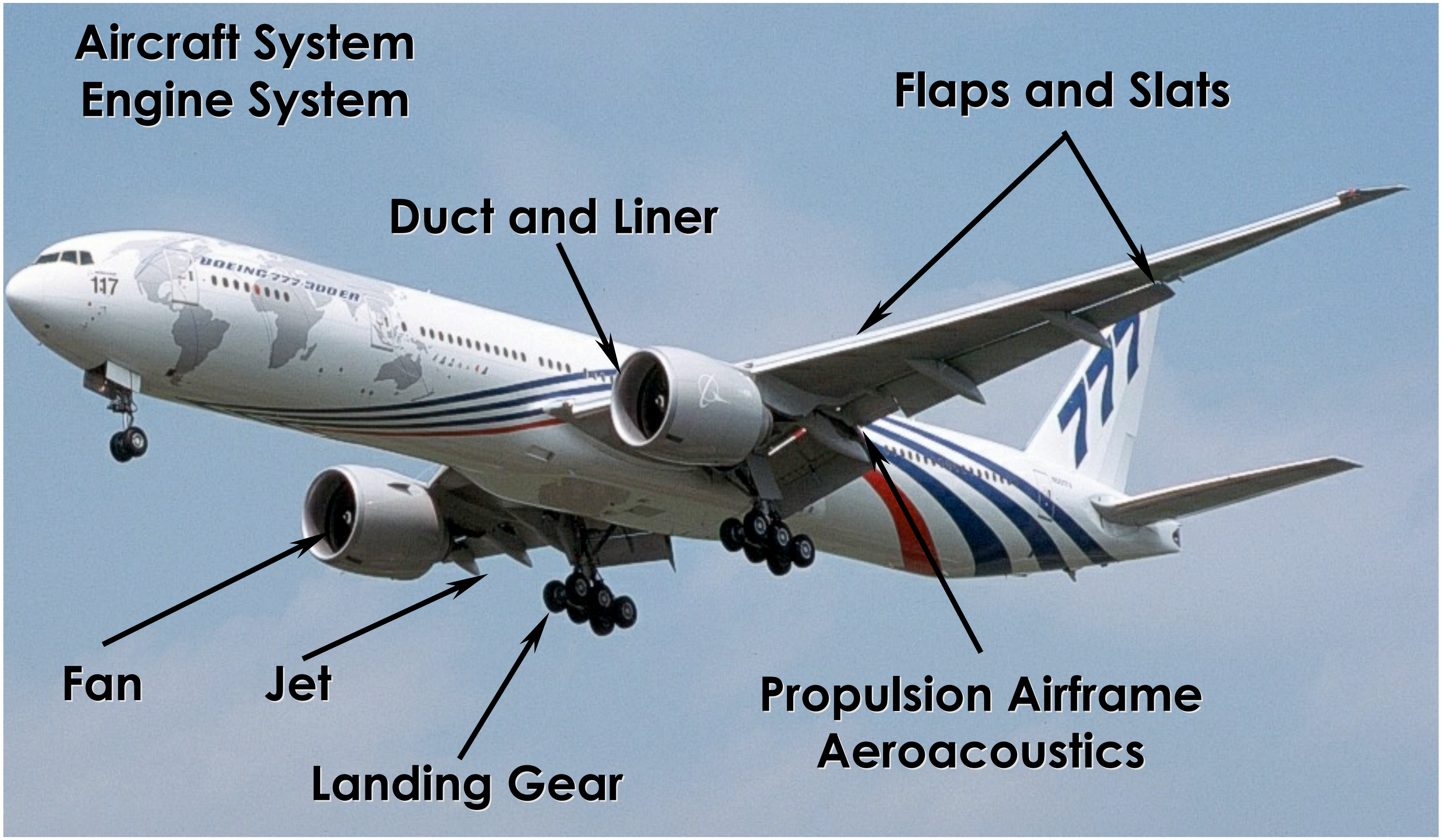
E_3 = Reality - Experiment

Verification identifies E_1

Validation identifies E_2


Reality
U_A
Approximations
Modeling Assumptions
U_M
Errors
Inputs
U_I
Experiment
U_X
Numerics
Verification
U_N
Computation
Experimental Data, D
$U_D = \sqrt{U_A^2 + U_X^2}$
Comparison Error
E = D - C
$U_E = \sqrt{U_D^2 + U_C^2}$
Computed Result, C
$U_C = \sqrt{U_M^2 + U_I^2 + U_N^2}$
U = Uncertainty
Validation

Topics
Systems and Components Assessed



Topic	Codes				
Airframe					
Flaps	ANOPP-L25				
Slats	ANOPP-L25	CFL3D			
Landing Gear	ANOPP-L25	CFL3D			
Propulsion Airframe Aeroacoustics	JET3D				
Aircraft System	ANOPP-L25				
Engine System	ANOPP-L25				
Fan	ANOPP-L25	RSI	VO72	Linflux	
Jet	ANOPP-L25	JeNo	JET3D		
Liner Physics	Two-Parameter	Crandall Full Solution	Composite Empirical	Fluid Mechanical	
Duct Acoustics	CDUCT-LaRC	LaRC-LEE2D	CHQ3D	CH3D	LEE2D

	Semi-Empirical
	Statistical + CFD
	Analytical + CFD
	Numerical/CAA

Why These Codes?

- Publicly available, will be available, or available to qualified users
- Representative of state-of-the-art or current capability at NASA
- Developed for or applied to the prediction of aircraft related noise
- Limited resources

Sample Results

Topic	Codes					
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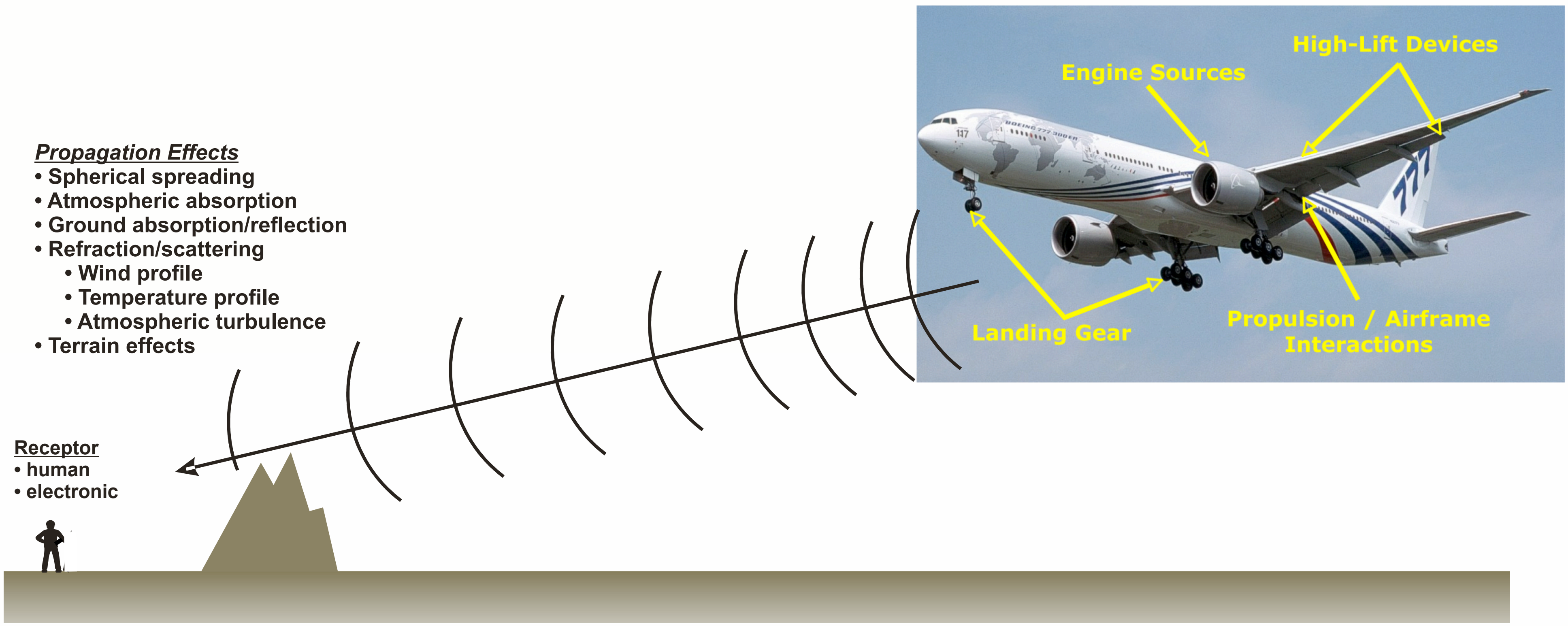
Aircraft System Noise Prediction

- NASA's **A**ircraft **NO**ise **P**rediction **P**rogram (**ANOPP**) was designed to predict the total aircraft noise signature from propulsion and airframe noise sources and to propagate the total noise to arbitrary ground observers.
- Since inception (1970's), NASA has continued to extend and improve capabilities. Current version: ANOPP-Level-25



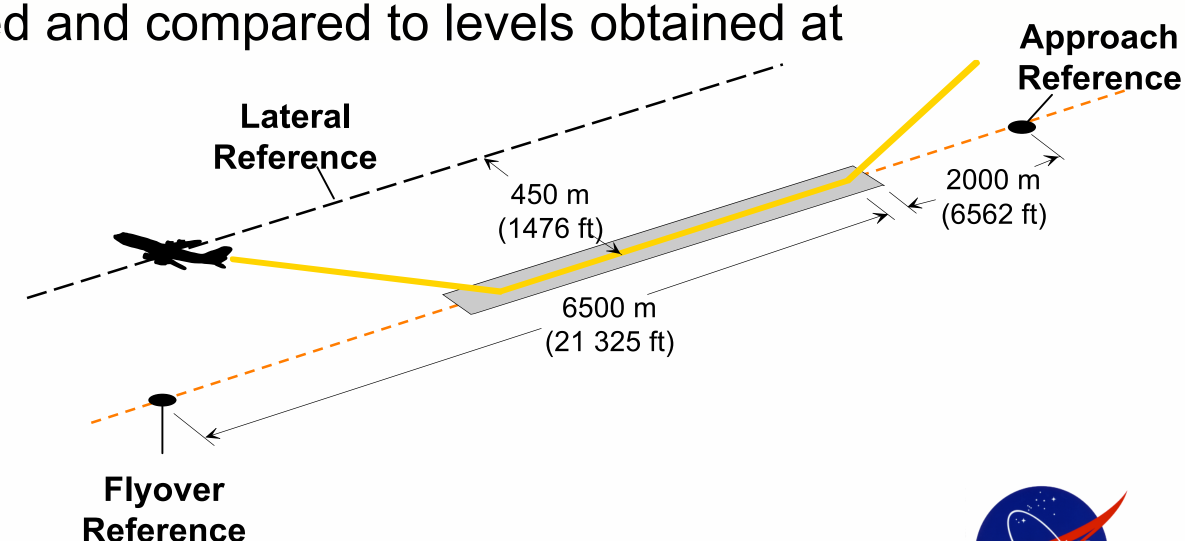
Receiver ← **Propagation** ← **Source**

Noise Analysis for B737-800 with CFM56-7B Engines

- Noise predictions performed using ANOPP Level 25
  - Source noise modules used:
    - Jet: Stone method per NAS3-00178, TO #10, 2003 (ANOPP L25 “ST2JET” module)
    - Fan: Heidmann hardwall procedure, revised by GEAE: NASA-CR-195480, 1996 (ANOPP L25 “HDNFAN Large Fan” method)
    - Acoustic liner: NASA-CR-202309 1996 GEAE method (ANOPP L25 “Treat” module)
    - Core: SAE ARP 876 Matta method (ANOPP L25 “GECOR” module)
    - Airframe (Gear, slats, flaps, trailing edges) FAA-RD-77-29 Fink method (ANOPP L25 “FNKAFM” module)
  - NPSS and WATE models provided engine state parameters for ANOPP
  - Propagation includes spherical spreading, atmospheric attenuation, ground effects, reflections, and lateral attenuation
- Trajectory simulation done using SAE AIR-1845 INM empirical procedures for a 737-800 and FLOPS for advanced vehicles
- Noise predictions performed and compared to levels obtained at certification points

Noise certification points:

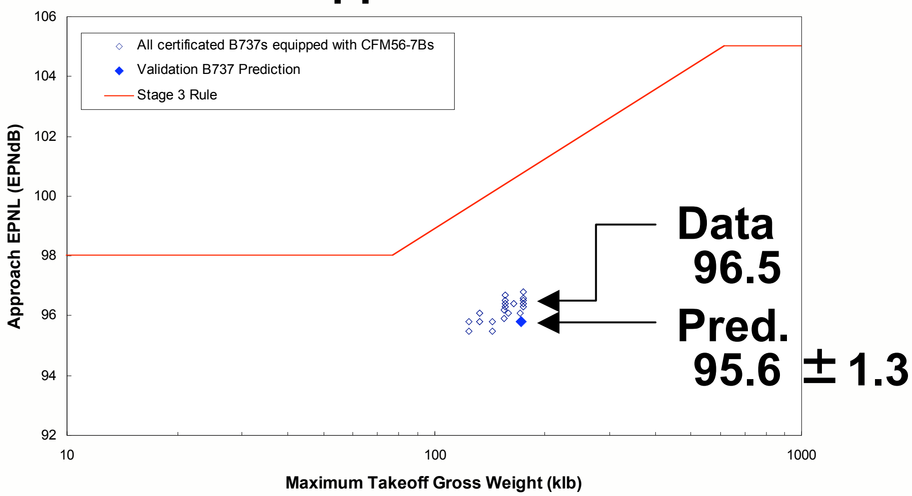
- Lateral
- Community/Flyover with cutback
- Approach



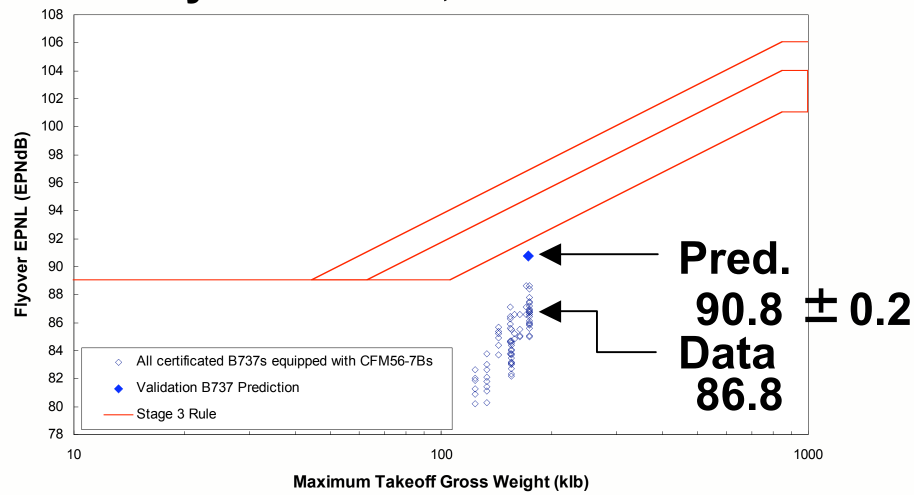
Comparison of ANOPP Predictions and Certification Noise Data

Total of 73 Certificated B737s equipped with CFM56-7B engines

Approach EPNL

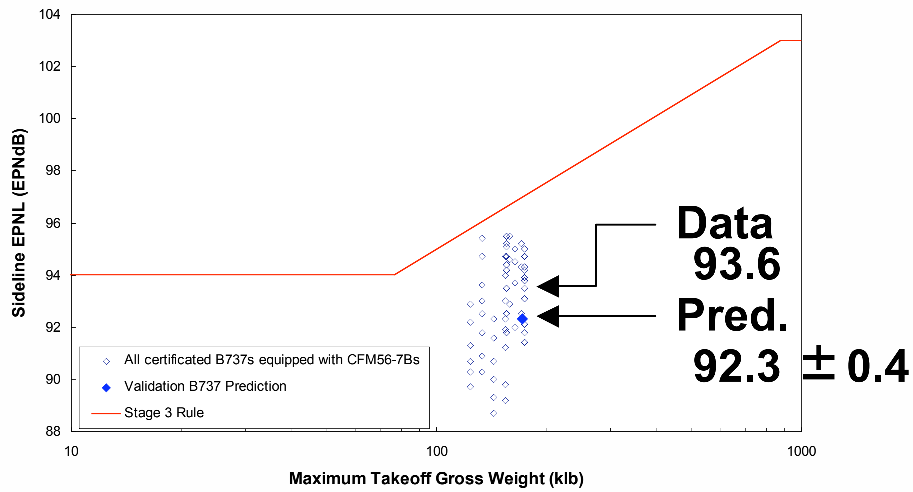


Flyover EPNL, with cutback



Lateral EPNL

Uncertainty based on 21 simulations to get 95% confidence intervals



Remarks on Noise Analysis Comparison

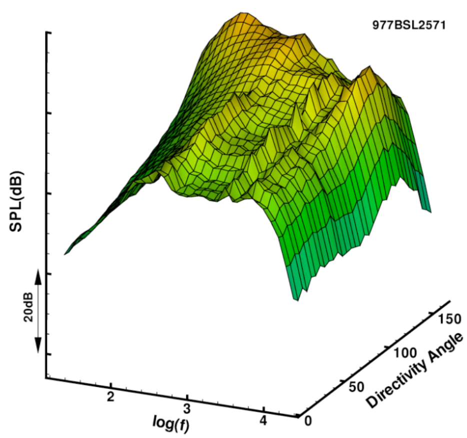
- Good agreement for lateral and approach observer, noise somewhat overpredicted at flyover observer
  - Analysis of noise predictions at the flyover condition indicated that fan noise predictions may be too high at cutback power
- ANOPP's hardwall fan noise and liner suppression predictions may not be entirely responsible for the flyover overprediction
  - Cycle & aeromechanical modeling
  - Trajectory & throttle setting assumptions
  - Many other potential discrepancies (and even cancelling errors)…
- EPNL is a complex, high-level, multidisciplinary metric with many independent variables affecting its outcome. Not the best data to be used in validation of prediction methods.
- Full aircraft noise data appropriate for validation purposes is very limited to non-existent (requires engine cycle definition, aircraft geometry details, noise directivity and at a minimum spectra.
  - proprietary nature of "**detailed"** engine cycle data, geometry and noise measurements limit access
  - Flight tests are expensive and measurements are highly dependent on configuration

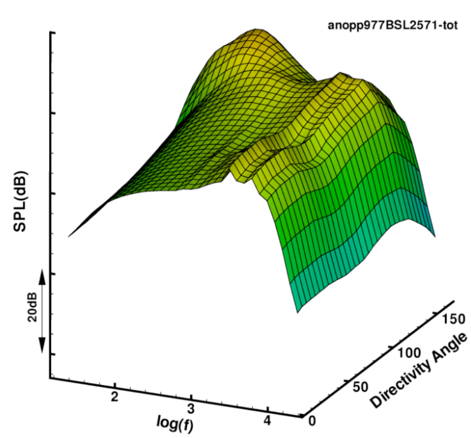
Engine Systems Assessment

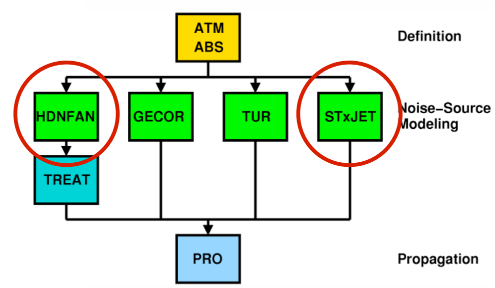
- ANOPP L25v3 predictions (NASA GRC)
- Existing (new) NASA/Honeywell EVNERT static engine test data
- Total engine noise (fan+combustor+turbine+jet) fan and jet models updated - current dominant sources
- 1/3-octave SPL and OASPL far-field comparison
- ANOPP uncertainty estimation due to performance parameter uncertainties (1% - 3% variation of 13 parameters)

TECH977 ENGINE TEST

ANOPP L25v3 PREDICTION

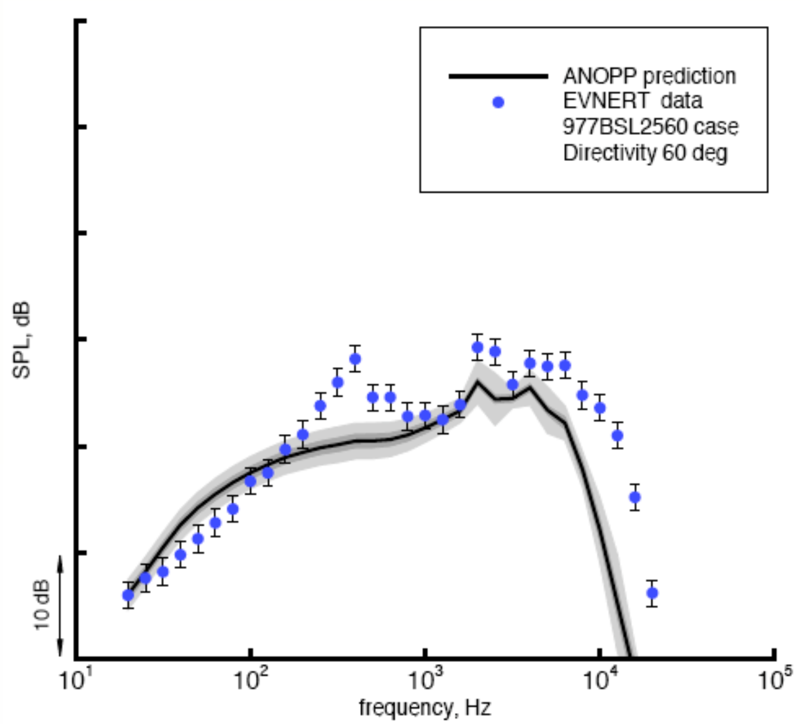




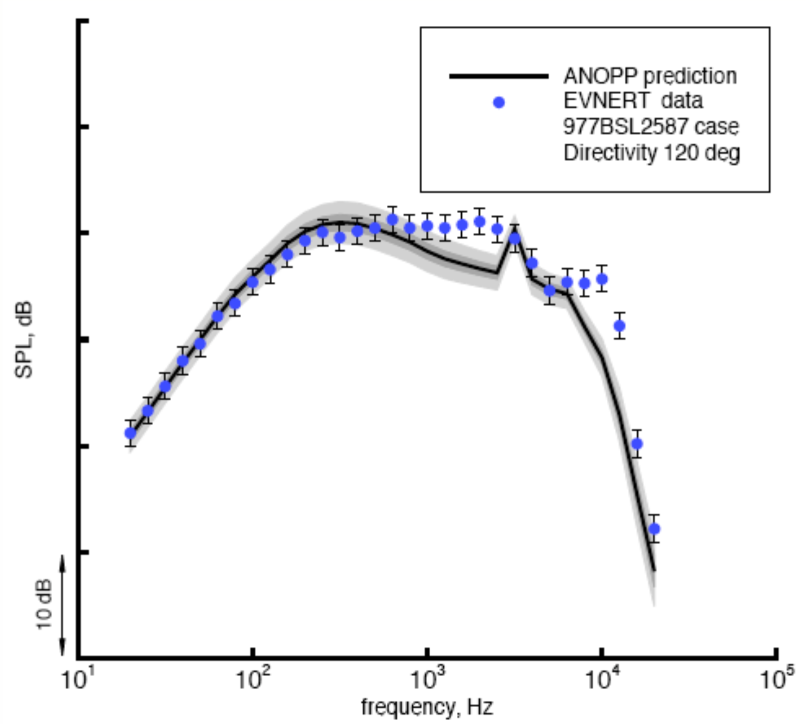


Example 1/3-Octave Spectra

APPROACH 60 DEG



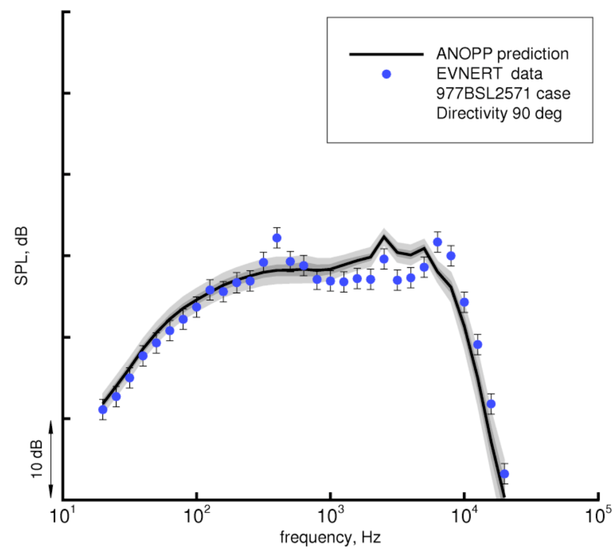
TAKEOFF 120 DEG



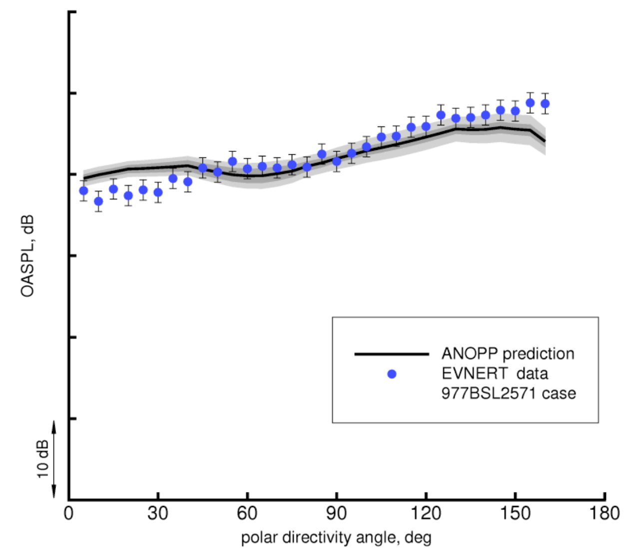
- ANOPP total noise predictions do surprisingly well

Further Examples and Comments

CUTBACK 1/3-OCTAVE SPL



CUTBACK OASPL



Recommendations:

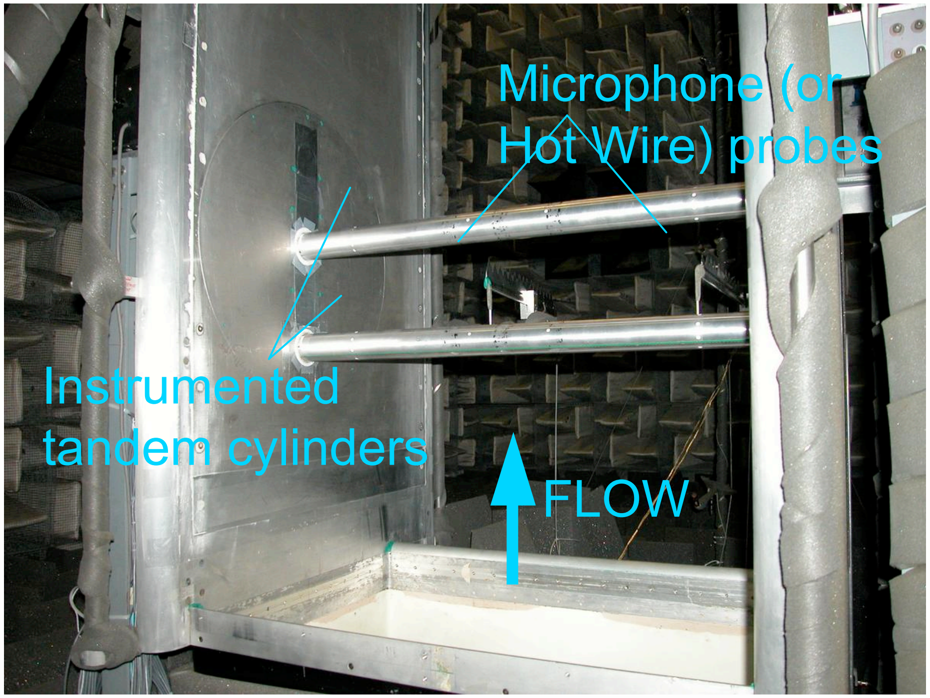
- Combustion-noise model needs improvement for future engines
- Noise generated by integrated combustor/turbine => direct/indirect combustion noise and self-generated turbine noise
- Development of high-fidelity combustion noise prediction capability for aeroengines => new reduced-order models
- Source separation diagnostic methods needed for validation

Airframe Noise Prediction

		Trailing-Edge Flap		Leading-Edge Slat		Landing Gear	
TEST CASES		DATA	PREDICTION	DATA	PREDICTION	DATA	PREDICTION
MODEL TESTS	NACA 63-215 & Flap	Acoustic	ANOPP				
	6.3% B-777 High Fidelity					Acoustic	ANOPP
	10% "B-757" Simplified					Acoustic	CFL3D/FWH
	30P/30N Model			Aero	CFL3D		
	Tandem Cylinders					Aero & Acoustic	CFL3D/FWH
FLIGHT TESTS	VC–10	Acoustic	ANOPP	Acoustic	ANOPP		
	DC–9–31			Acoustic	ANOPP		
	G–550	Acoustic	ANOPP			Acoustic	ANOPP

- ANOPP – Semi-empirical, Fink & Boeing models
- CFL3D – CFD based prediction

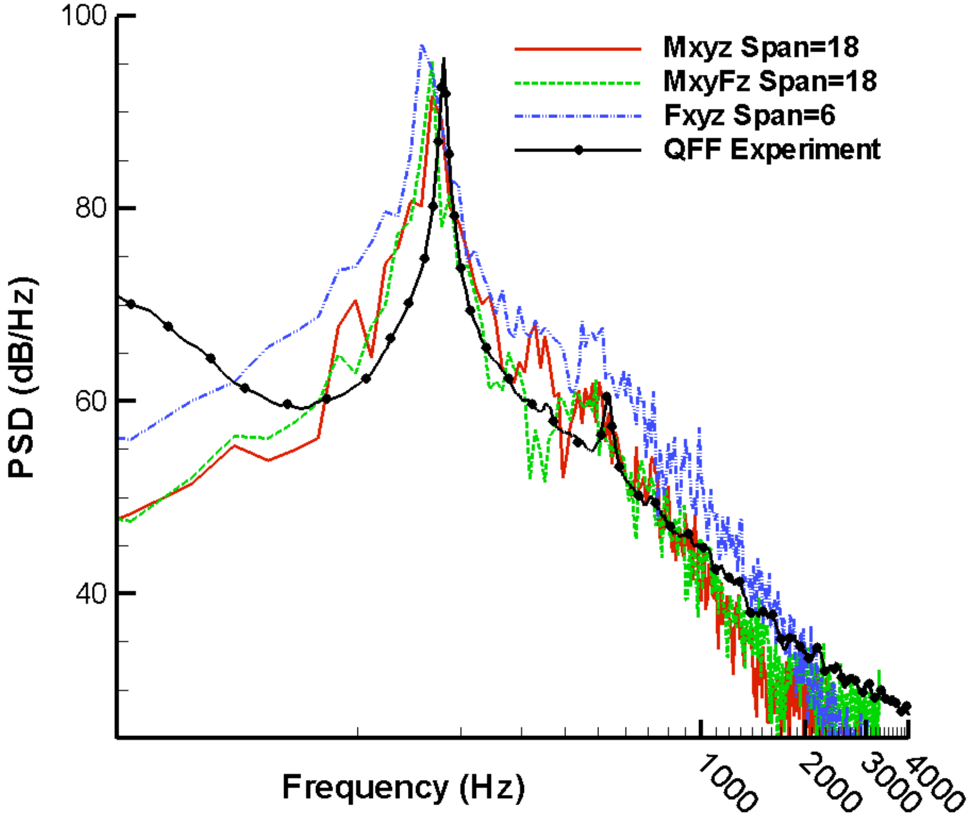
Tandem Cylinder Prototype for Landing Gear Interactions

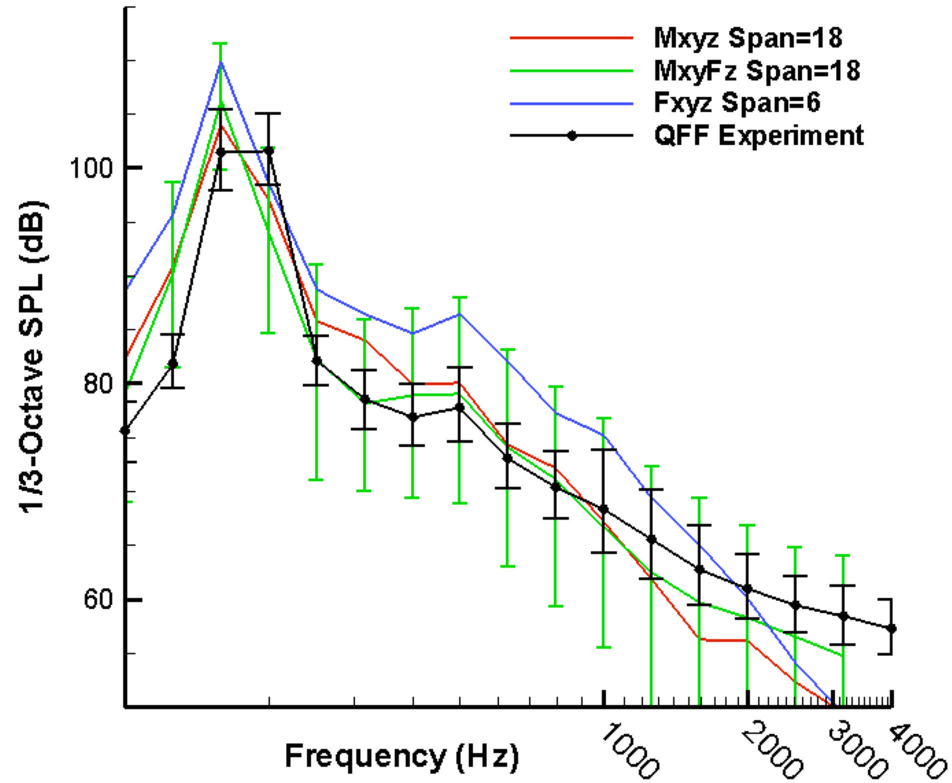


- Measurements in NASA Basic Aerodynamic Research Tunnel and Quiet Flow Facility

- **CFL3D**
  - Unsteady simulations of noise sources using a 2nd-order CFD code
    - Unsteady, hybrid RANS/LES calculations
  - Coupled with a Ffowcs Williams-Hawkings solver to predict the far-field noise

Acoustic Radiation





- Main features captured by prediction
- CFL3D has long run times → low number of cases → higher uncertainty and less ability to determine range of applicability

Airframe Noise Prediction

- Semi-Empirical methods
  - Very efficient (minutes to hours)
  - Reasonable predictions of spectral content
  - Amplitudes sometimes have large errors
    - Extrapolation outside of experimental database
    - Impossible to capture the unique features of every aircraft
- CFD methods
  - Very inefficient (months)
  - Reasonable predictions of spectral content and amplitudes
    - High-frequency content often lost because of grid resolution
  - Possible to capture the unique features of an aircraft
- A compromise between fidelity and efficiency is needed

Sample Results

Topic	Codes				
Airframe					
Flaps	ANOPP-L25				
Slats	ANOPP-L25	CFL3D			
Landing Gear	ANOPP-L25	CFL3D			
Propulsion Airframe Aeroacoustics	JET3D				
Aircraft System	ANOPP-L25				
Engine System	ANOPP-L25				
Fan	ANOPP-L25	RSI	VO72	Linflux	
Jet	ANOPP-L25	JeNo	JET3D		
Liner Physics	Two-Parameter	Crandall Full Solution	Composite Empirical	Fluid Mechanical	
Duct Acoustics	CDUCT-LaRC	LaRC-LEE2D	CHQ3D	CH3D	LEE2D

	Semi-Empirical
	Statistical + CFD
	Analytical + CFD
	Numerical/CAA

Propulsion Airframe Aeroacoustics (PAA) Computational Tools Assessed

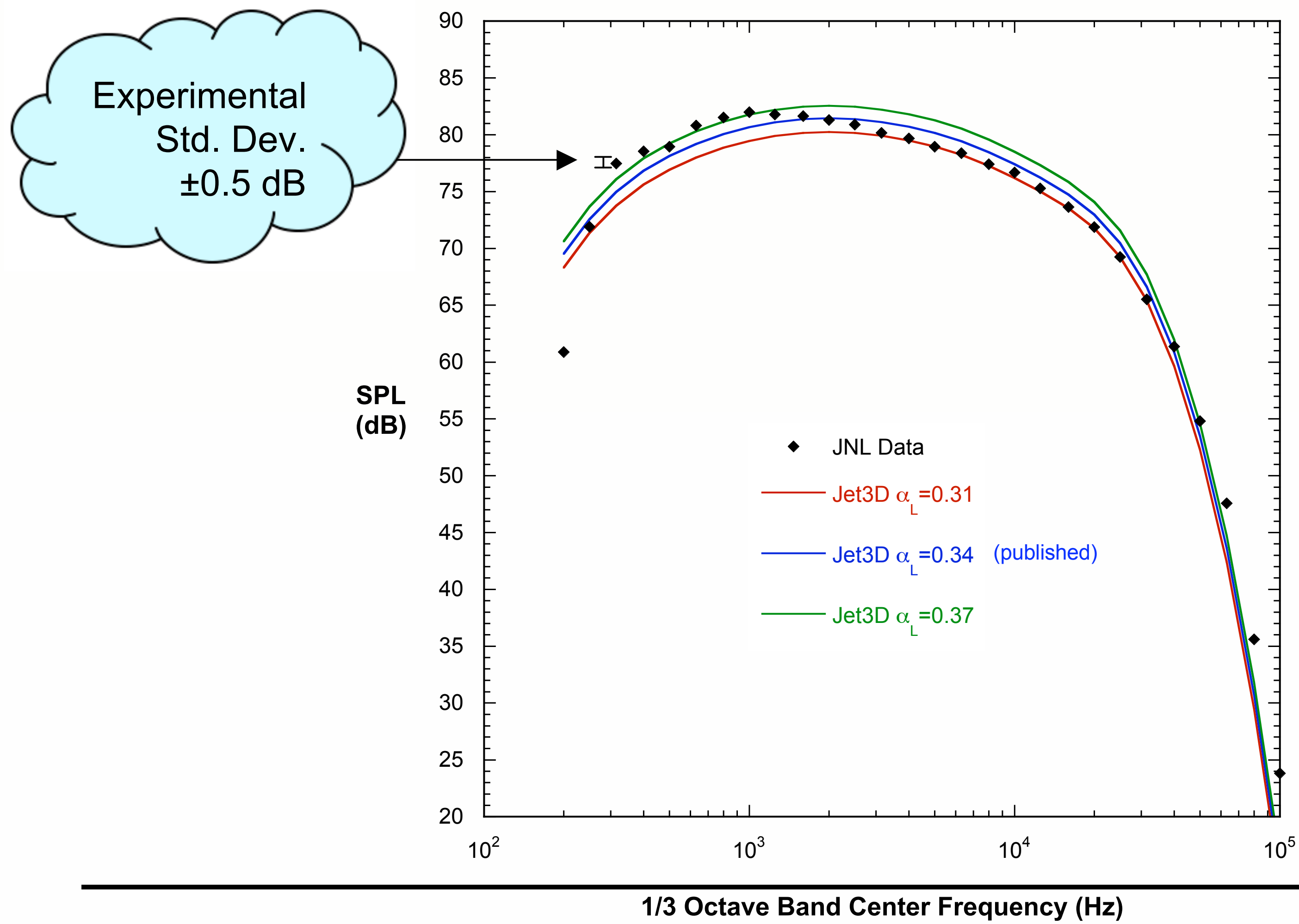
- **PAB3D - CFD**: Structured grid, Reynolds-averaged Navier-Stokes solver with nonlinear algebraic Reynolds stress turbulence models.

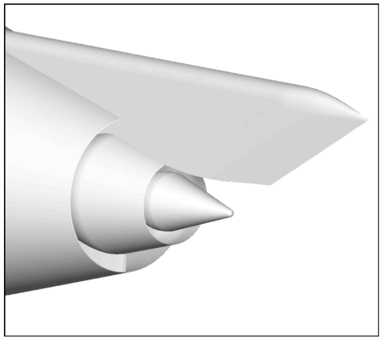
  Focused on propulsion/aerodynamic applications over the last 20 years - afterbody separation, jet mixing, thrust vectoring, nozzle internal performance, etc.

- **Jet3D – Jet Noise Prediction**: Modern implementation of Lighthill's Acoustic Analogy, able to handle complex 3D turbulent flows and installed jet configurations.
- Jet3D uses mean flow and anisotropic turbulence computed by PAB3D to model two-point space-time correlations and construct the Lighthill stress tensor.

Propulsion Airframe Aeroacoustics Sample Prediction: Effect of Primary Constant for Characteristic Length, α_L

- Nozzles and data from JNL Pylon Effects Experiment, BPR 5 Separate Flow Nozzle Config 6
- Takeoff condition, M=0.28 freestream
- Prediction published in AIAA 2003-3169, α_L=0.34 used for this work





Round/Pylon

Results at 88° inlet angle, 100D radius

Propulsion Airframe Aeroacoustics – Gap Summary

PAA experimental gaps:

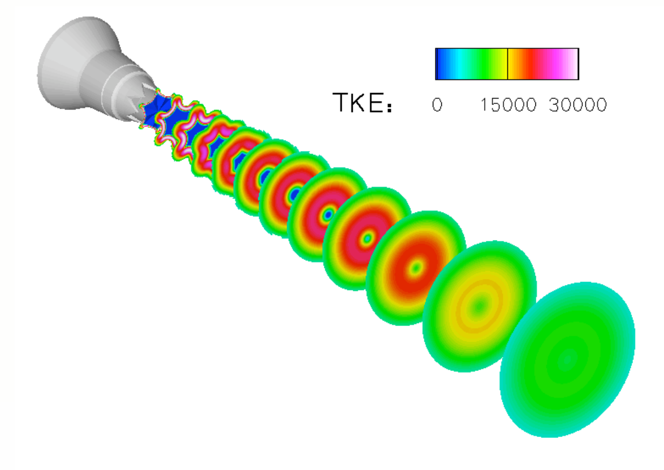
- Comprehensive aircraft system level experimental project with key parametric study of nozzle/pylon/wing/flap elements including both shielding and reflection effects. Data set should include far field, phased array, and, at least, mean flow surface and in flow data.

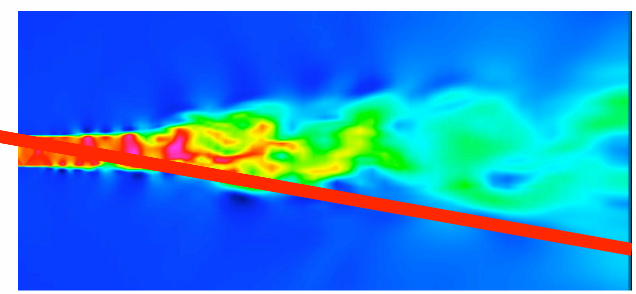
PAA prediction gaps:

- Versatile, easy 3D geometry manipulation and grid generation and unstructured flow solvers with off-body grid adaptation (USM3D code set in development).
- Engine source/airframe acoustic propagation and interaction (shielding/reflection) effectively linked to flow/noise tools.
- Exhaust/airframe interaction prediction method gaps:
  - RANS turbulent model improvement for heated, complex interacting free shear layers
  - Long term approach is to transition Jet3D to use PANS/LES/DNS flow solution which will allow near-complete specification of the Lighthill Stress Tensor with significantly less modeling (ie, 2-pt correlation models not needed)
  - Develop method for jet interaction with wing and flap using the unsteady flow solution and Jet3D

Assessment of Jet Noise Prediction

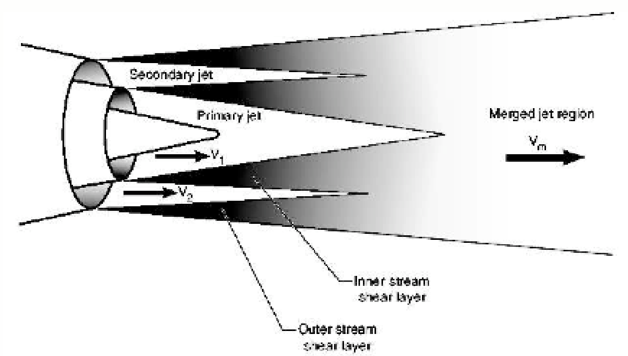
- Types of Codes available
  - Semi-Empirical
    - Input: Vjet, Tjet, Ambient, Axisymmetric Nozzle Geometry
    - Output: SPL (freq, observer location)
    - Basis: Scaled Equivalent Sources
    - E.g. ST2Jet module in ANOPP
  - Statistical
    - Input: RANS CFD of jet plume
    - Output: SPL (freq, observer location)
    - Basis: Acoustic Analogy
    - E.g. Jet3D, JeNo
  - Time-resolved
    - Input: Nozzle geometry/plume grid
    - Output: Time records very near, very far from jet
    - Basis: Filtered Navier-Stokes Eqns
    - E.g. Unnamed individual research codes

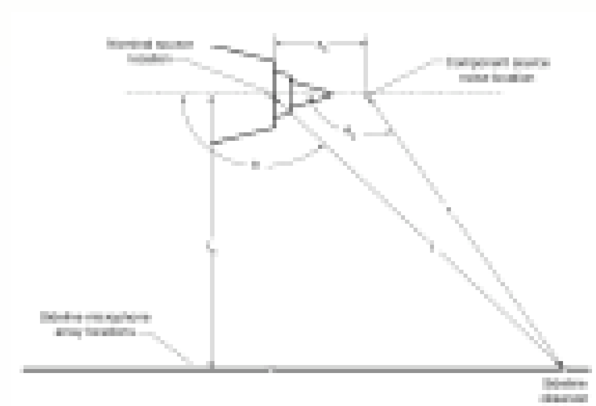




Assessment Parameter Space

- 266 cases considered, covering broad range of parameters:
  - BPR (0 — 14)
  - Mach (0.35 — 2.0)
  - Acoustic Mach (0.3 — 2.4)
  - Temperature Ratio (0.8 — 3)
  - Axial geometry (internal/external mixer, C-D)
  - Azimuthal geometry (axisymmetric, chevrons, lobed mixer)

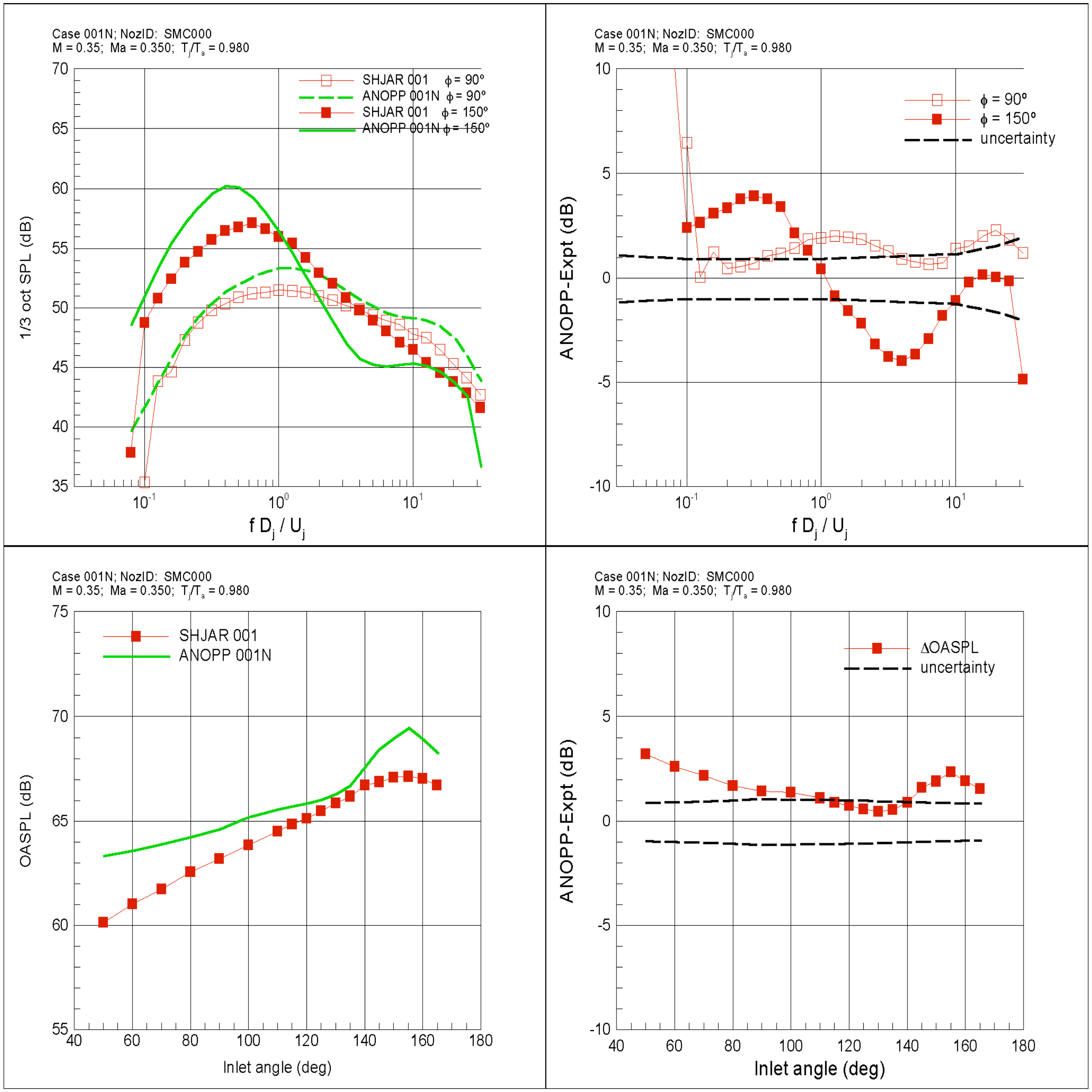




Assessment Figure Format

1/3 octave spectra
ϕ = 90°, 150°
predicted vs
experiment

Spectral difference
ϕ= 90°, 150°
with uncertainty
band



OASPL
predicted vs
experiment

OASPL difference,
with uncertainty
band

‘Typical’ results of different codes

Semi-Empirical

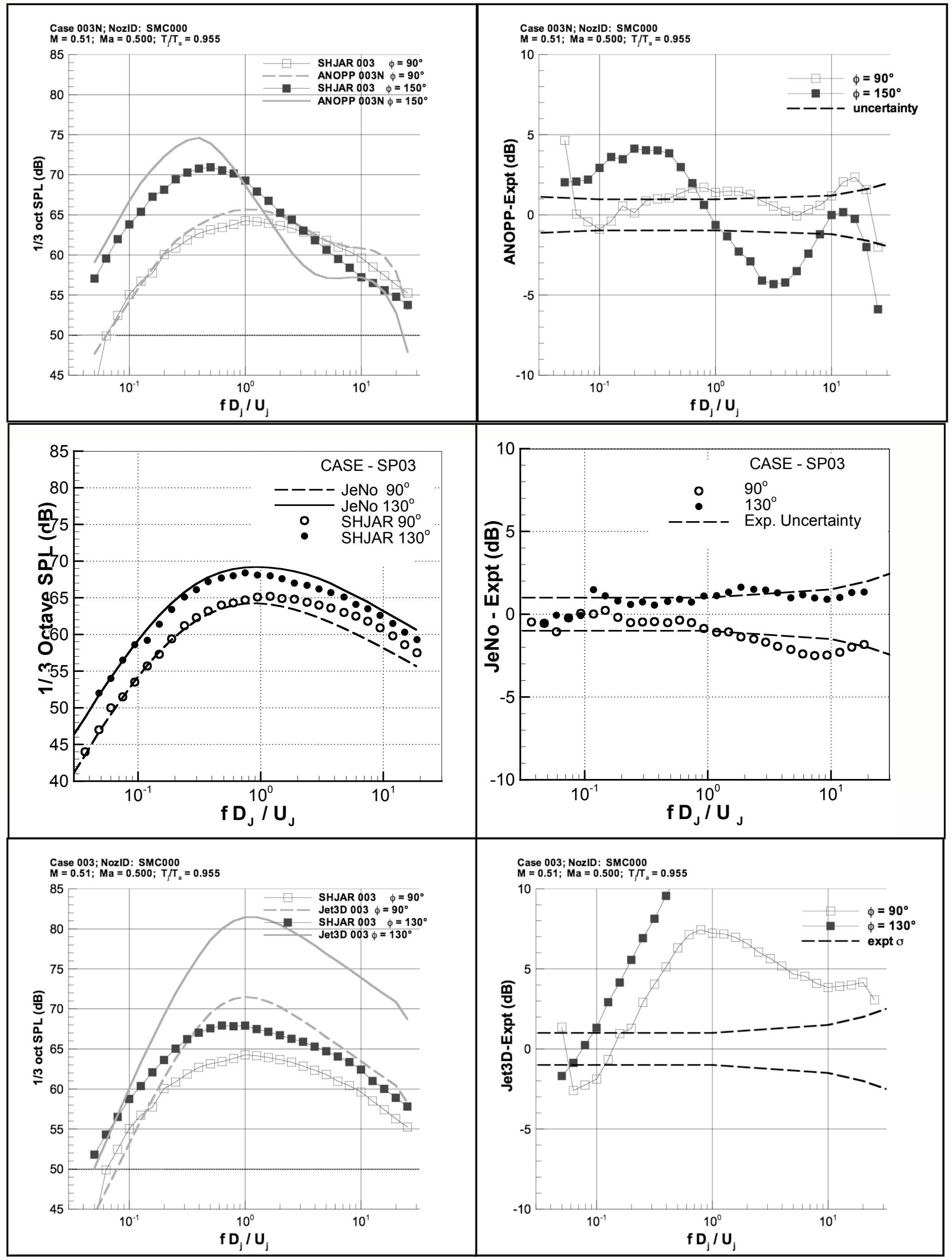
ANOPP vs Expt

Statistical

JeNo vs Expt

Statistical

Jet3D vs Expt



Jet Noise Prediction Assessment Summary

- Overall findings
  - No empirical nor statistical model predicts noise of *all* subsonic axisymmetric nozzle flows within experimental uncertainty.
  - The ANOPP code predicts spectral directivity *to within 2dB* for axisymmetric nozzles over a broad range of conditions.
  - The statistical code JeNo v1.0 predicts spectral directivity to within experimental uncertainty for subsonic *cold* jets, but deviates when either jet speed or temperature is elevated.
  - The spectral code Jet3D does not predict any of the jets very well, missing both the directivity and the peak frequency.
- Recommendations
  - Use ANOPP for round jets, minding the 2dB error bar.
  - Add temperature-related sources to JeNo. Enhance source model to better describe noncompactness.
  - Investigate shortcomings of Jet3D for basic jets.

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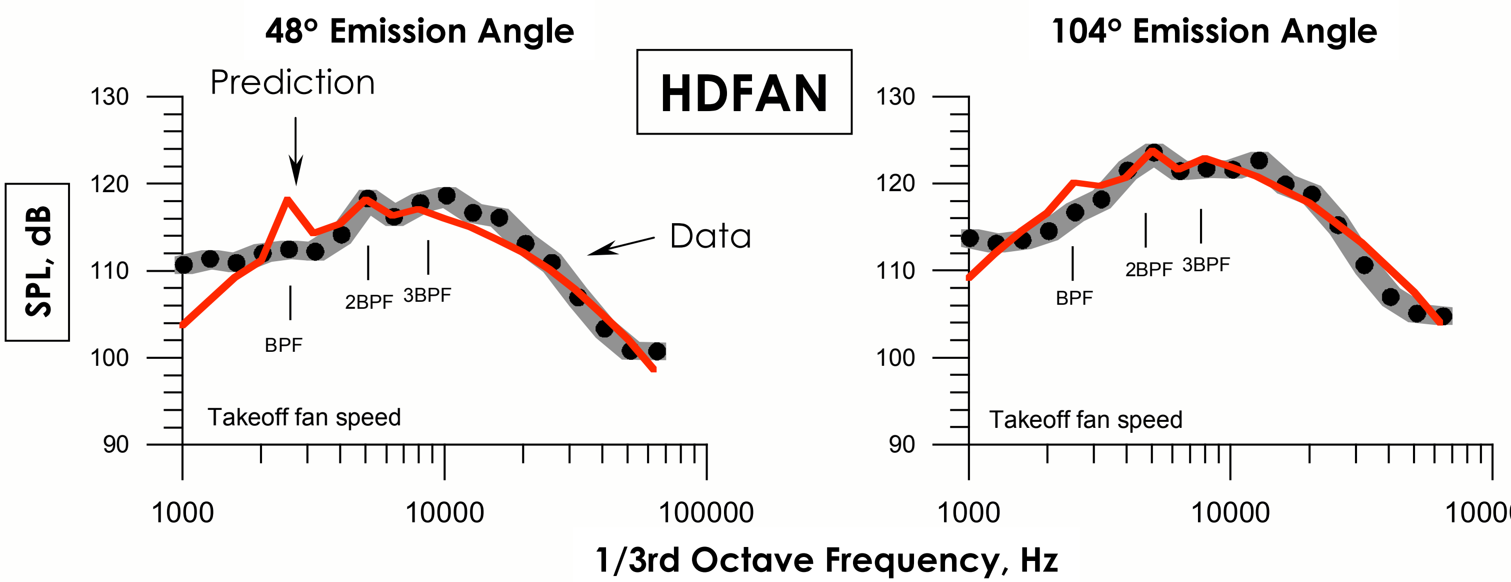
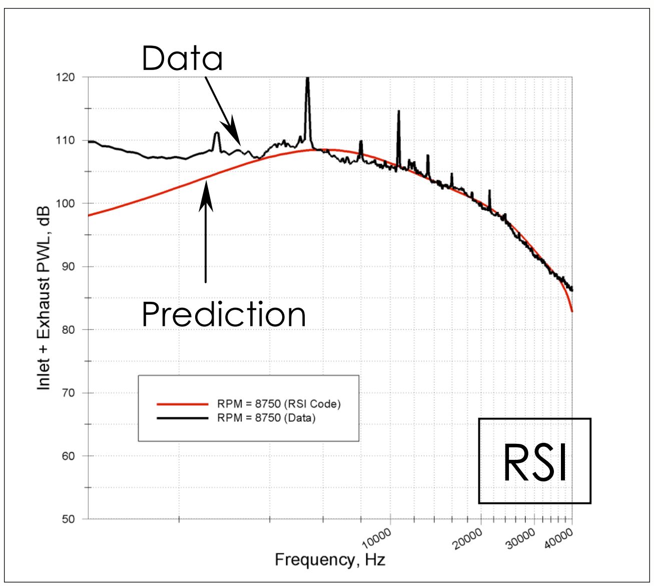
Fan Noise Prediction Assessment Summary

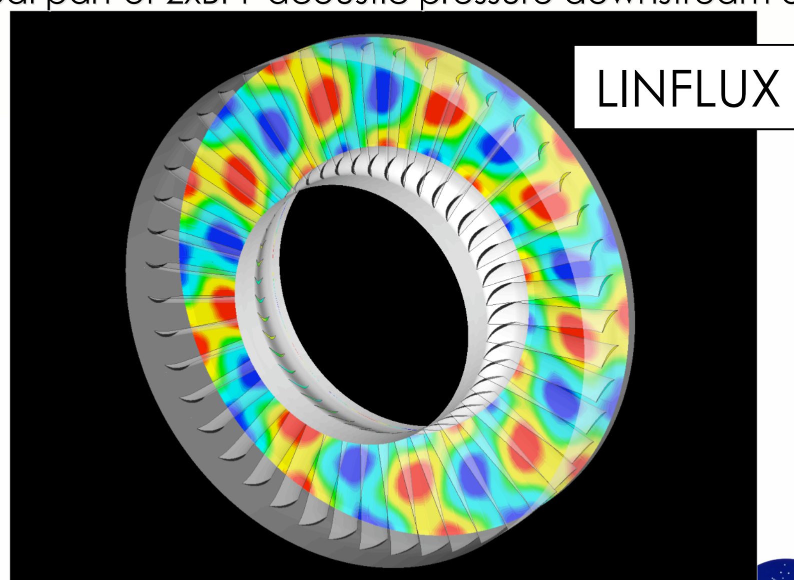
- **Goal:** Assess current fan noise prediction capability
- **Approach:** Compare predictions from representative codes to benchmark datasets
- **Codes:** Representative codes include:
  - Empirical: HDFAN module in ANOPP L25/V3
  - Analytical: V072 & RSI codes
  - Computational (i.e., CAA): LINFLUX code
- **Benchmarks:** Measured data from three 22-inch scale model fans covering the following bypass ratios:
  - ADP: Ultra high bypass ratio
  - SDT: High bypass ratio
  - QHSF: Low bypass ratio

Some Representative Results (ADP Fan)





Real part of 2xBPF acoustic pressure downstream of OGV



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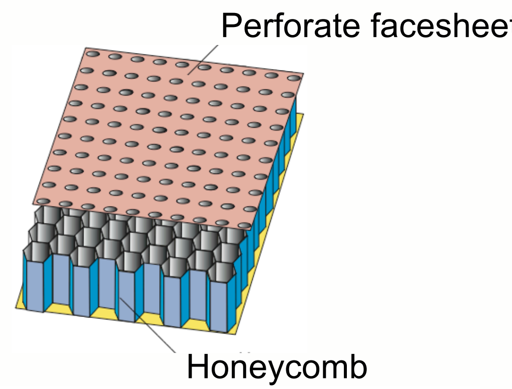
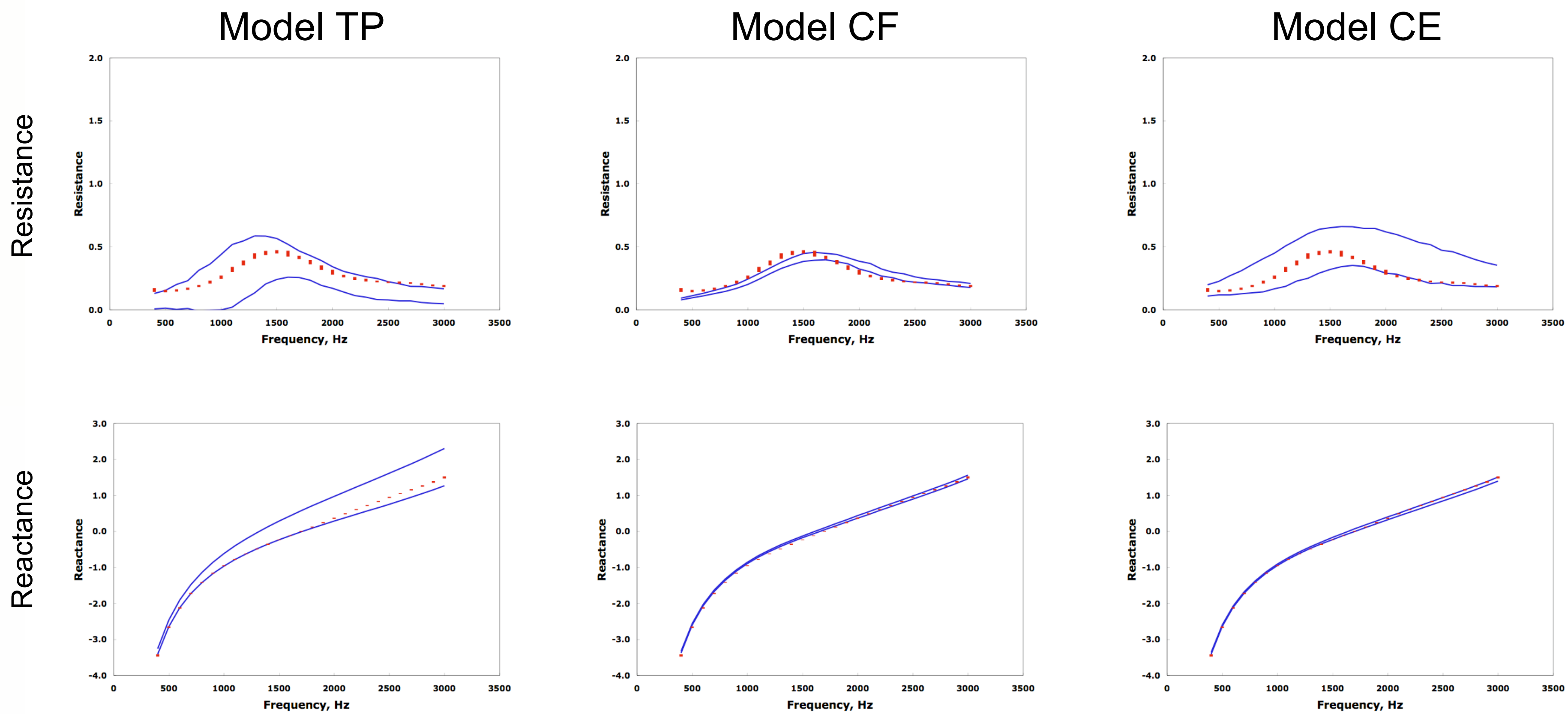
Jet	ANOPP-L25	JeNo	JET3D		
Liner Physics	Two-Parameter	Crandall Full Solution	Composite Empirical	Fluid Mechanical	
Duct Acoustics	CDUCT-LaRC	LaRC-LEE2D	CHQ3D	CH3D	LEE2D

(yellow)	Semi-Empirical
(green)	Statistical + CFD
(cyan)	Analytical + CFD
(purple)	Numerical/CAA

Impedance Comparisons

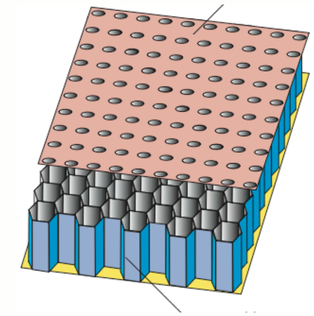


- 14 NIT Measurements (Red), 31 Simulations (Blue)
- 95% Confidence Intervals Shown
- No Flow

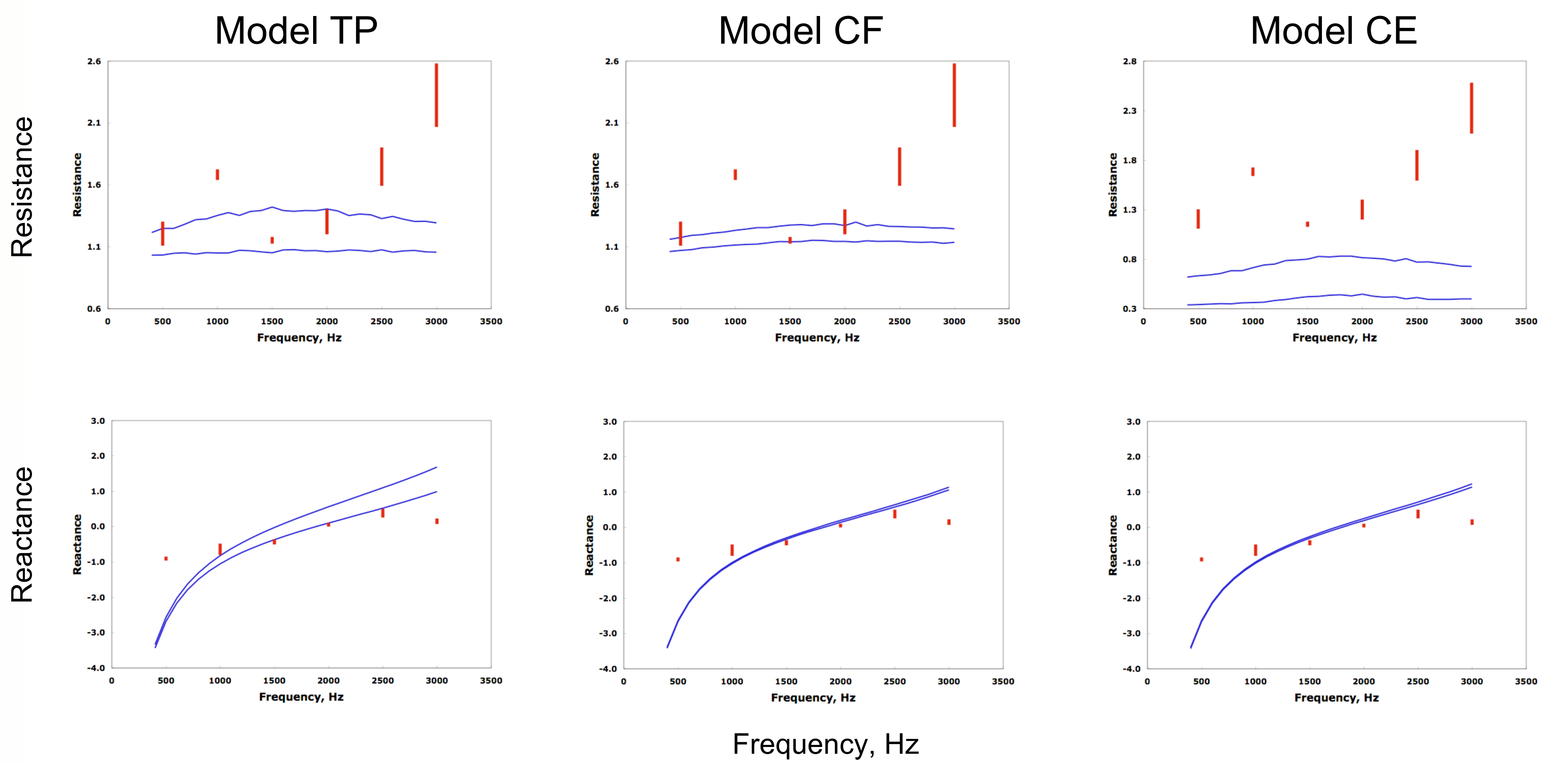


Frequency, Hz

Impedance Comparisons with Flow

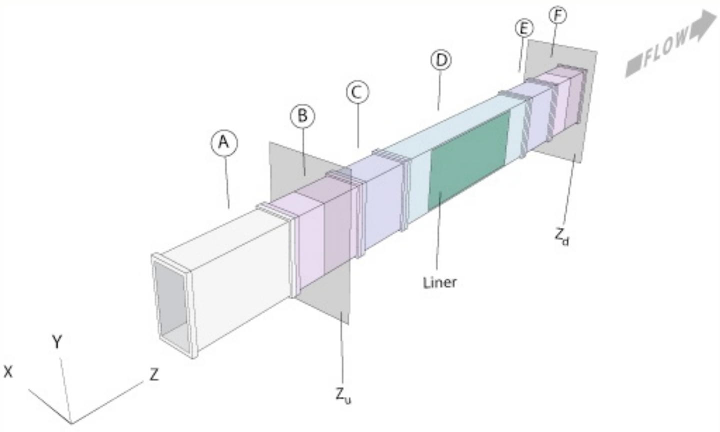


- 10 GIT Measurements (Red), 31 Simulations (Blue)
- 95% Confidence Intervals Shown
- Flow condition, M = 0.4



Acoustic Attenuation in a Flow Duct

- 10 GIT Measurements (Red), 31 Simulations for each code
- 95% Confidence Intervals Shown
- Flow condition, M = 0.4



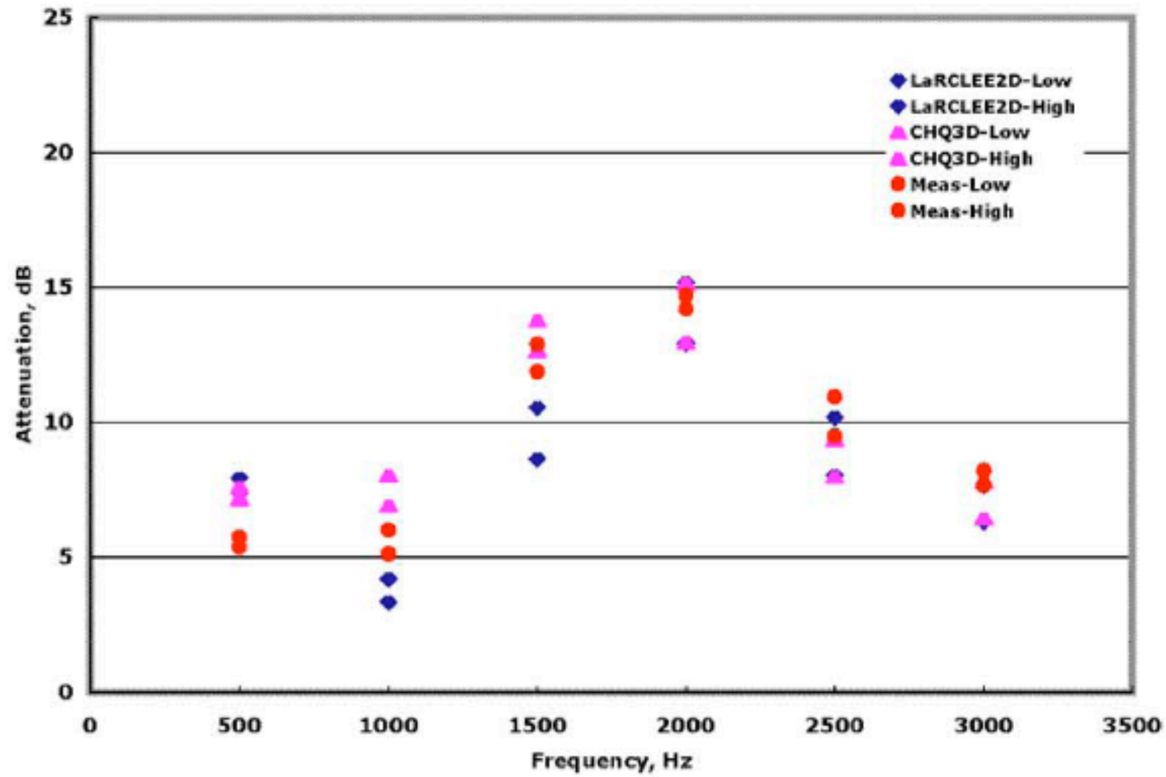
$$\phi(z) = \int_0^b \int_0^a I(x,y,z)\,dx\,dy$$

Attenuation

$$\Delta dB = 10\log_{10}\left(\frac{\phi(z_u)}{\phi(z_d)}\right)$$

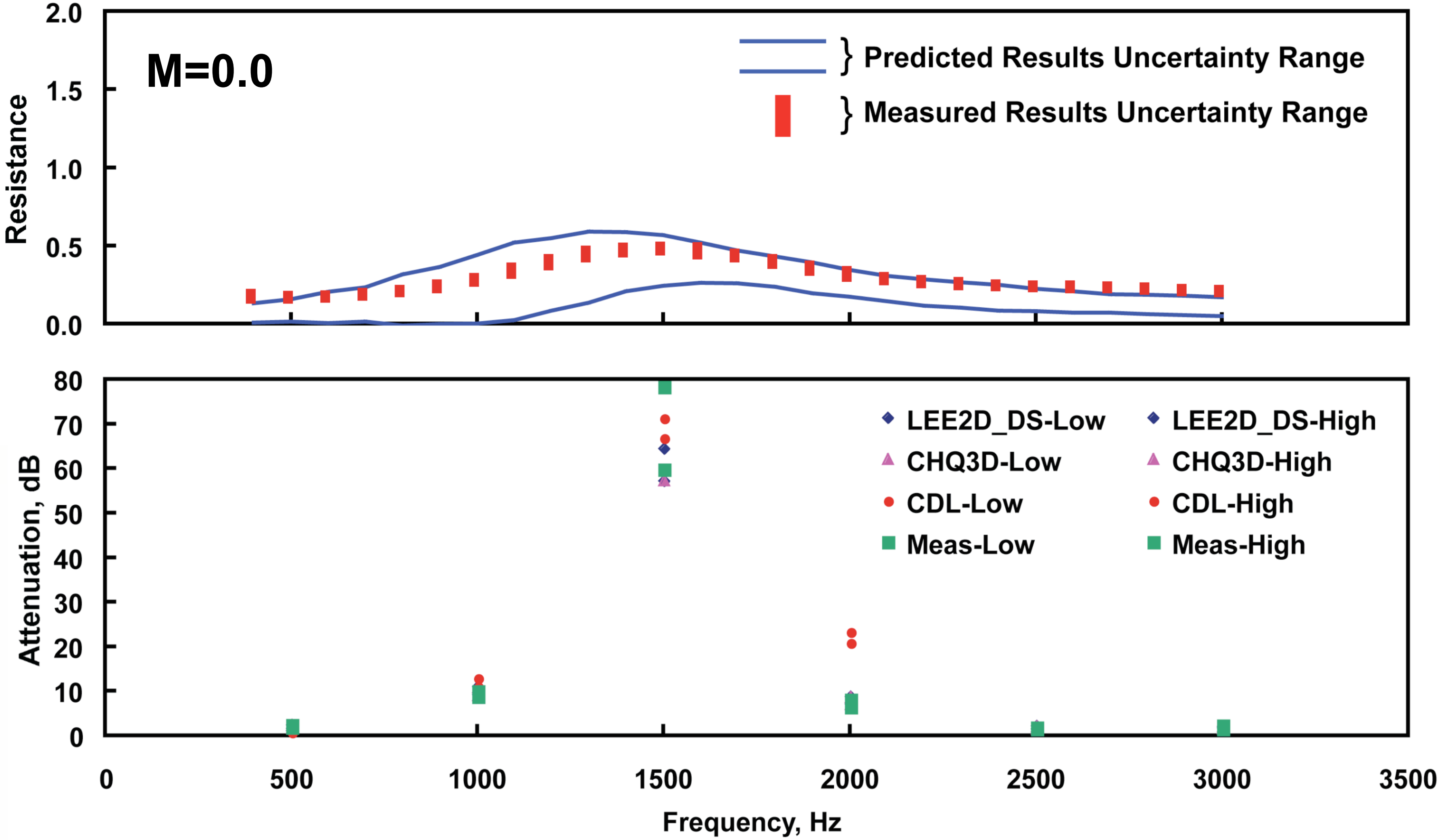
LaRCLEE2D - FEM, Linearized Euler (Blue)

CHQ3D - FEM, Convected Helmholtz (Pink)



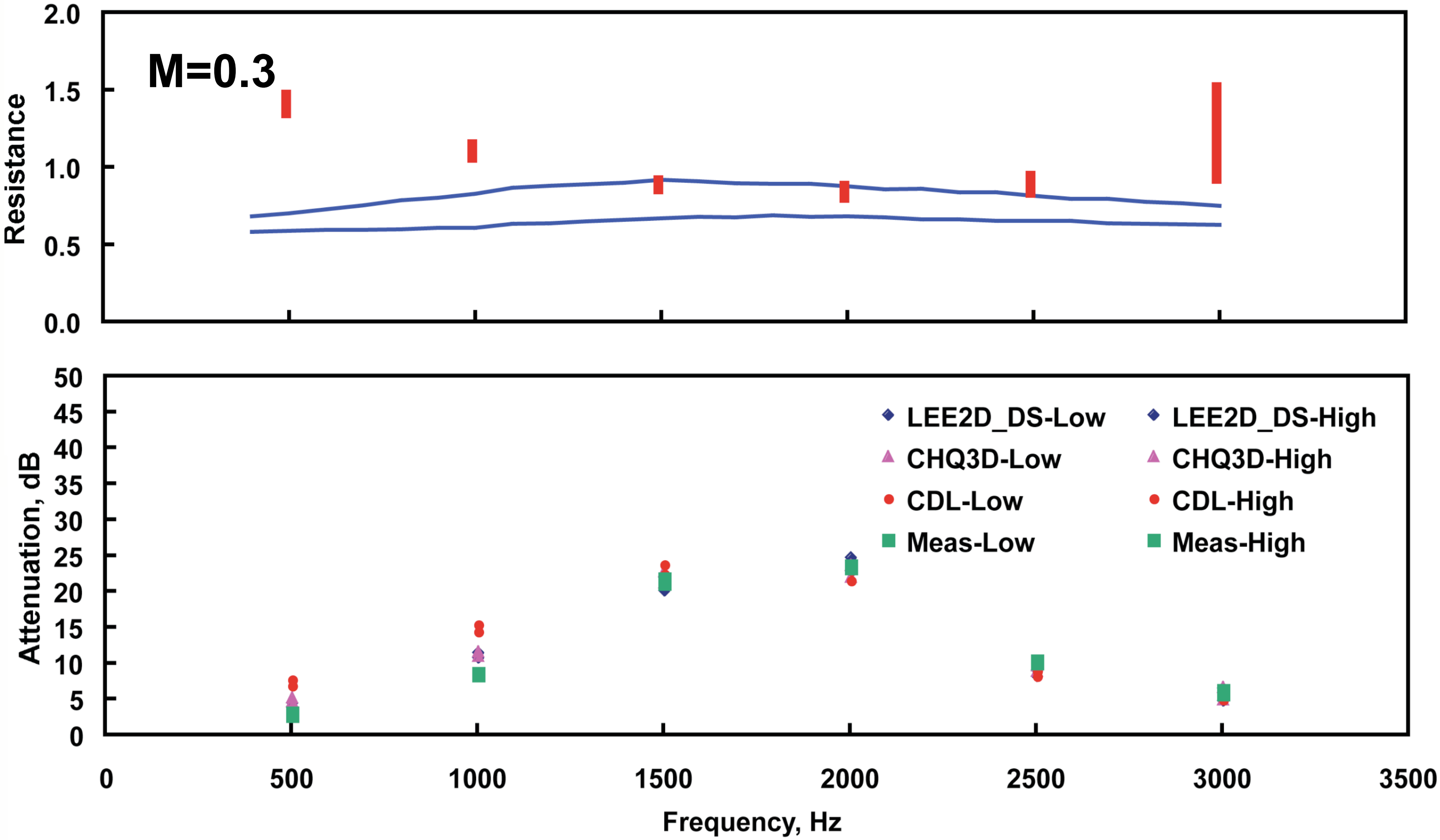
Liner Physics / Duct Acoustics

Comparison of representative measured and predicted confidence intervals for typical single-layer perforate-over-honeycomb liner



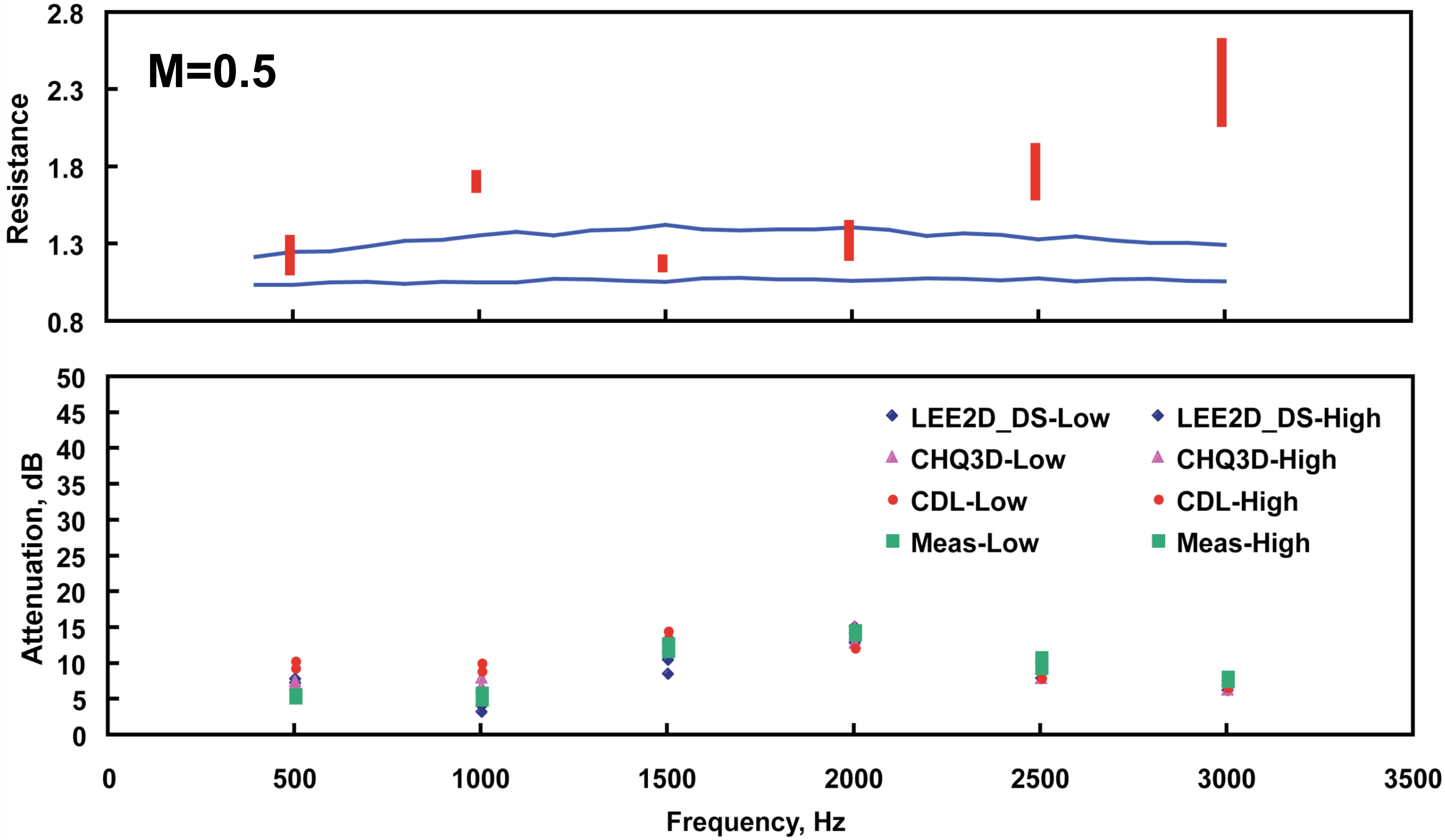
Liner Physics / Duct Acoustics

Comparison of representative measured and predicted confidence intervals for typical single-layer perforate-over-honeycomb liner



Liner Physics / Duct Acoustics

Comparison of representative measured and predicted confidence intervals for typical single-layer perforate-over-honeycomb liner



Liner Physics / Duct Acoustics

Key Findings

- Consistent trends observed in computational results
  - Comparison of four impedance prediction models
  - Comparison of five propagation codes
- Difference between predicted and measured results increases with mean flow velocity
- Impedance prediction and SPL attenuation confidence intervals are inversely related
- Measured confidence intervals tend to be much smaller for reactance than for resistance
- Differences between predicted and measured SPL attenuations are accentuated by choice of single-layer liner
  - Due to dominance of resonance effect
  - Expect less frequency dependence for two and three-layer liners

Liner Physics / Duct Acoustics

Plans

- Incorporate 3-D aeroacoustic effects into the impedance eduction model
  - Non-uniform mean flow
  - Boundary layer growth (evaluate with new Grazing Flow Impedance Tube)
  - Effects of geometry (evaluate curvature with Curved Duct Test Rig)
  - Higher-order modes
- Conduct tests with multiple "calibration" liners to validate eduction model
  - Linear (independent of mean flow and SPL)
  - Liner impedance can be predicted from first principles
- Conduct impedance prediction & propagation model input-parameter sensitivity studies
- Incorporate more efficient parallel solvers
  - Increase fidelity
  - Reduce computational time
- Provide increased fidelity propagation/radiation modules for use in system analysis tools (e.g., ANOPP)

Concluding Remarks

- Individual topics summarized throughout the presentation, systems and components
- Small sample of results presented
- Over 40 contributors to this assessment
- Detailed results to be given in a forthcoming NASA Technical Publication

Concluding Remarks

Computational predictions are important, they contribute to:

- MDAO capability
- Supplement and guide experiments and testing
- System performance for certification

Establish credibility by following verification and validation practices in noise prediction:

- Primary means of assessing accuracy
- Gives confidence in computed results

Concluding Remarks

Users of prediction codes and their results should require detailed documentation of V & V (assessment) activities, ie. errors and uncertainties in code output and experimental data.

Requires investment and resources to follow V & V practices for:

- Developing codes.
- Conducting experiments.
- Assuring availability of data.

Requires management commitment.