ANOPP2 Status and Progress Toward Integrated Acoustic Sensitivity Analysis and Optimization

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NASA's 2nd Generation Aircraft Noise Prediction Program

Acknowledgements

Transformative Aeronautics Concepts Program: Transformational Tools and Technologies Project

Advanced Air Vehicles Program: Advanced Air Transport Technology, Commercial Supersonic Technology, and Revolutionary Vertical Lift Technology Projects

Integrated Aviation Systems Program: Environmentally Responsible Aviation Project

Outline

- Status
  - 2nd Generation Capabilities
  - Aircraft noise prediction requirements
  - ANOPP2 within multi-disciplinary environment
  - Recent Applications
  - Progress since release of ANOPP2 1.0 (ANOPP2 1.1)
- Sensitivity Analysis
- Conclusion

Current Capabilities

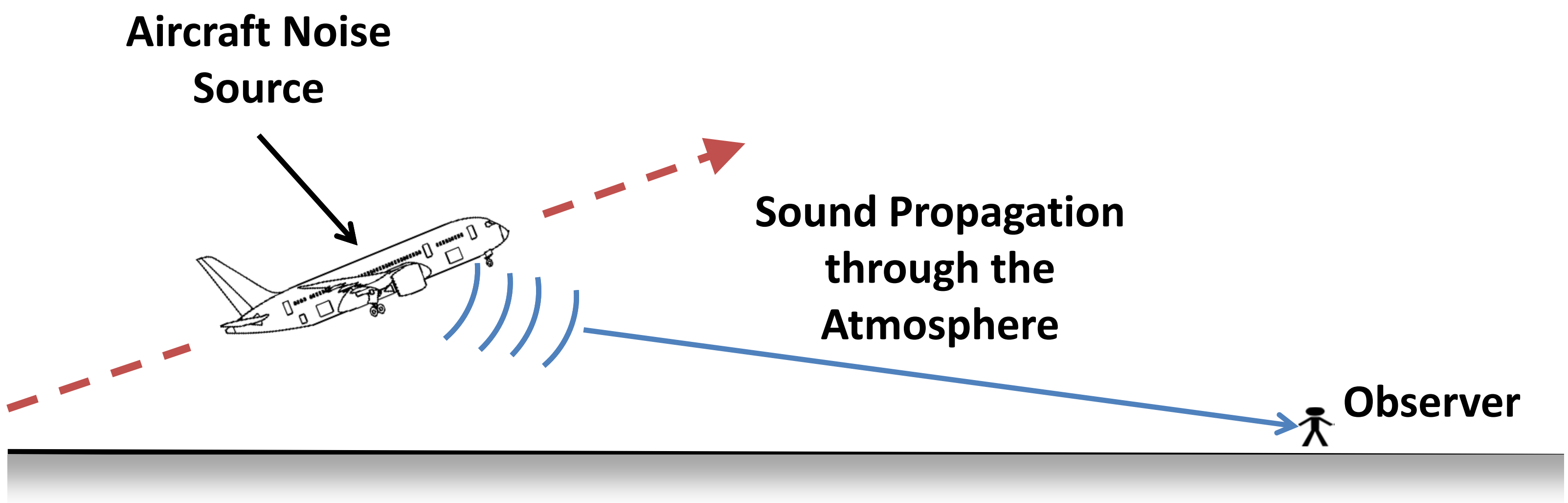
ANOPP

- Fast
- Semi-empirical component noise predictions
- Aircraft modeled as point: component sources at single point for propagation to receiver
- Limited noise metric options, simple ground contours
- Predominantly developed/validated for conventional tube-and-wing transport aircraft
- Useful noise tool but with ‘critical’ limitations

ANOPP2

- Depends on resolution: fast to intensive (includes ANOPP)
- Mixed-fidelity prediction models enabling tailored accuracy/resolution of installed sources
- Representative aircraft configuration: component sources at true locations, enable direct computation of installed effects and accurate propagation to receiver
- Nearly unlimited noise metric options, arbitrary flight trajectories, ground contours
- Direct application for arbitrary aircraft configurations/operations
- Enables ‘design for noise’ capability to explore current and future aircraft/component designs
- Analysis of noise physics from component to system level required for noise reduction technology

Requirements for Aircraft Noise Prediction



- Flight Path
  - Position, time, velocity, orientation angles, throttle setting, flap setting, etc.
- Engine Settings
  - Performance (velocities, temperatures, densities) as function of Mach number, throttle setting, altitude, etc.
- Airframe Properties
  - Wing properties, body geometry, landing gear configurations, slat/flap configuration, etc.
- Additional Information
  - Atmospheric properties, ground specifications, observer locations, etc.

ANOPP2 Aircraft Noise Prediction

Outline of *Program* using ANOPP2

Aircraft Definition and Mission
- Atmosphere Data Structure
- Flight Path Data Structure
- Engine System Data Structure
- Geometry Data Structure
- Observer Data Structure

Select 'Functional Modules' (partial list)
- ANOPP
- Flight Effects, Propagation
- PAA Effects
- Surrogate Model
- Farassat's Formulations
- Wind Tunnel Measurements

Predict Noise for Mission
- User defines computational settings
- Results stored on Observer Data Str.

Results: noise, mission, aircraft

ANOPP2 Configuration Files

ANOPP2 Configuration File	Source
Flight Path Configuration	Externally Computed Flight Path Definition (ex: FLOPS)
Engine State Data	NPSS: Engine State
Measurement Data	Measured/Predicted Noise
Flow Data	Externally Computed Flow Properties
Plugin Configuration	External Functional Noise Module

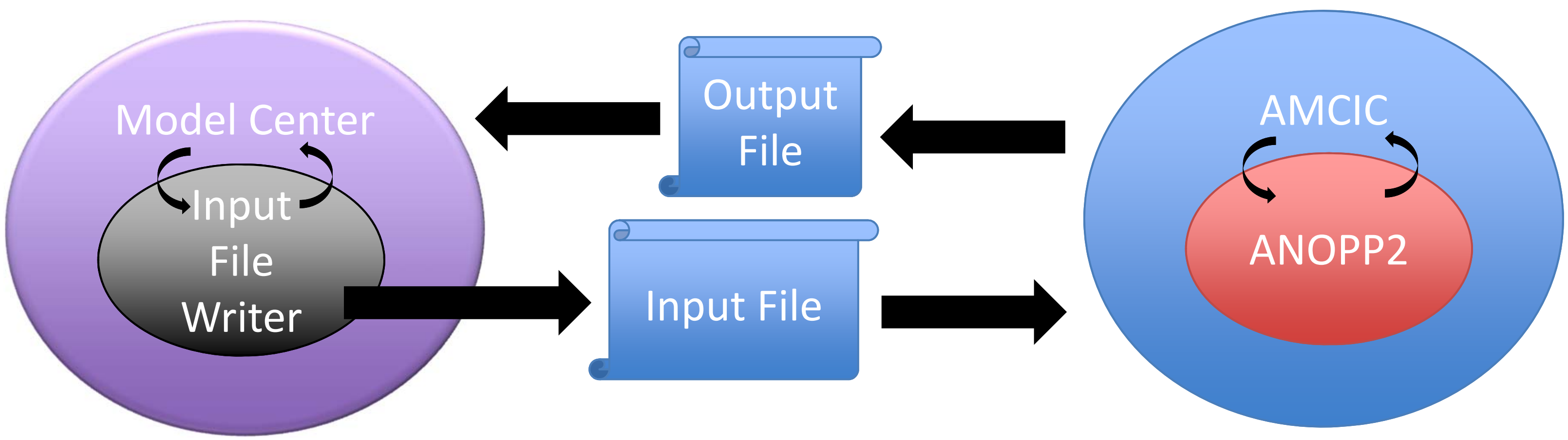
- Acoustics
  - Time histories, $1/3^{rd}$-Octaves, Narrowband
    - Auralizations
  - PNL, PNLT vs. emission angle
  - EPNL, SEL (certification point, contour)
- Aircraft/Prediction Information and Metadata
  - Flight Trajectory (Throttle, Mach, Altitude, etc.)
  - Engine State
  - Source Geometric and Flow Properties

Multi-Disciplinary Environment

- Currently coupling with 2 MDAO environments: Model Center and OpenMDAO
  - Offer significantly different platforms
  - Unique challenges in communication
  - ANOPP2 ideally situated to handle both platforms
  - Sequential progression is adopted to gradually incorporate component integration
- FY 2014
  - Initial Model Center coupling (ANOPP2 Model Center Interface Code (AMCIC))
  - Tube-and-wing aircraft where noise was ‘optimized’ based on simple property
- FY 2015
  - Upgrade AMCIC for initial scattering capability (not-completed yet)
  - Initial OpenMDAO coupling (ANOPP2 OpenMDAO Interface Code (AOIC)): Same capability as AMCIC in FY 2014
- Additional capability added in future years

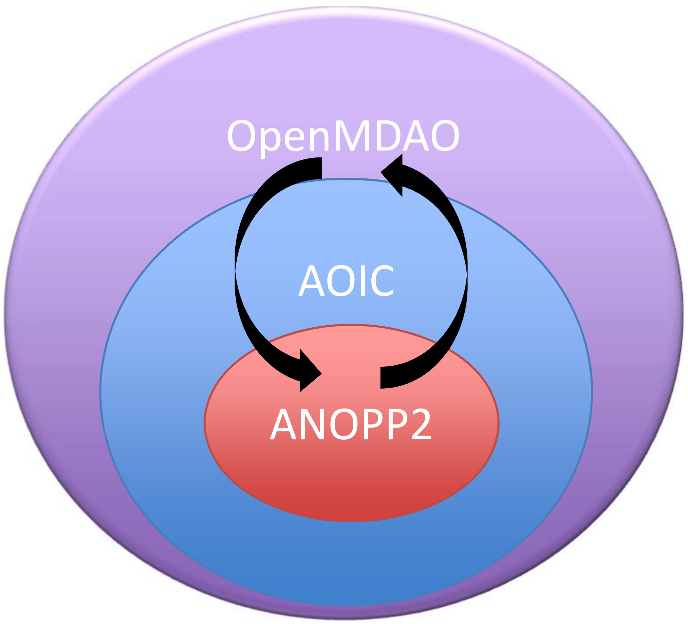
AMCIC

- ANOPP2 Model Center Interface Code (AMCIC)
  - First attempt at interface ANOPP2 with design environment
  - Interface code reads in file generated by Model Center, creates ANOPP2 input, and calls executable that calls ANOPP2 routines
  - Development of AMCIC and ANOPP2 Module will increase communication capability between software



AOIC

- ANOPP2 OpenMDAO Interface Code (AOIC)
  - Development of Python interfaces in ANOPP2 allows direct communication between OpenMDAO and ANOPP2 without file I/O
  - Much faster communication and development time
  - Still requires development of interface code for communication



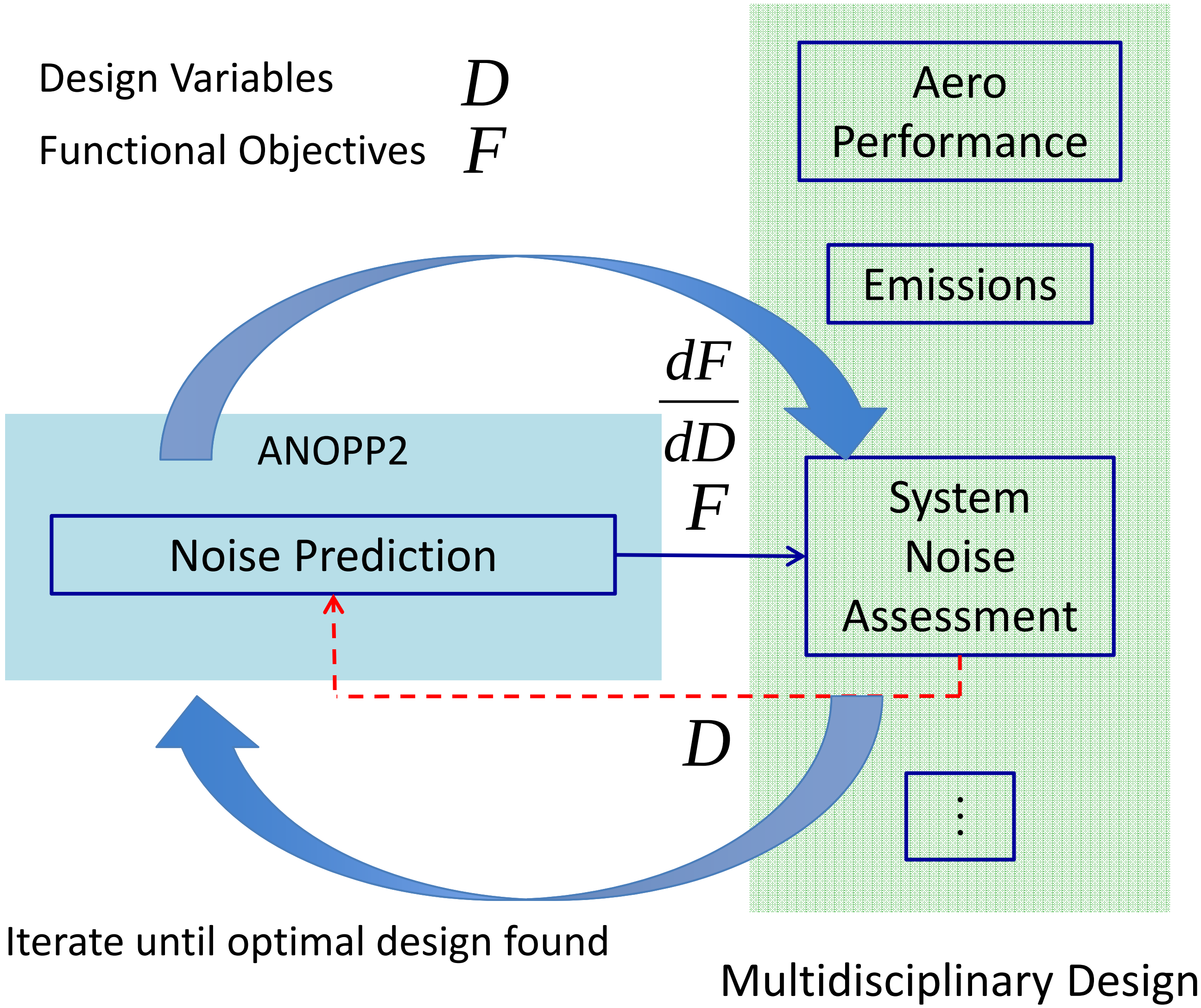
Progress Since Release

- Library Improvements
  - ANOPP2 now distributed with OpenMP and MPI capable library
  - Testing includes parallel operations for Linux operating systems with C++ or Fortran User Code
- Developing hooks for OpenMDAO and Model Center
  - Model Center Interface Code (AMCIC) developed during FY 2014 undergoing improvements in FY 2015
  - OpenMDAO Interface Code (AOIC) undergoing initial development
- Training on April 20th and April 23rd
  - Overwhelming interest in ANOPP2 training!
  - Additional training might be of value (Other functionality)
- Bug fixes/Kernel Improvement
  - ANOPP2 is young and fixes/improvements occur continuously
  - Many changes to ANOPP2 kernel that are invisible to user for improved speed, efficiency, and clarity
- Testing system
  - All APIs within ANOPP2 are continuously being tested with every code change
  - Additional language support (Python) on all operating systems
- User created Functional Modules (Plugins)
  - Available on Windows, Mac, and Linux and can be written in Fortran or C++
  - Plugins are composed of exactly the same routines available to user

Outline

- Status
- Sensitivity Analysis
  - Brief Introduction to Design Optimization
  - Acoustic Based Sensitivity
  - Sensitivity of Common Acoustic Metrics
  - Sensitivity of Formulation 1A (S1A)
- Conclusion

Design for Noise



CFD-Based Design Optimization

- Optimize objective function based on design variables
  - Objective Function(s)
    - Lift, Drag, Noise
  - Design Variables(s)
    - Geometrical Parameters, Flight Path Properties
  - CFD-Based Optimization using Lagrange Multiplier
    - Only simplified form shown

$$\frac{\partial Q(D)}{\partial t} + R(D,Q) = 0 \qquad L(D,Q,\Lambda) = F(D,Q) + \Lambda\left(\frac{\partial Q(D)}{\partial t} + R(D,Q)\right)$$

E. J. Nielsen and B. Diskin "Discrete Adjoint-Based Design Optimization of Unsteady Turbulent Flows on Dynamic Unstructured Grids" AIAA Journal Vol. 48, No. 6, June 2010

ANOPP2

Design Optimization

- Really want sensitivity so we can optimize

0

$$\frac{dL}{dD}=\left(\frac{\partial F}{\partial D}+\frac{\partial F}{\partial Q}\frac{\partial Q}{\partial D}\right)+\Lambda\left(\frac{\partial}{\partial Q}\left(\frac{\partial Q(D)}{\partial t}+R\right)\frac{\partial Q}{\partial D}+\frac{\partial R}{\partial D}\right)$$

- And rearrange

Very Big Matrix

$$\frac{dL}{dD}=\Lambda\frac{\partial R}{\partial D}+\frac{\partial Q}{\partial D}\left(\frac{\partial F}{\partial Q}+\Lambda\frac{\partial}{\partial Q}\left(\frac{\partial Q(D)}{\partial t}+R\right)\right)$$

- Now have adjoint equation

$$-\frac{\partial F}{\partial Q}=\Lambda\frac{\partial}{\partial Q}\left(\frac{\partial Q(D)}{\partial t}+R\right)$$

Acoustic Sensitivity

- Know everything except the acoustic sensitivity

$$\frac{\partial F}{\partial Q} = \frac{\partial F}{\partial p'}\frac{\partial p'}{\partial Q}$$

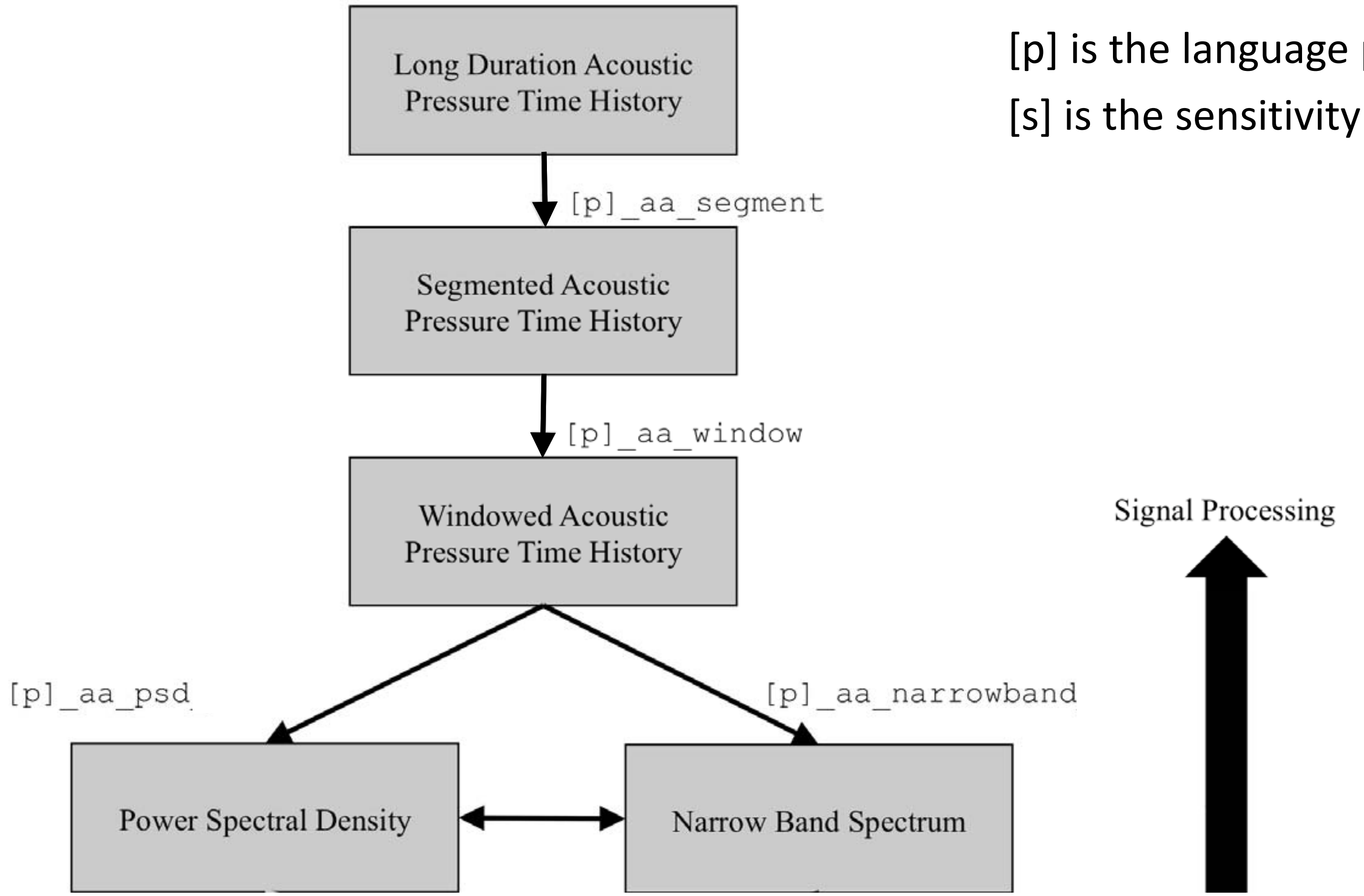
- What is the object function?
  - Can be any of the numerous acoustic metrics
  - EPNL, SEL, A-Weighted OASPL, PNL/PNLT
- Must also get sensitivity of all metrics in between

$$\frac{\partial EPNL}{\partial p'} = \frac{\partial EPNL}{\partial PNLT}\frac{\partial PNLT}{\partial SPL}\frac{\partial SPL}{\partial PSD}\frac{\partial PSD}{\partial p'_s}\frac{\partial p'_s}{\partial p'}$$

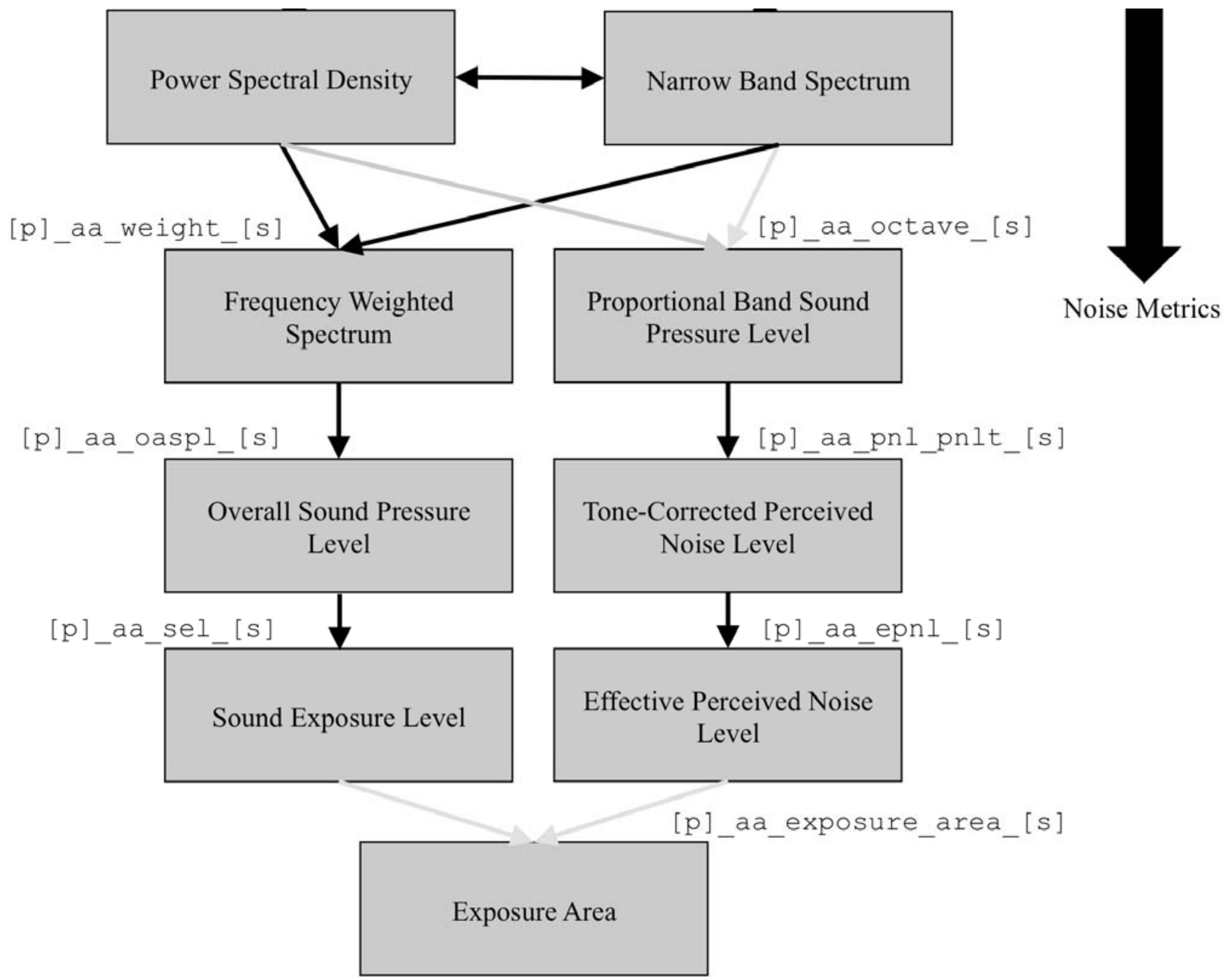
Supported Sensitivities (1 of 2)

[p] is the language prefix

[s] is the sensitivity suffix



Supported Sensitivities (2 of 2)



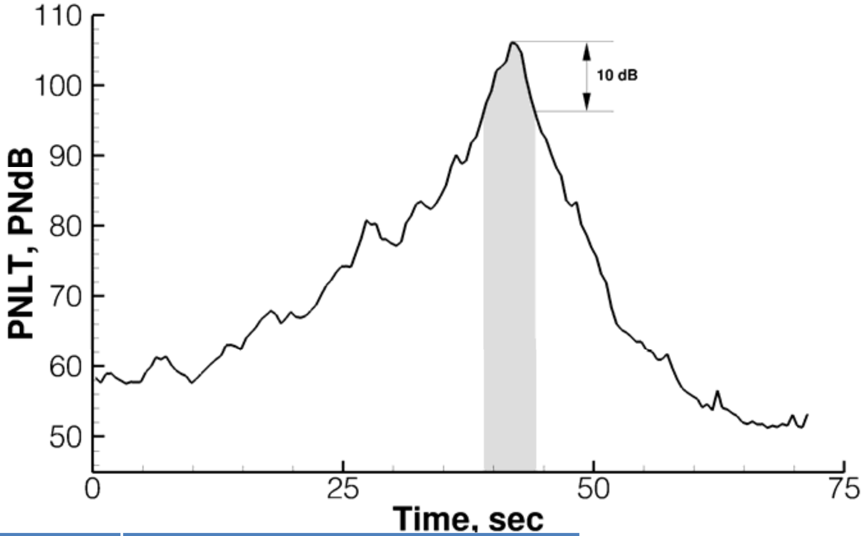
Validation

- Implementation of sensitivity validated through complex differentiation and central differencing

$$f'(x) = \frac{\mathrm{Im}\left[f(x+i\varepsilon)\right]}{\varepsilon} + O(\varepsilon^2) \qquad \varepsilon = 1e^{-10}$$

$$f'(x) = \frac{f(x+\Delta) - f(x-\Delta)}{2\Delta} + O(\Delta^2)$$

$$\Delta = 1e^{-2}$$



- For Example: EPNL

	EPNL	$dEPNL/dPNLT_{max}$
Complex Differentiation	96.03973	0.1586321
Central Differencing	96.03973	0.1590729
Sensitivity Analysis	96.03973	0.1586321

Sensitivity Analysis

- Second half of acoustic sensitivity

$$\frac{\partial F}{\partial Q} = \frac{\partial F}{\partial p'}\frac{\partial p'}{\partial Q} = \frac{\partial F}{\partial p'}\frac{\partial p'}{\partial Q_s}$$

FW-H Surface

- Can calculate the acoustic pressure from the flow solution using Formulation 1A

$$4\pi p'_m = \int_{f=0} \left[\left(\dot{Q}J + Q\dot{J} \right) A + \left(QJ \right) B \right]_{ret} du_1\, du_2$$

$$4\pi c_\infty p'_d = \int_{f=0} \left[\left(\dot{L}_i J + L_i \dot{J} \right) C_i + \left(L_i J \right) D_i \right]_{ret} du_1\, du_2$$

Formulation S1A (Sensitivity of 1A)

- Take the analytical derivative of 1A

$$4\pi \frac{\partial p'_m}{\partial Q_s} = \int_{f=0} \left[\left(\frac{\partial \dot{Q}}{\partial Q_s} J + \frac{\partial Q}{\partial Q_s} \dot{J} \right) A + \left(\frac{\partial Q}{\partial Q_s} J \right) B \right]_{ret} du_1 \, du_2$$

$$4\pi c_\infty \frac{\partial p'_d}{\partial Q_s} = \int_{f=0} \left[\left(\frac{\partial \dot{L}_i}{\partial Q_s} J + \frac{\partial L_i}{\partial Q_s} \dot{J} \right) C_i + \left(\frac{\partial L_i}{\partial Q_s} J \right) D_i \right]_{ret} du_1 \, du_2$$

- Only takes into account flow solution
  - Significantly more complicated when grid sensitivity is also included
  - Final form of S1A will include grid sensitivity

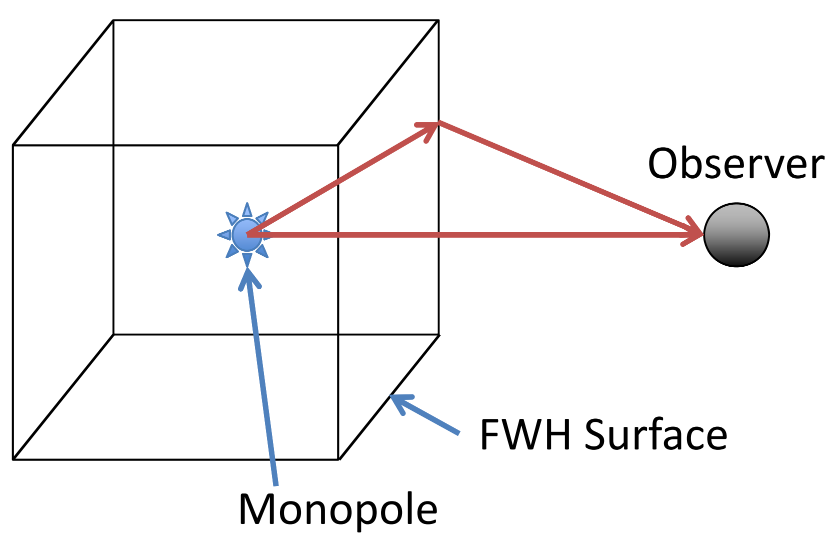
Demonstration of S1A

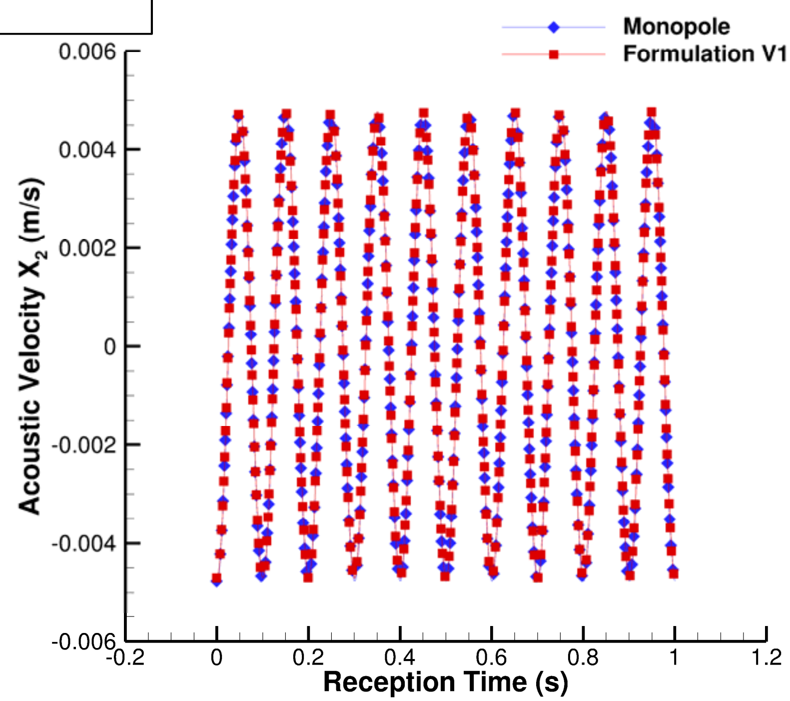
$$u'_{i,m}(x_i,t) = \frac{1}{\rho c}\int\limits_{f=0}\left[\dot{Q}(A_i J)\right]_{ret} du_1 du_2 + \frac{1}{\rho c}\int\limits_{f=0}\left[Q(B_i J + A_i \dot{J})\right]_{ret} du_1 du_2$$

$$u'_{i,d}(x_i,t) = \frac{1}{\rho c^2}\int\limits_{f=0}\left[\dot{L}_j(A_{ij} J)\right]_{ret} du_1 du_2 + \frac{1}{\rho c^2}\int\limits_{f=0}\left[L_j(B_{ij} J + A_{ij} \dot{J})\right]_{ret} du_1 du_2 -$$

$$\frac{1}{\rho}\int\limits_{-\infty}^{t}\int\limits_{f=0}\left[L_j(C_{ij} J)\right]_{ret} du_1 du_2 dt'$$

Formulation V1A

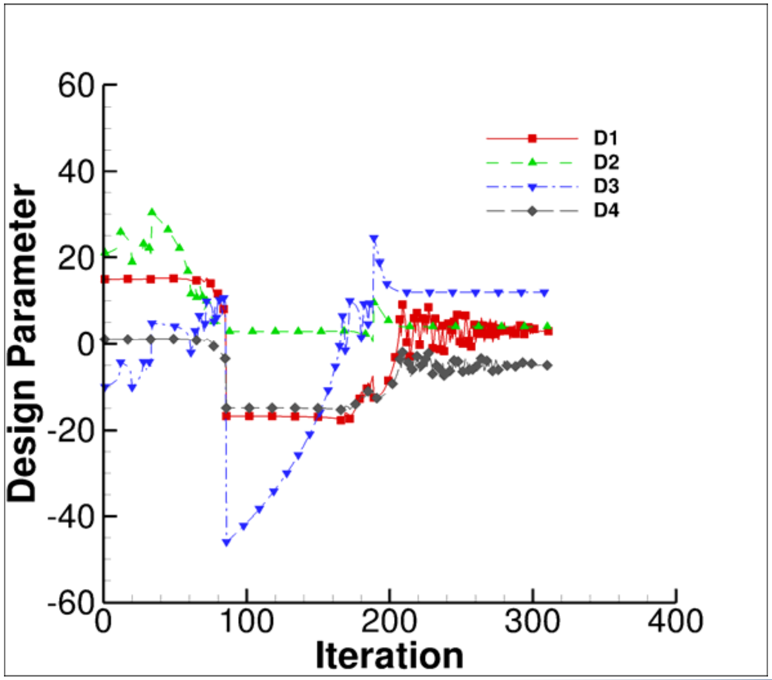


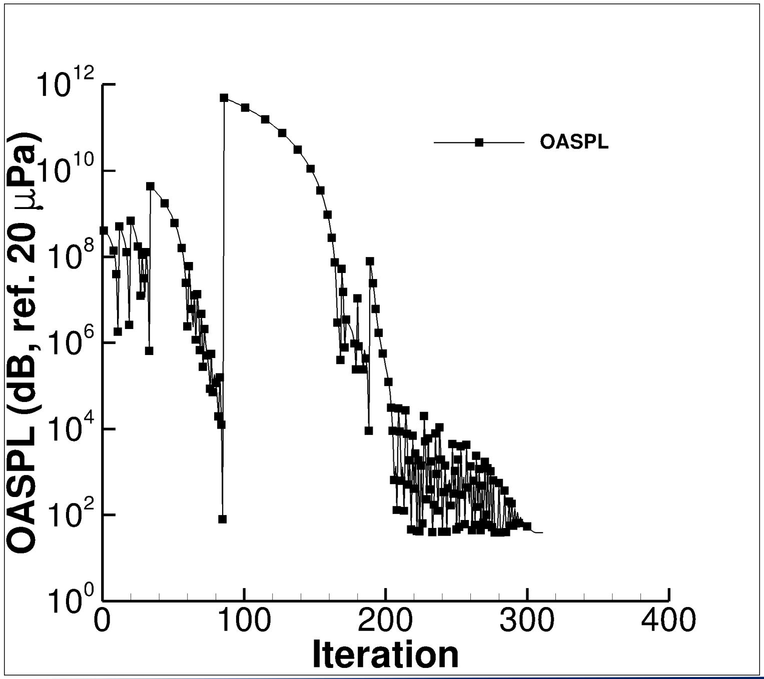


Demonstration of S1A (Preliminary)

- Iterate on 'design parameter': strength of the monopole
- Functional is OASPL at observer
- Method of steepest decent for optimization (not ideal)

$$q = (D_1 - 3)^2 + (D_2 - 4)^3 + (D_3 - 12)^3 + (D_4 + 5)^2 + 1$$





Outline

- Status
- Sensitivity Analysis
- Conclusion

Conclusions

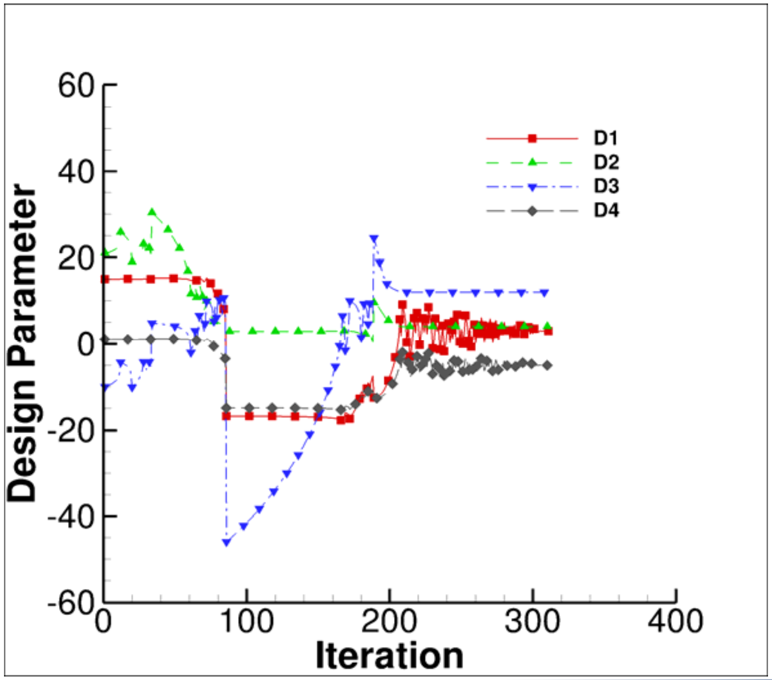
- Status: Continually Improving ANOPP2
  - Excited about interest in training and welcome feedback
  - Coupling with multi-disciplinary environments
  - Many different applications that provide direction in development
- Acoustic Sensitivity: New capability that brings acoustics into CFD-based design optimization
  - Acoustic metric sensitivity being developed within ANOPP2
  - Formulation S1A being developed and preliminary results promising

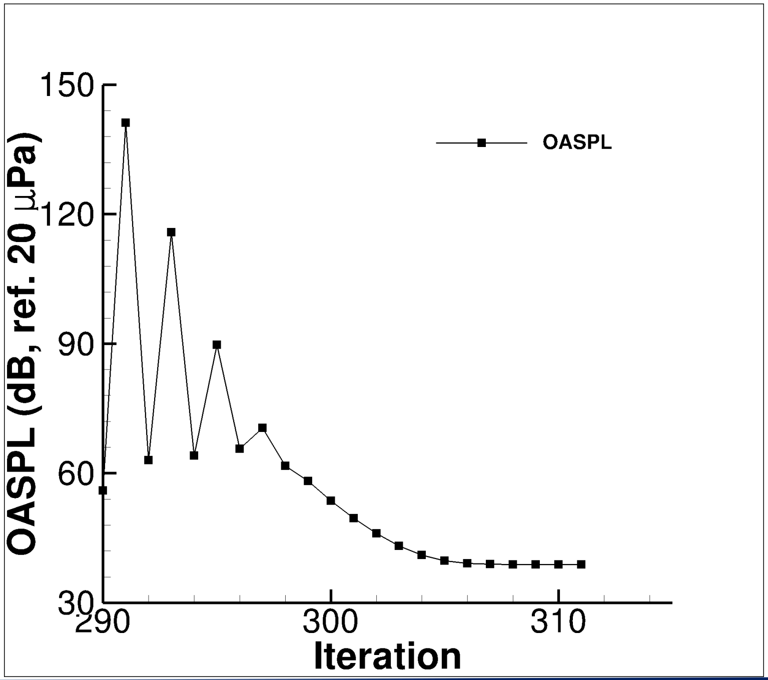
Questions

Demonstration of S1A (Preliminary)

- Iterate on ‘design parameter’: strength of the monopole
- Functional is OASPL at observer
- Method of steepest decent for optimization (not ideal)

$$q = (D_1 - 3)^2 + (D_2 - 4)^3 + (D_3 - 12)^3 + (D_4 + 5)^2 + 1$$





System Noise of 13 ERA Phase II Vehicles

Vehicle / Engine	short name	# of Engines	Landing gear	Engine Scale Factor	TOGW (lbs)
T&W: Regional Jet / direct drive	RJ-DD	2	G550	0.964	89,362
T&W: Single Aisle, small GTF	SA-GTF	2	737	1.042	144,057
T&W: Twin Aisle, med. GTF	STA-GTF	2	767	1.051	287,469
T&W: Large Twin Aisle, large DD	LTA-DD	2	777	0.992	592,563
T&W: Large Twin Aisle, large GTF	LTA-GTF	2	777	1.004	595,364
T&W: Very Large Twin Aisle, med GTF	VLTA-GTF	4	777	0.942	674,846
HWB: Small Twin Aisle, med GTF	HWB216-GTF	2	767	1.005	318,221
HWB: Large Twin Aisle, large DD	HWB301-DD	2	777	1.005	568,333
HWB: Large Twin Aisle, large GTF	HWB301-GTF	2	777	0.961	564,839
HWB: Very Large Twin Aisle, med GTF	HWB400-GTF	3	777	1.205	708,808
T&W: Over Wing Nacelle 98, direct drive	OWN98-DD	2	G550	0.964	89,320
T&W: Over Wing Nacelle 160, small GTF	OWN160-GTF	2	737	1.014	140,761
T&W: Mid-Fuselage Nacelle, large GTF	MFN301-GTF	2	777	0.928	559,201

- **"baseline" vehicle** = includes ERA technology inherent in airframe and engine design.
  - Light weight structures
  - Modernized flap system (single-element design) and Krueger flap for leading edge
  - Advanced Geared TurboFan Engine (GTF) and Advanced Direct Drive Engine (DD)
  - PAA shielding appropriate to each configuration
  - Specialized technologies: PAA shielding chevrons, scarf exhaust nozzle, quiet spoiler
- **"baseline + ITD"** = ITD noise reduction technology: soft vane (fan noise), partial main landing gear fairing and flap-side edge treatment.

System Noise Prediction Process

ANOPP2

Aircraft Flight Definition

Source Noise (ANOPP)
Jet: ST2JET + *AOA correction*
Core: GECOR (SAE)
Fan: Heidmann: Krejsa model, ACD*(GTF)
Landing gear (nose & main): BoeingLG
Flap-side-edge: BoeingFlap
Leading edge (Krueger): estimated using BoeingSlat
Spoiler: estimated using modified/calibrated BoeingFlap
Trailing edge: Fink

PAA Effects:
engine noise shielding

ITD noise technology reduction through suppression of specific source noise (fan, gear, flap, slat)

Propagation & Noise Metrics

EPNL predicted at CFR 36 locations

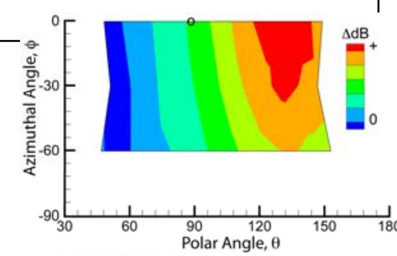
Flight profiles that meet CFR 36 Aircraft geometries ← FLOPS MVL-aero ←

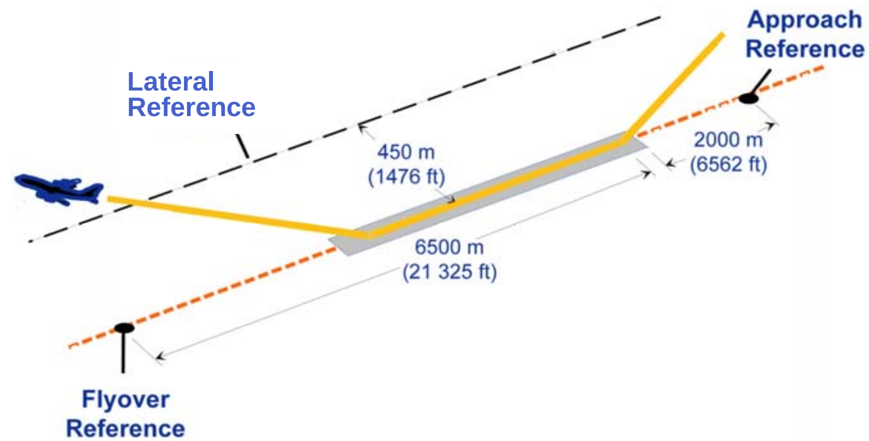
- Low speed aero
- Engine operating limits
- Airframe geometric definition
- Aircraft weights

Engine states and geometric parameters ← NPSS

ITD 35A: Soft Vane fan noise reduction
GTF source fan noise
ITD 50A: LG and Flap ITD data for RJ prediction & noise reduction,
LG and Flap 2025 level of noise suppression function for all vehicles except RJ

PAA effects: LSAF data
14x22 HWB data

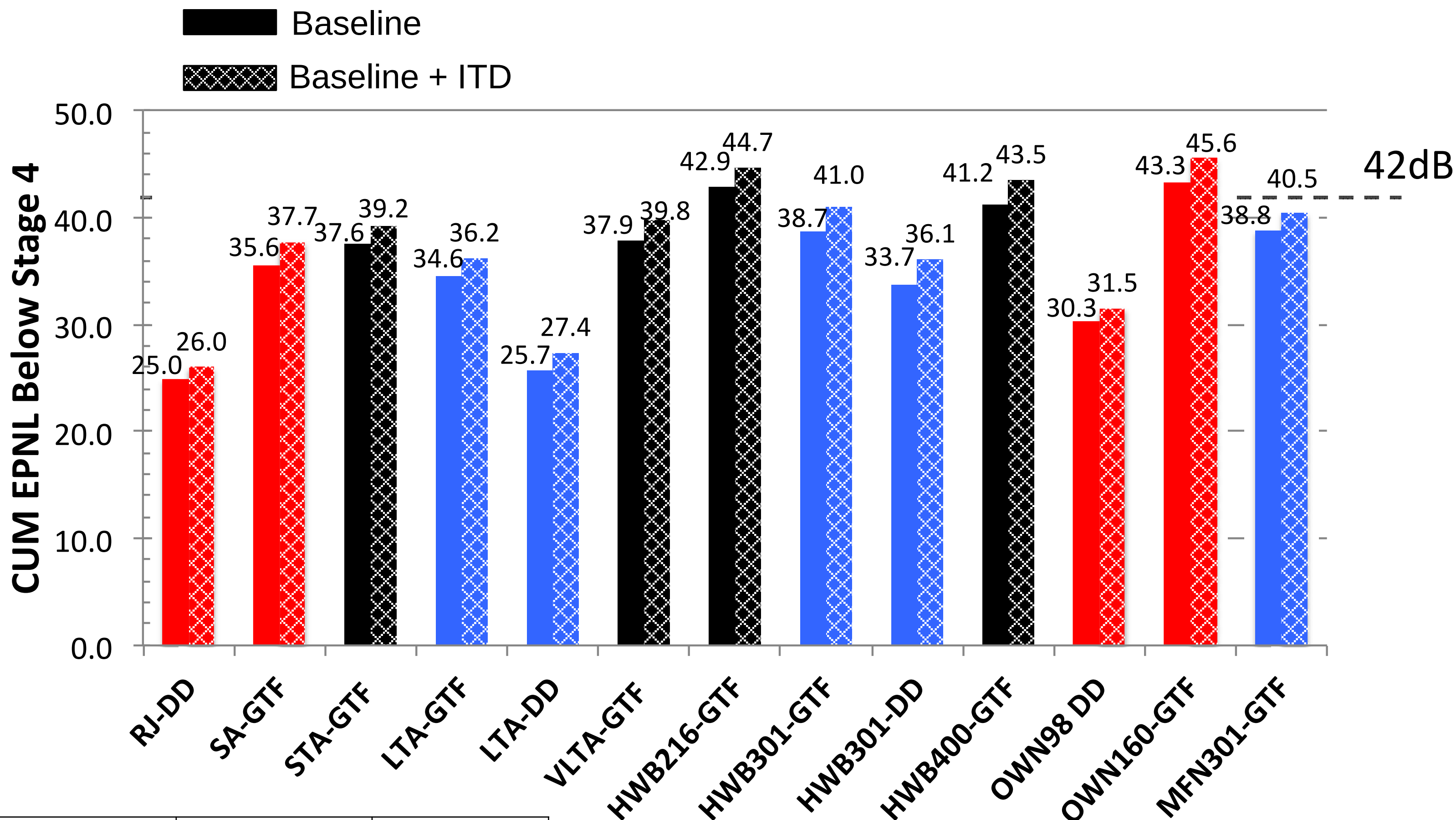




*ACD= Acoustic Data Module within ANOPP to allow for external noise input

Thomas, Burley: Acoustic Technical Working Group Meeting, Oct, 2014

Baseline (with Krejsa fan noise model) + ITD Technology Results



Engine	TOC (ADP)		Cruise		SLS	
	BPR	FPR	BPR	FPR	BPR	FPR
sm DD	9.60	1.60	9.90	1.55	9.80	1.50
lg DD	14.75	1.50	15.25	1.46	16.25	1.37
sm GTF	23.15	1.30	23.75	1.28	24.75	1.23
med GTF	21.45	1.30	22.00	1.28	22.40	1.26
lg GTF	20.40	1.35	20.95	1.32	22.40	1.26

ITD Technologies added:

- **Soft vane**
- **Partial Landing Gear Fairing**
- **Flap Side Edge Treatment**