Perception-Influenced Acoustic Design of Novel Air Vehicles

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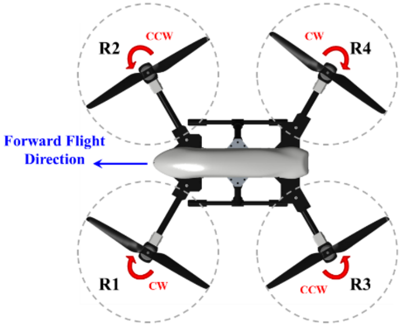

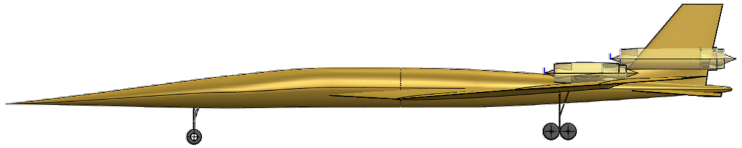

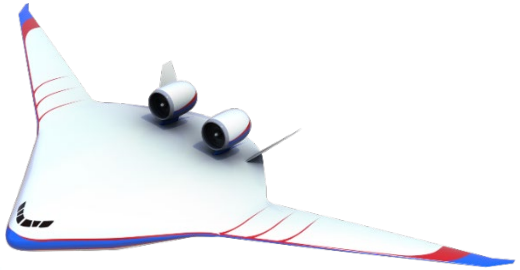

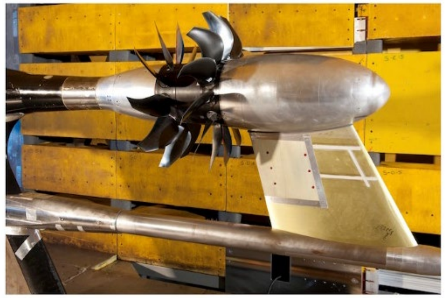

Mobility Innovation eXchange in Aero/Acoustics (MIXA)
The Ohio State University
14 November 2024

Outline

- Background
- Design for Noise
- Perception-Influenced Design
  - Auralization
  - Psychoacoustic Testing
- Applications
  - Supersonic Transports
  - Contrarotating Open Rotor Propulsors
  - Advanced Subsonic Commercial Transports
  - Urban Air Mobility
- Concluding Remarks

Background

- Human response to aircraft community noise is a complex perception phenomenon that is a function of both acoustic and non-acoustic factors.
- The aircraft vehicle design process requires a multidisciplinary approach to achieve a set of design goals that typically include performance, emissions, fuel/energy consumption, and noise.
  - Noise goals usually specified in terms of certification metrics, which may not fully reflect acoustic factors related to human response, nor are intended to reflect non-acoustic factors.
- ICAO noise certification requirements are part of a balanced approach which strives to manage aircraft noise “in the most cost-effective manner.”

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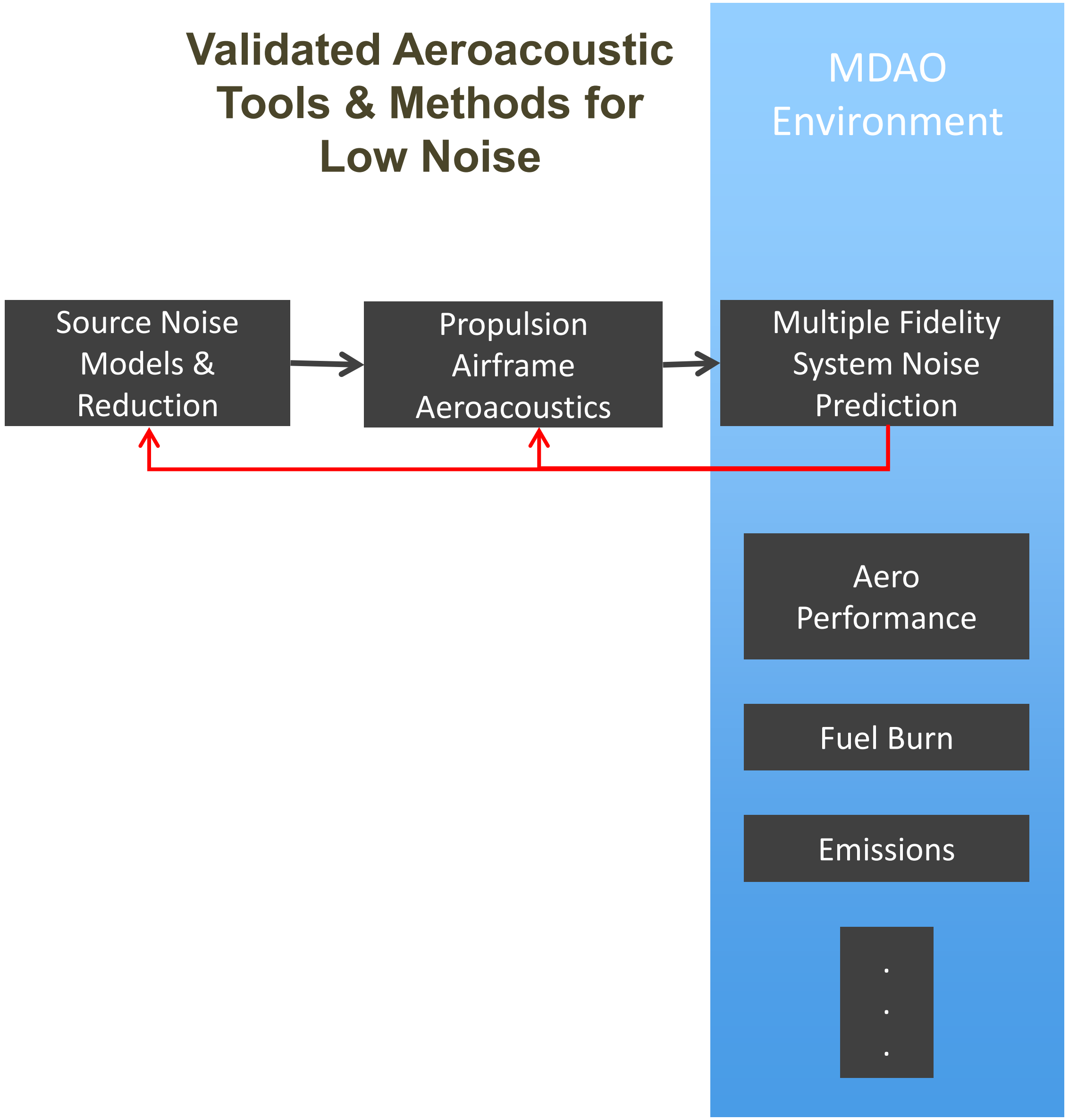
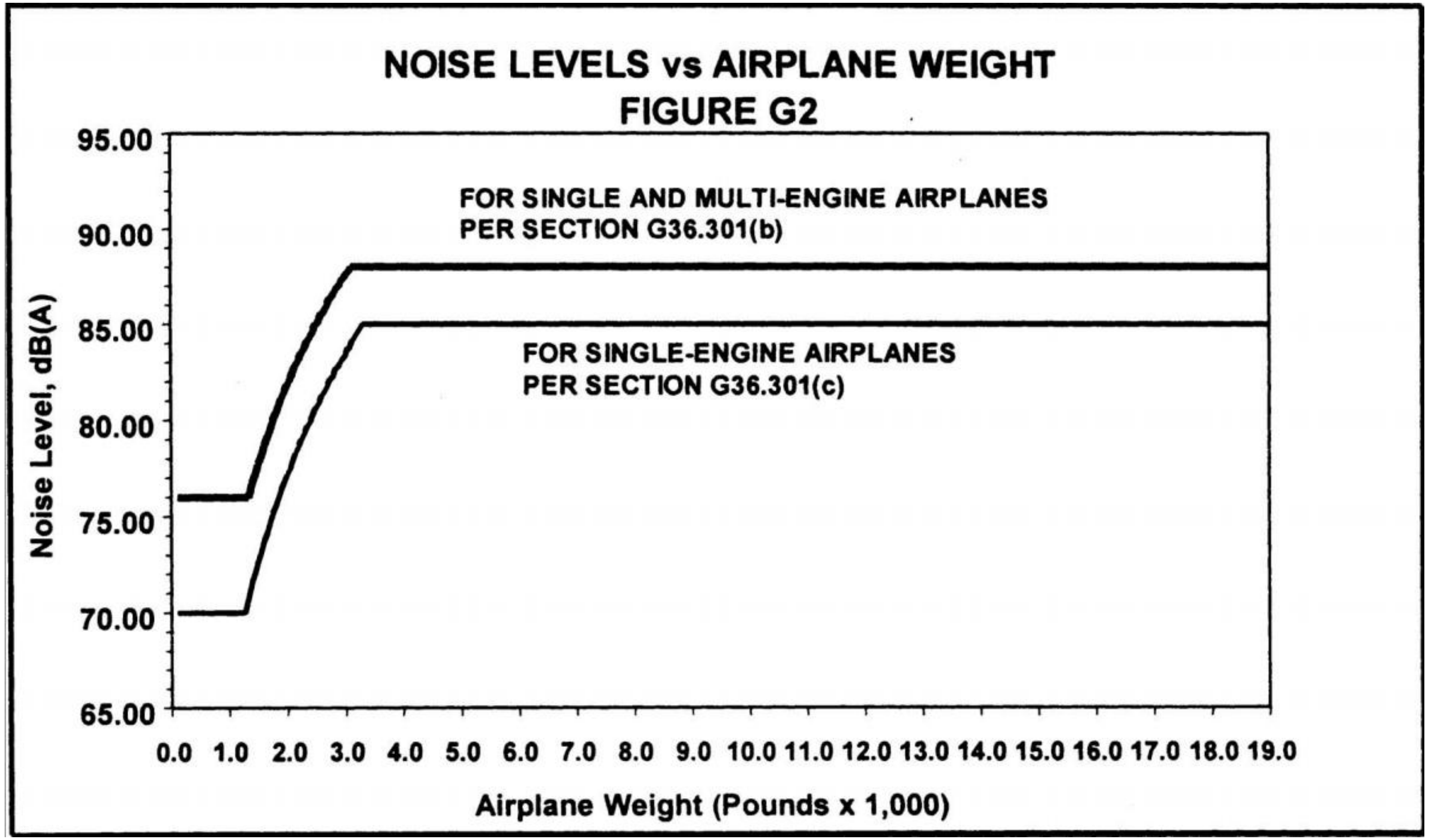
Metrics-Driven Design Process for Noise



Propeller-Driven Aircraft
(ICAO Chapter 10, FAR 36 Appendix G)

Takeoff Noise Limits for Single and Multi-Engine Airplanes



Source: https://federalregister.gov/a/06-50

Optimized Acoustic Design

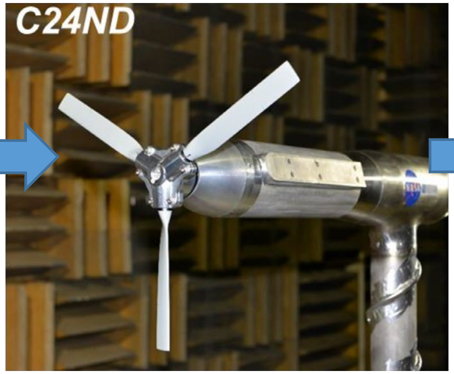
Measured
Background
Predictions

Baseline Geometry

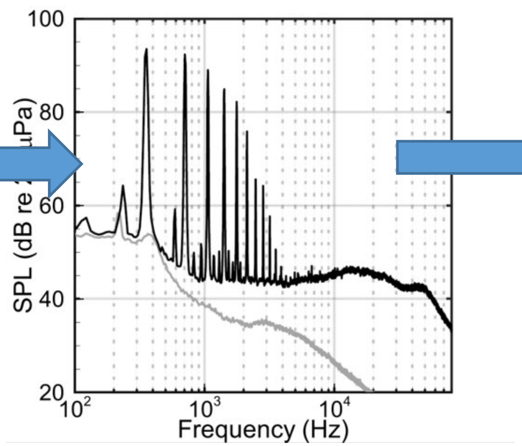
$$\phi = \mathrm{TAN}^{-1}\left(\frac{P}{\pi D}\frac{R}{r}\right)$$

Parameter	Value
c, in. (mm)	1.5 (38.1)
P, in. (mm)	16.0 (406.4)
D_p, in. (mm)	24.0 (609.6)

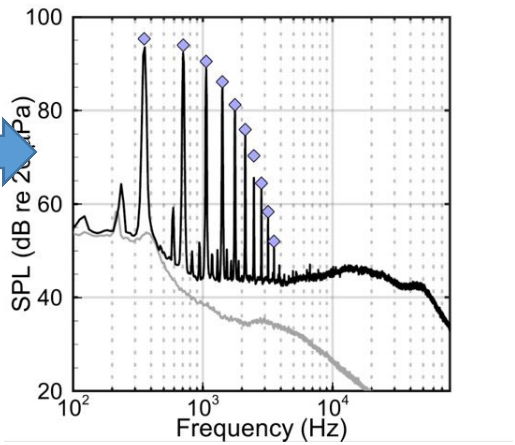
Baseline Tunnel Entry



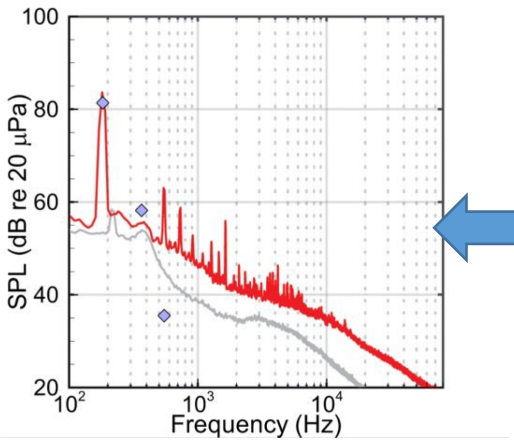
Baseline Data



Analysis Using Optimization Tools

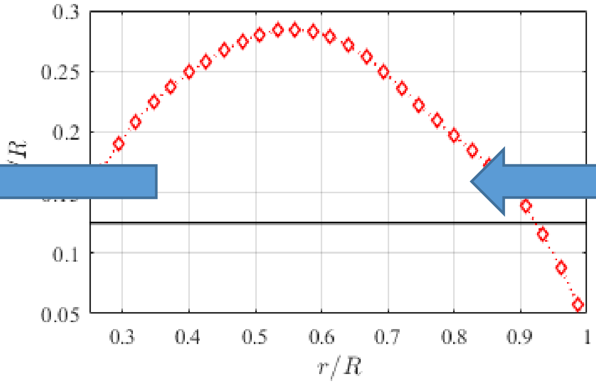


Validation Data

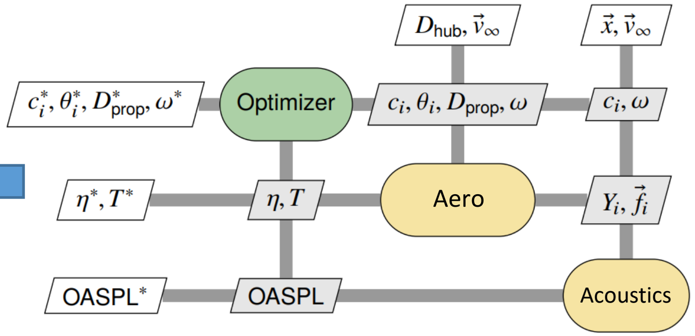


Optimization Tunnel Entry

Optimized Geometry

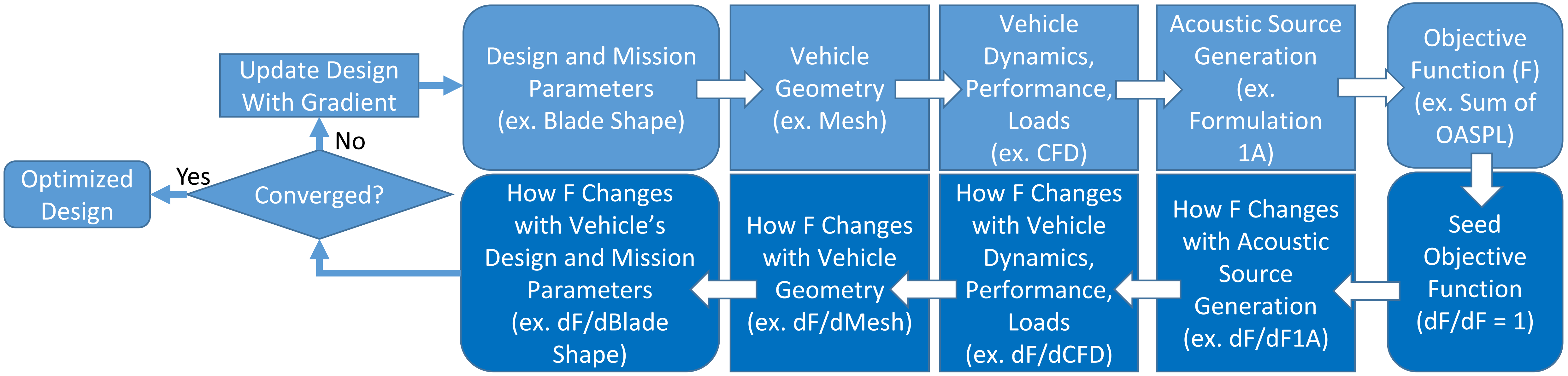


Design Optimization



Zawodny, Pettingill, Lopes, Ingraham, "Experimental Validation of an Acoustically and Aerodynamically Optimized UAM Proprotor, Part 1: Test Setup and Results," NASA TM-20220015637, 2023, https://ntrs.nasa.gov/citations/20220015637.
Blake, Thurman, Zawodny, Lopes, "Broadband Predictions of Optimized Proprotors in Axial Forward Flight," AIAA Aviation 2023, San Diego, 2023, https://doi.org/10.2514/6.2023-4183.

Optimization using Backwards Differentiation



Benefits:

- Best used for small number of objectives (e.g., noise metric) with many design variables.
- Does not iterate over random design changes.

Simple Backwards Differentiation Example

Forward Program

```
x1 = 2;
x2 = x1^3 + x1^2 + 1;
x3 = x2*8;
y = x3^2 + 10;
```

Backwards Differentiation

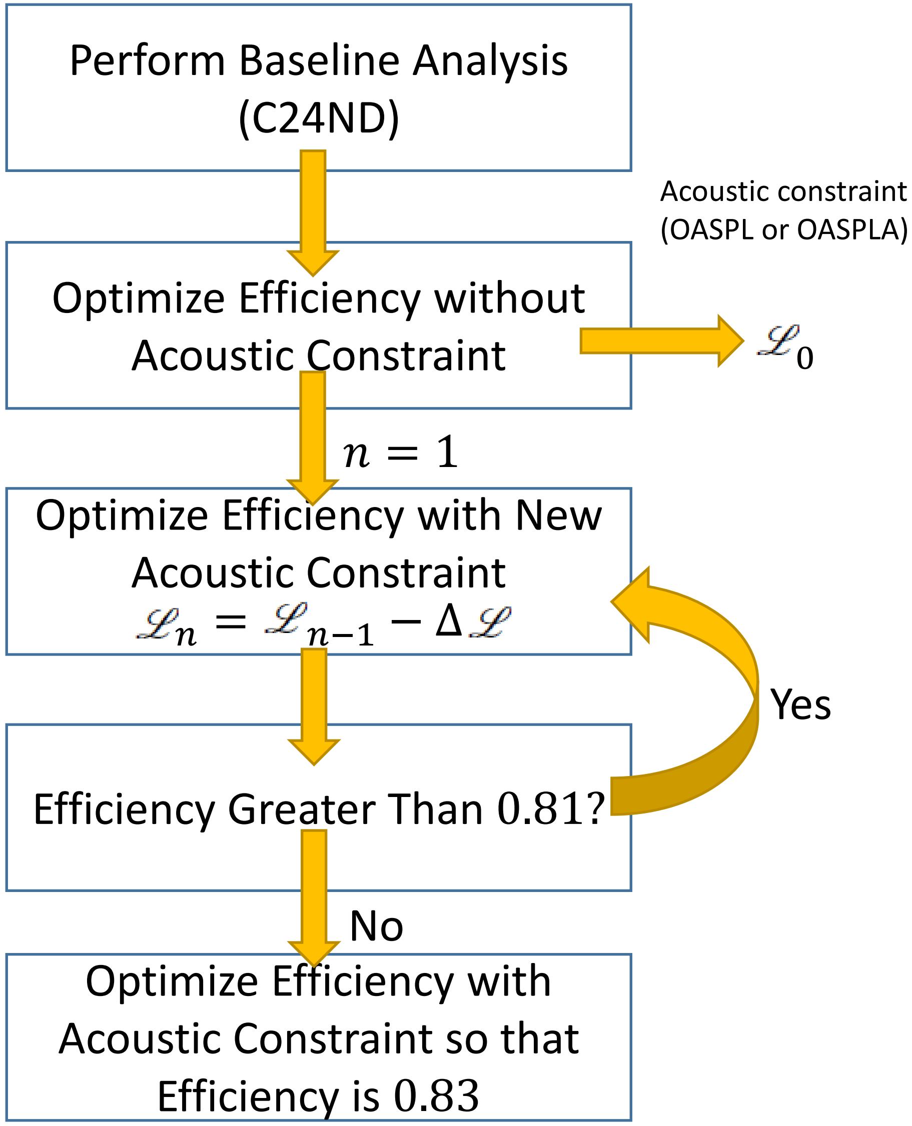
```
% y = x3^2 + 10;
% O = y, I = x3
% dy/dI = dy/dO*dO/dI;
dy_dx3 = 2*x3;
% x3 = x2*8;
% O = x3, I = x2
% dy/dI = dy/dO*dO/dI;
dy_dx2 = dy_dx3*8;
% x2 = x1^3 + x1^2 + 1;
% O = x2, I = x1
% dy/dI = dy/dO*dO/dI;
dy_dx1 = dy_dx2*(3*x1^2 + 2*x1);
```

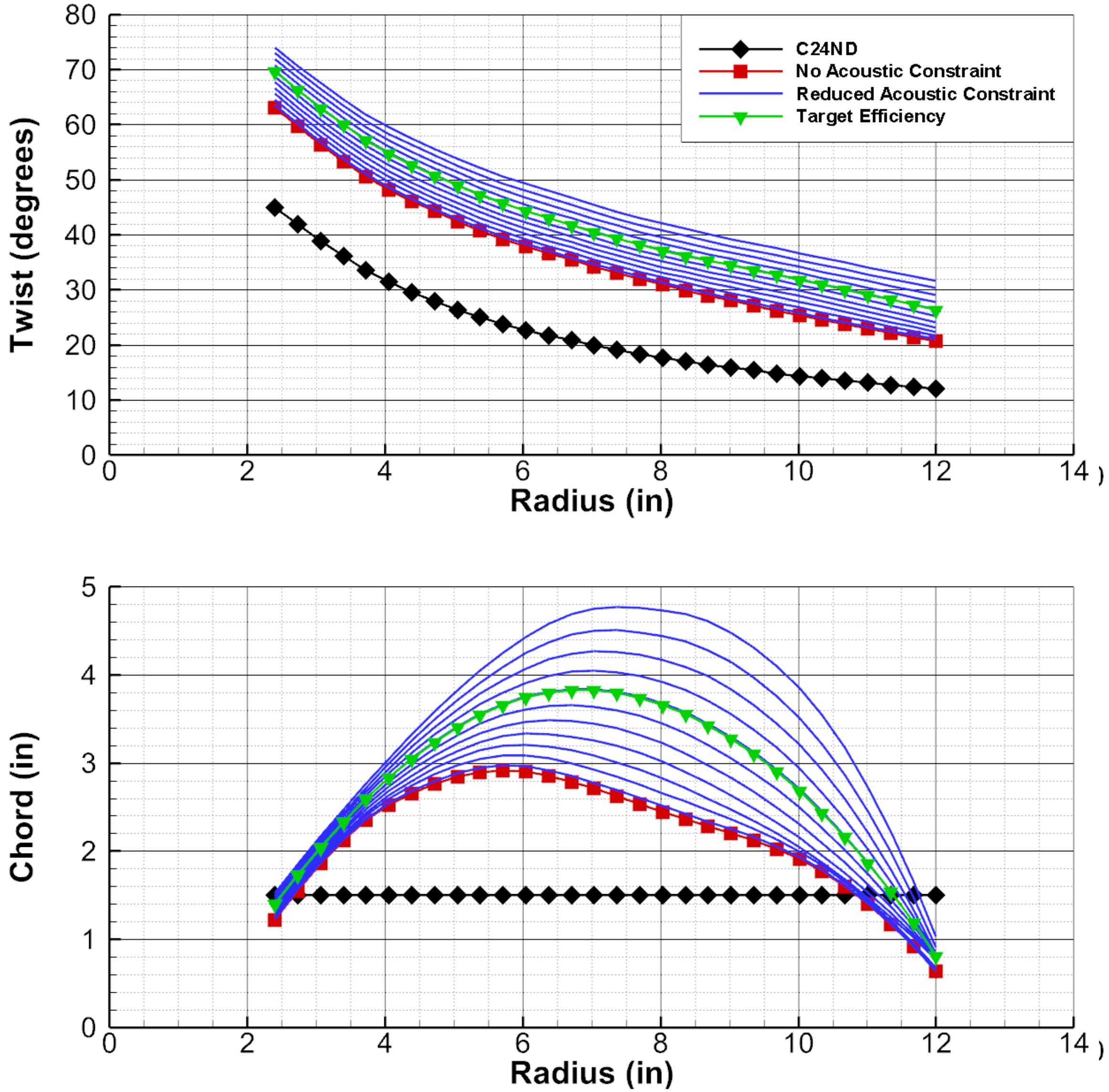
Sensitivity of y to x1 → (dy_dx1)

Tools exist to automatically perform backwards differentiation (e.g., Adept)

Defining a Pareto Front

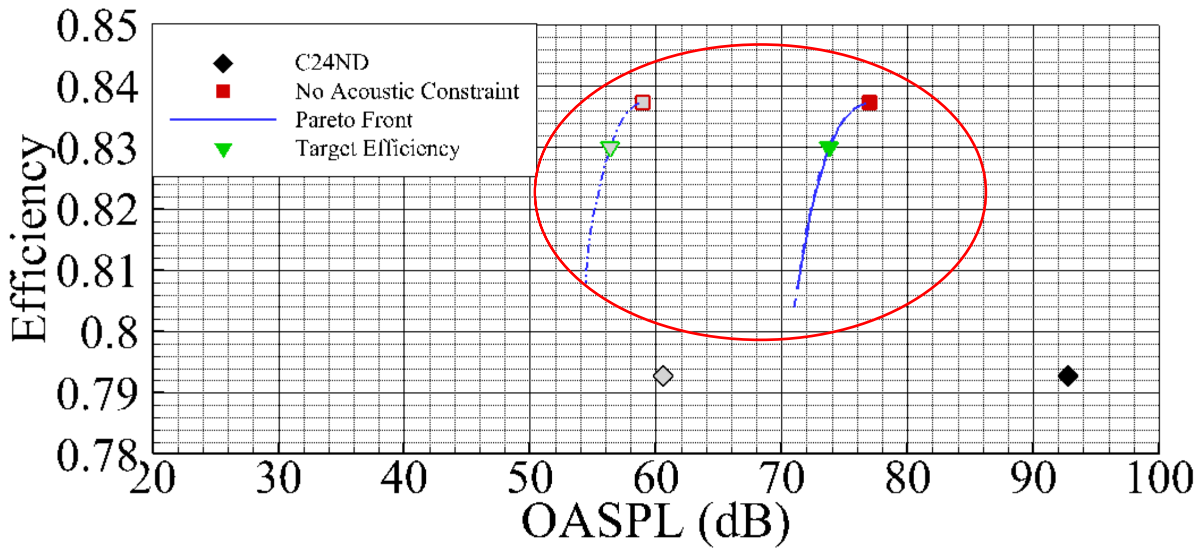
Lopes, Ingraham, "Influence of the Perception, Observer Position, and Broadband Self-Noise on Low-Fidelity UAM Vehicle Perception-Influenced-Design (PID) Optimization," VFS 79th Annual Forum, 2023, https://ntrs.nasa.gov/citations/20230004003

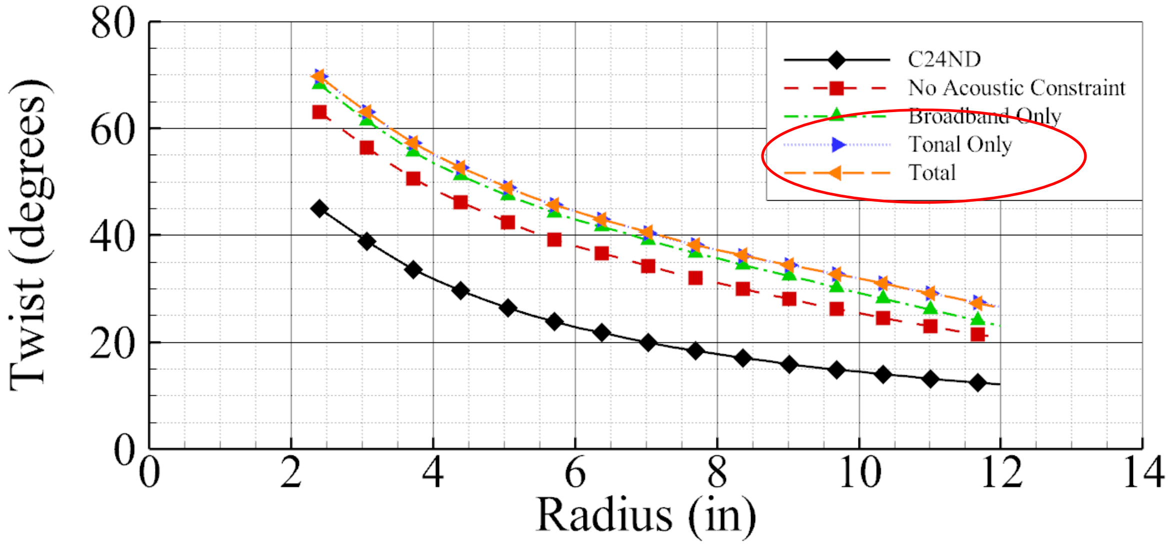


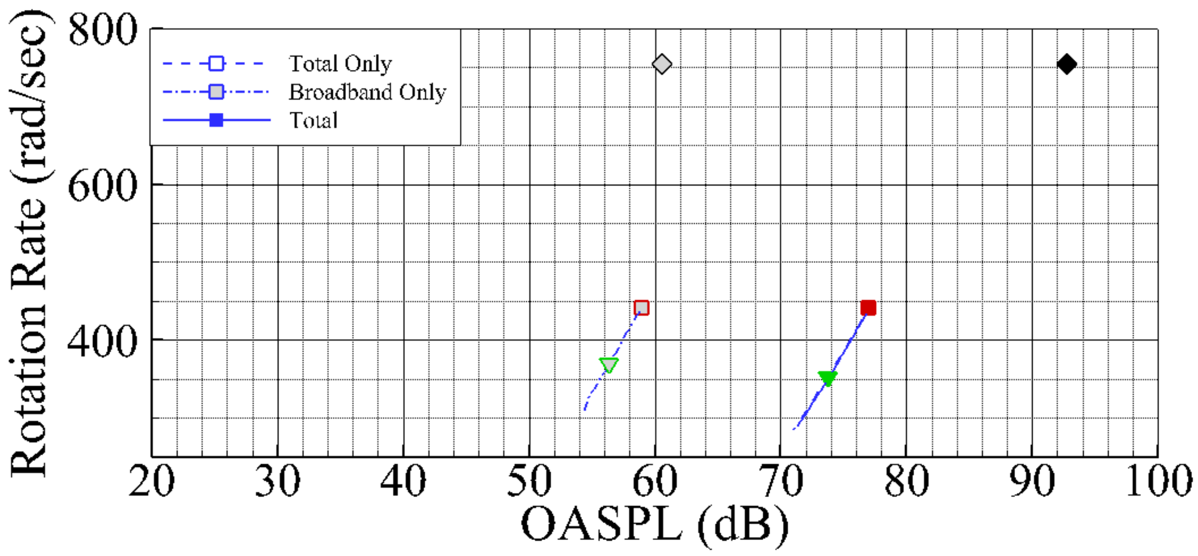


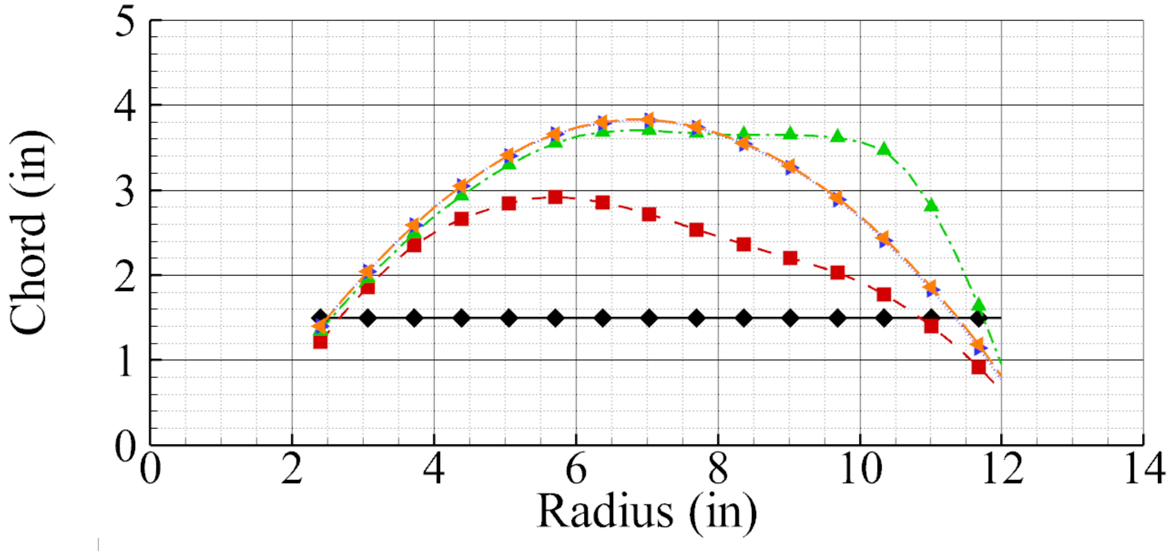
In-Plane, Unweighted

Lopes, Ingraham, "Influence of the Perception, Observer Position, and Broadband Self-Noise on Low-Fidelity UAM Vehicle Perception-Influenced-Design (PID) Optimization," VFS 79th Annual Forum, 2023, https://ntrs.nasa.gov/citations/20230004003



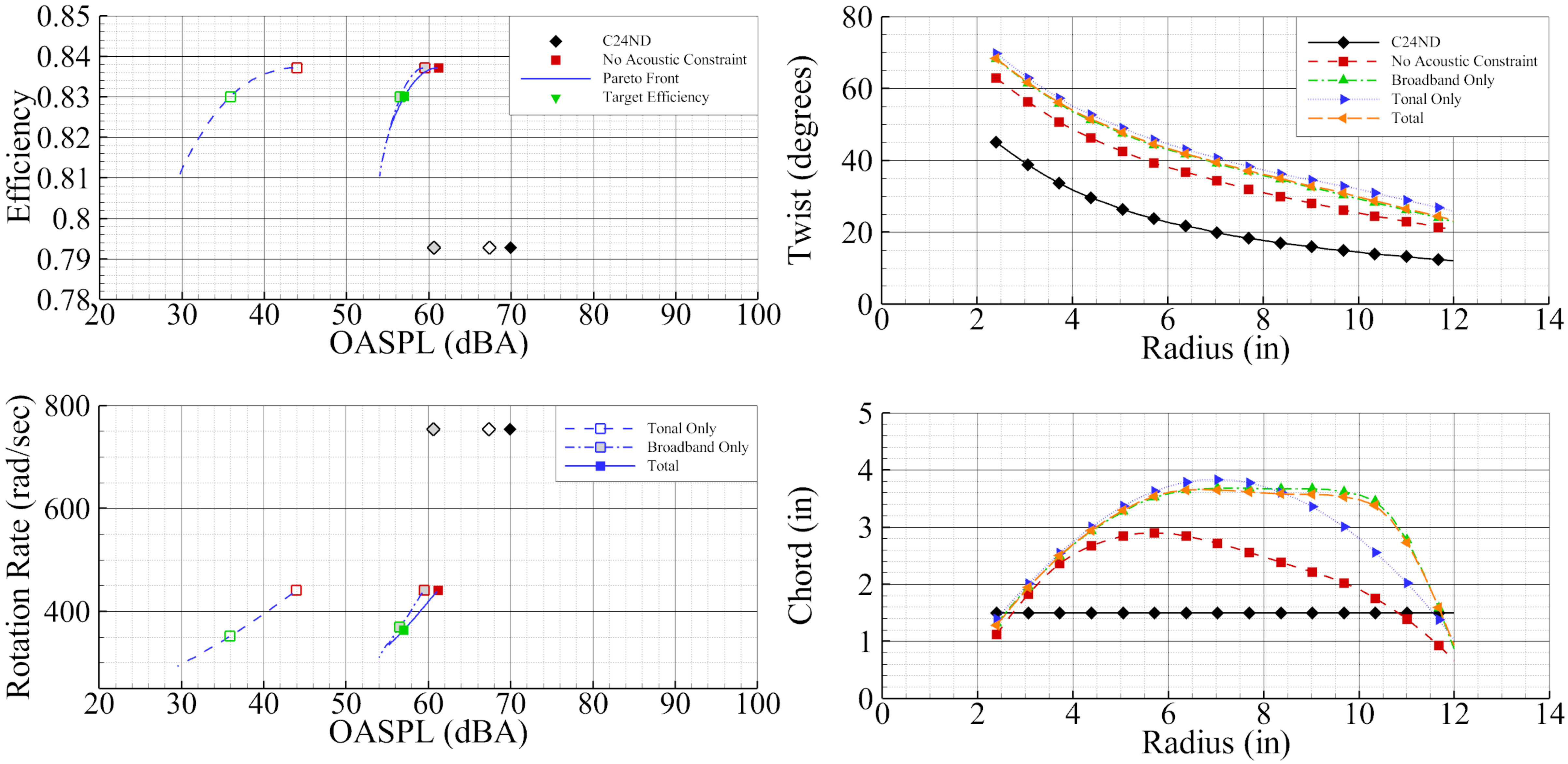






Out-Of-Plane, Weighted

Lopes, Ingraham, "Influence of the Perception, Observer Position, and Broadband Self-Noise on Low-Fidelity UAM Vehicle Perception-Influenced-Design (PID) Optimization," VFS 79th Annual Forum, 2023, https://ntrs.nasa.gov/citations/20230004003



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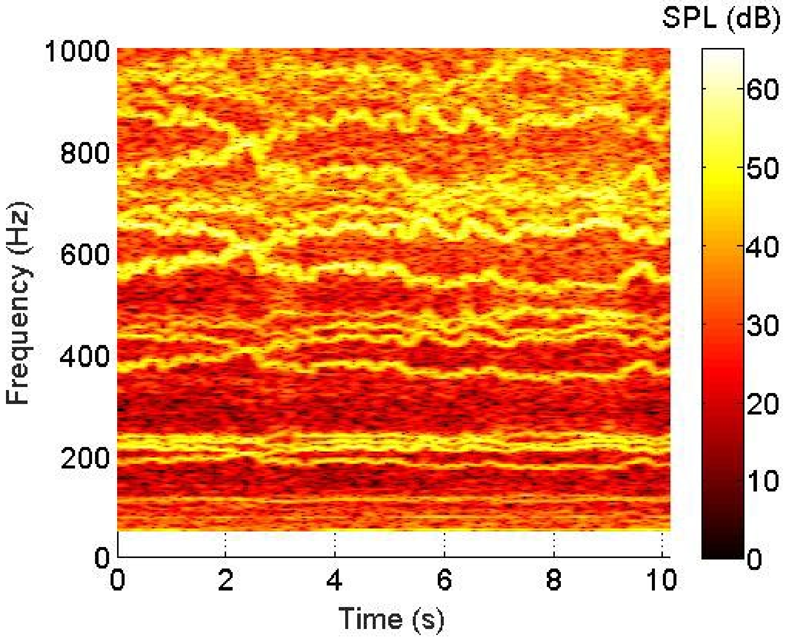
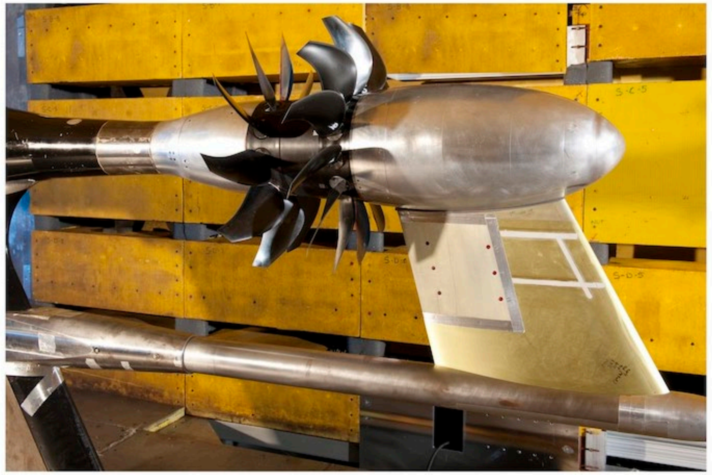
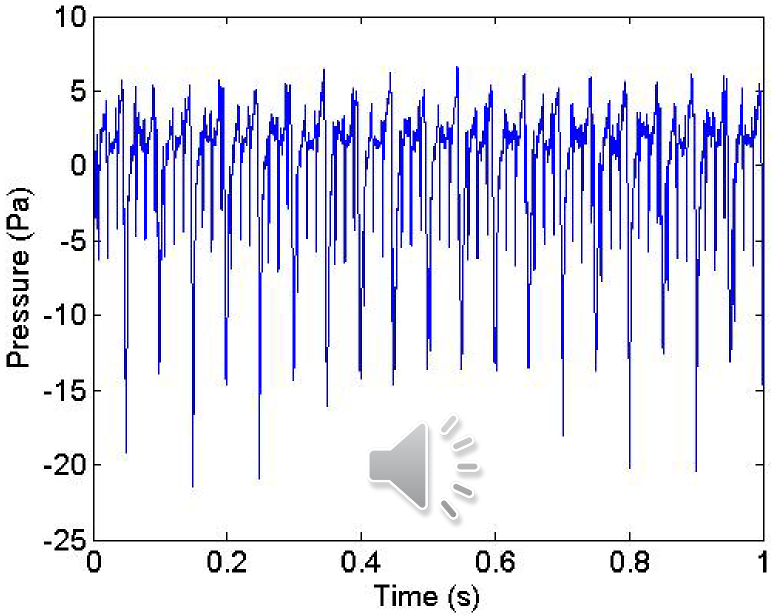
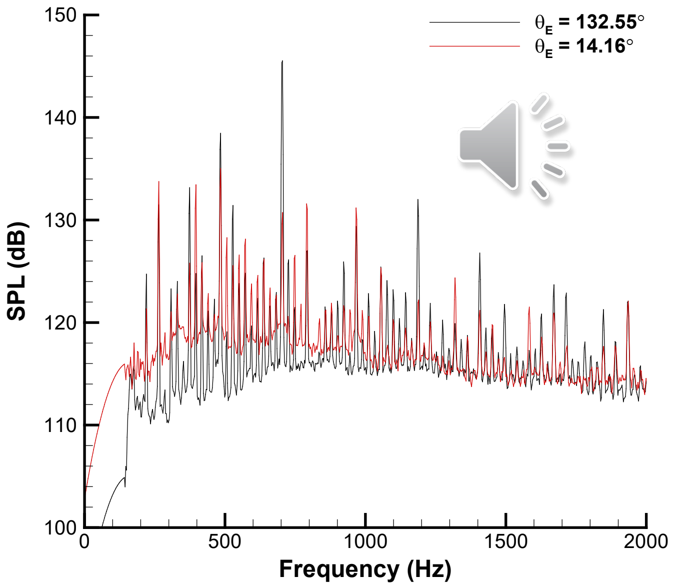
How Well do Certification Metrics Reflect Human Response to this System?



… or to These Systems?







An Axiom

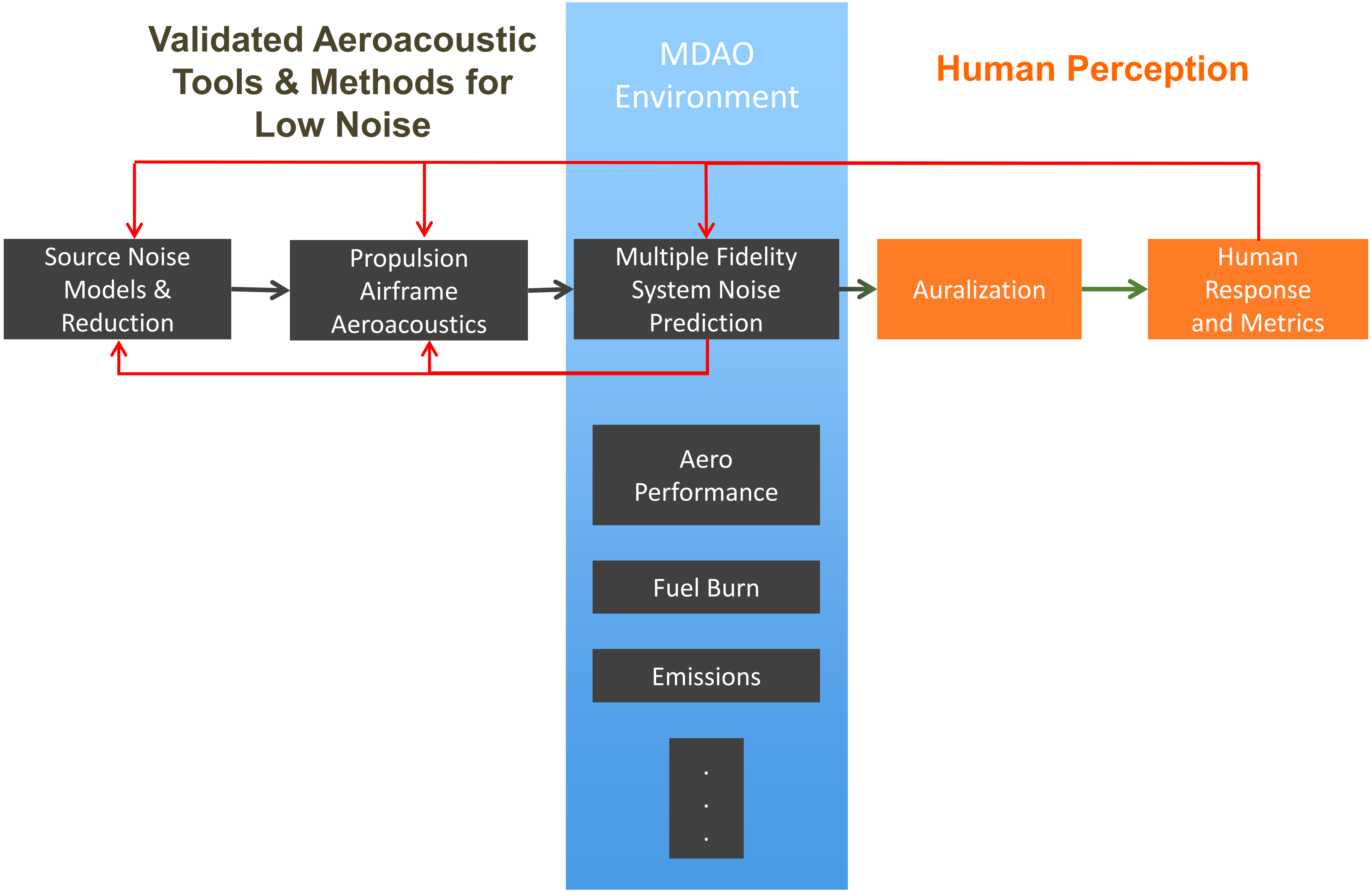
Given that aircraft noise design will continue to be based solely on acoustical factors for the foreseeable future, and

given that current certification requirements are not focused on achieving low-annoyance designs, then

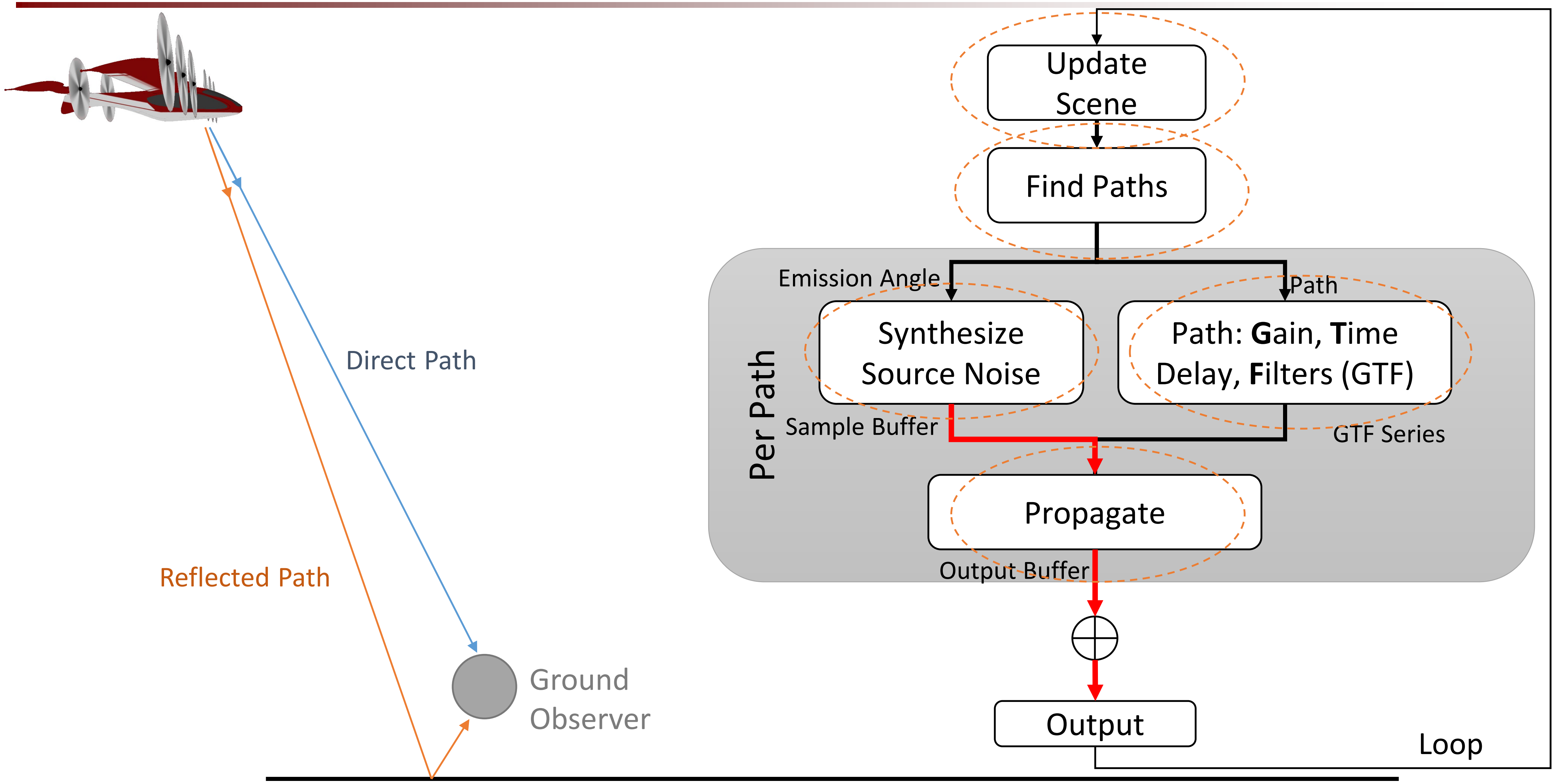
it should be possible to achieve reduced community noise impact by simultaneously meeting noise certification and other design requirements, <u>as well as</u> other acoustic requirements(s), which directly address human response.

We refer to this as Perception-Influenced acoustic Design (PID).

Perception-Influenced Acoustic Design



Auralization: Standard Flyover Use Case



Rizzi, Sahai, "Auralization of air vehicle noise for community noise assessment," *CEAS Aeronautical Journal*, 2019, https://doi.org/10.1007/s13272-019-00373-6/

NAF and Advanced Plugin Library

NAF (https://software.nasa.gov/software/LAR-18541-1)
NAF APL (https://software.nasa.gov/software/LAR-19278-1)

Programs
- NAFSNAP: Source Noise and Propagation
- NAFExample
- ANOPP2 Interface Examples
  - Quickstart-modified
  - F1A Synthesis

Path Finder / Traverser
- Straight Line
- Receiver-based

Directivity Loaders
- NetCDF
- TXT (ASCII)
- Plot3D

Synth / Component
- Directivity Loader
- Restart Component
- 1/3 Octave Band
- Narrowband
- Modulated 1/3 OB
- Pure Tone
- Periodic
- Multiple Pure Tone
- F1A Synthesis
- Wave File
- Random

Ground Reflection
- Infinitely Hard Ground
- Delany-Bazley Impedance model

Other
- Postprocessors
  - ANOPP2 Metrics
  - Psychoacoustic Analysis
  - Normalization
- Preprocessor
  - F1A Synth
- Trajectory
  - CSV file - track
  - Higher-order motion file

Atmosphere
- Parameter definitions
  - Uniform
  - Isothermal
  - Lapse
  - Balloon File
- Absorption Standard
  - ANSI
  - SAE ARP 866A

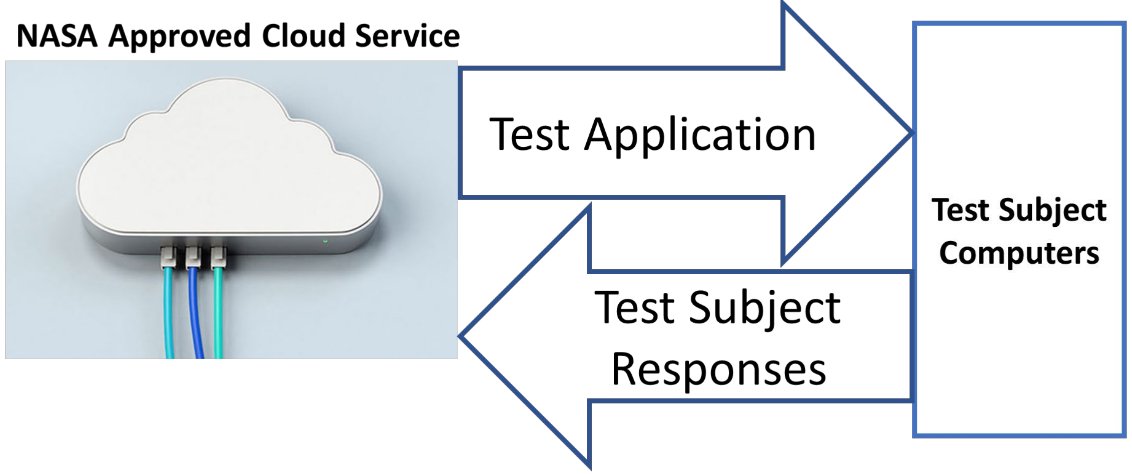
NAF Psychoacoustic Analysis Library now includes sensitivities for loudness and sharpness SQ metrics.

NASA Langley Psychoacoustic Testing Capabilities

Exterior Effects Room (EER)

Interior Effects Room (IER)

Remote Psychoacoustic Testing Platform



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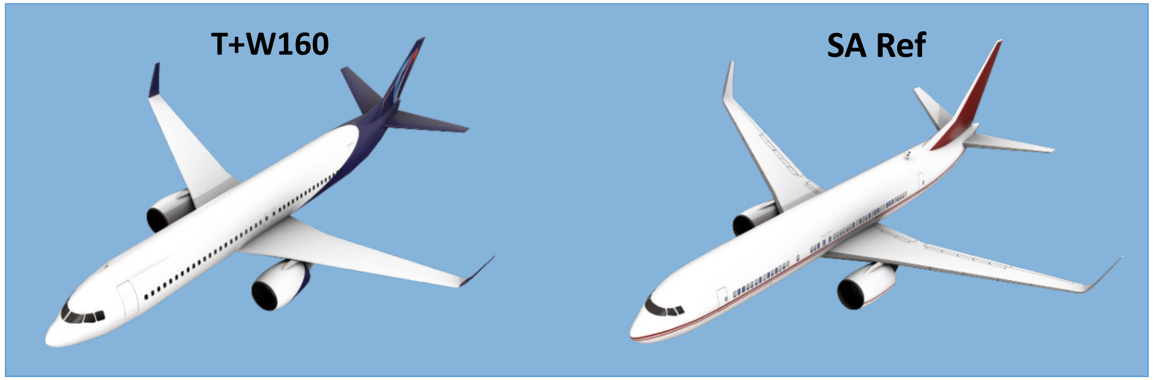
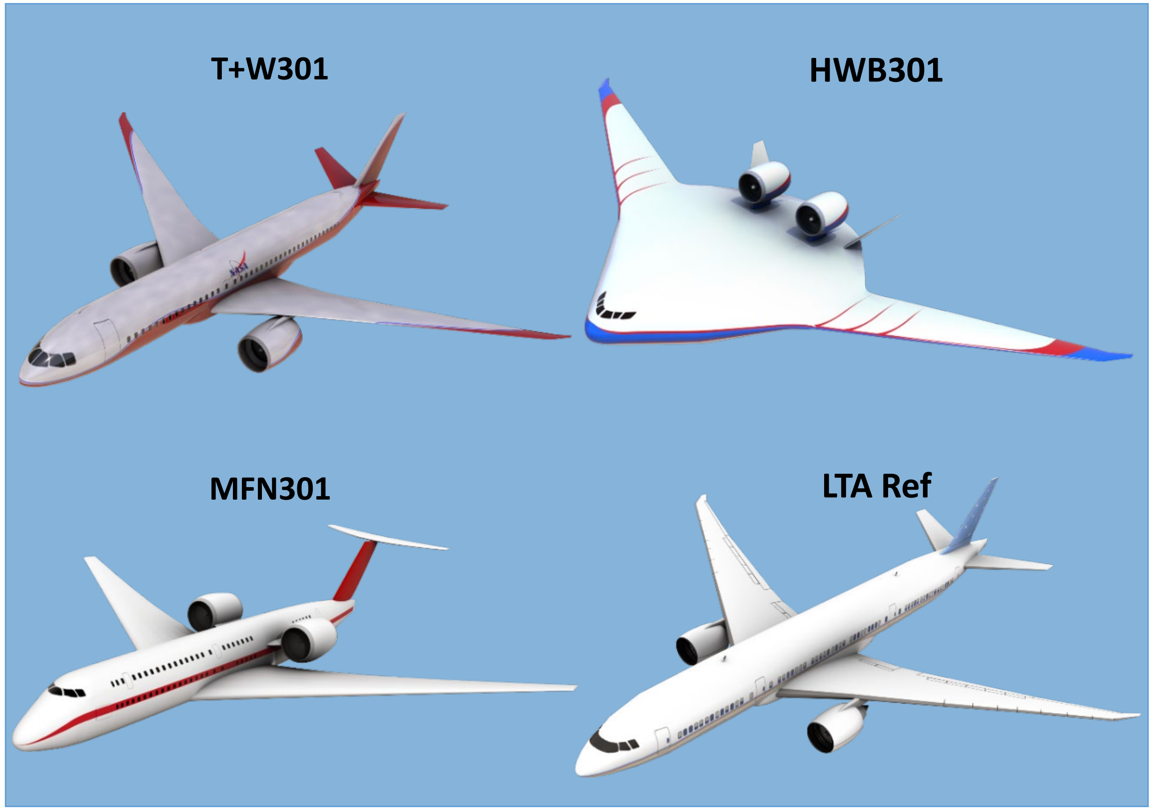
Selected N+2 and Reference Aircraft

Rizzi, Burley, Thomas, "Auralization of NASA N+2 Aircraft Concepts from System Noise Predictions," 22nd AIAA/CEAS Aeroacoustics Conf., AIAA 2016-2906, Lyon, 2016, https://doi.org/10.2514/6.2016-2906.

- Single-Aisle Class
  (160 PAX, 2875 nm)
  - N+2 T&W Configuration
    - UHBR GTF
  - Ref T&W Configuration
    - 737-800, CFM56-like



- Large Twin-Aisle Class
  (301 PAX, 7500 nm)
  - T&W Configuration
    - UHBR direct drive
    - UHBR GTF
  - HWB Configuration
    - UHBR GTF
  - MFN Configuration
    - UHBR GTF
  - Ref T&W Configuration
    - 777-200LR, GE90-110B- like

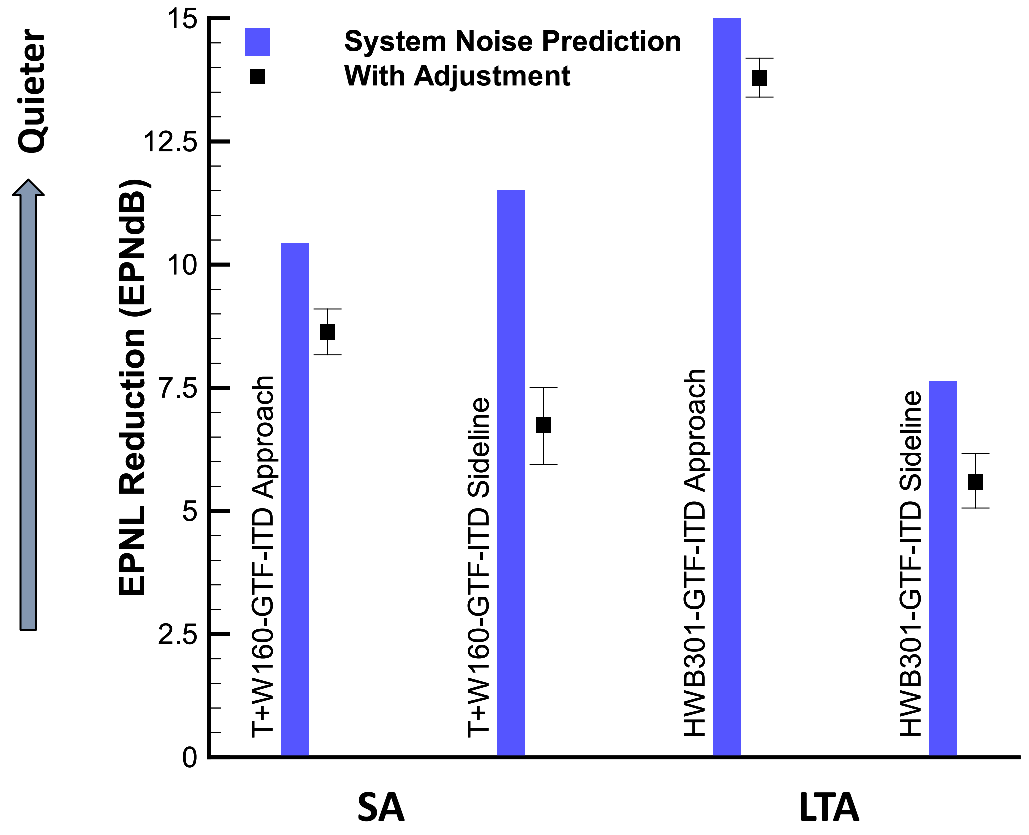


Example – LTA reference & HWB301-GTF-ITD (Sideline)

Psychoacoustic Test Results

Rizzi, Christian, "A psychoacoustic evaluation of noise signatures from advanced civil transport aircraft," 22nd AIAA/CEAS Aeroacoustics Conf., AIAA 2016-2907, Lyon, 2016, https://doi.org/10.2514/6.2016-2907.

Comparison of EPNL reduction



Psychoacoustics Test Results

- Calculated EPNL significantly overestimates perceived differences
  - Large twin aisle HWB: 1.2 dB (approach) and 2 dB (sideline).
  - Single aisle T&W: 1.8 dB (approach) and 4.8 dB (sideline).
- Differences at each cert. point are on the order of cumulative differences of 1-2 EPNdB noise reduction associated with soft vane, partial main gear fairing, and MDOF liners.

Even for N+2 aircraft that sound similar to today's reference aircraft, there is a significant component of annoyance that is not captured by PNLT & EPNL.

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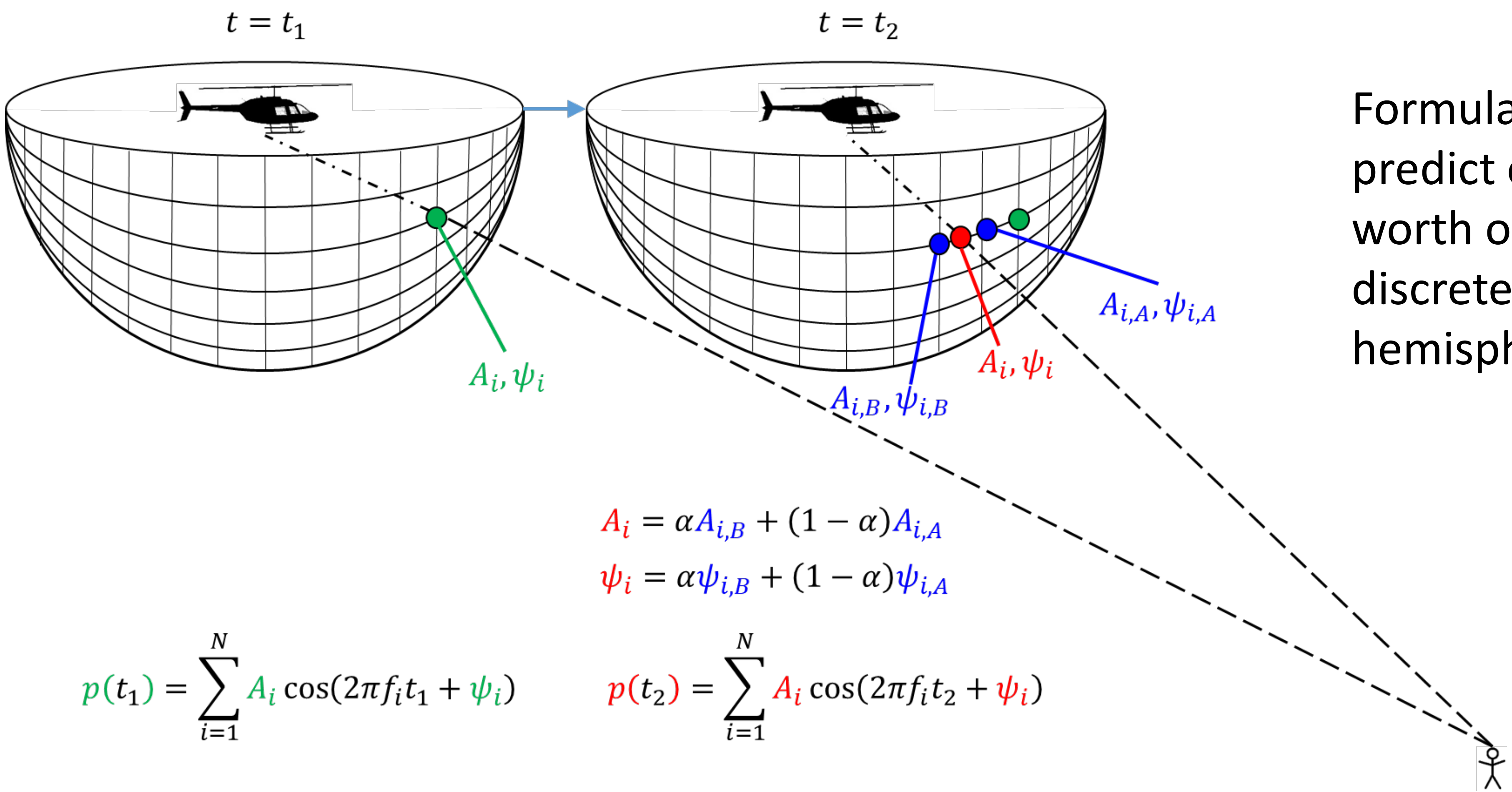
Urban Air Mobility

- Auralization Developments
  - F1A Synthesis
  - Modulated Broadband Synthesis
- Psychoacoustic Studies

Additive Synthesis of Loading and Thickness Noise



Formulation 1A (F1A) used to predict one blade passage worth of sound pressures at discrete set of points on hemisphere

$$A_i = \alpha A_{i,B} + (1-\alpha) A_{i,A}$$

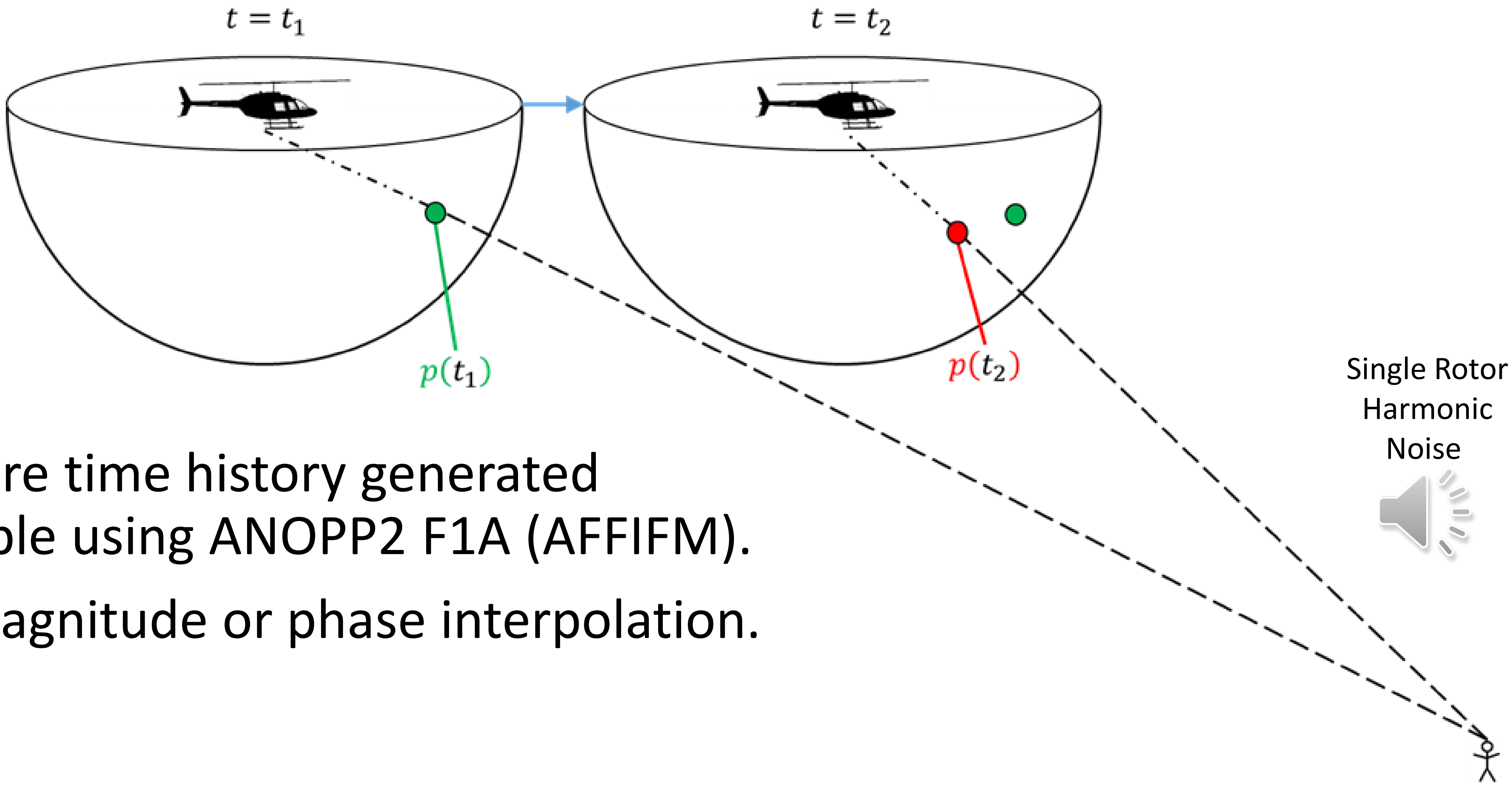
$$\psi_i = \alpha \psi_{i,B} + (1-\alpha) \psi_{i,A}$$

$$p(t_1) = \sum_{i=1}^{N} A_i \cos(2\pi f_i t_1 + \psi_i) \qquad p(t_2) = \sum_{i=1}^{N} A_i \cos(2\pi f_i t_2 + \psi_i)$$

Interpolation of magnitude and phase over discrete set of source noise predictions may introduce audible artifacts for additive synthesis.

F1A Synthesis

Krishnamurthy, Tuttle, Rizzi, "A Synthesis Plug-in for Steady and Unsteady Loading and Thickness Noise Auralization," 26th AIAA/CEAS Aeroacoustics Conference, AIAA-2020-2597, Virtual Meeting, 2020, https://arc.aiaa.org/doi/10.2514/6.2020-2597.



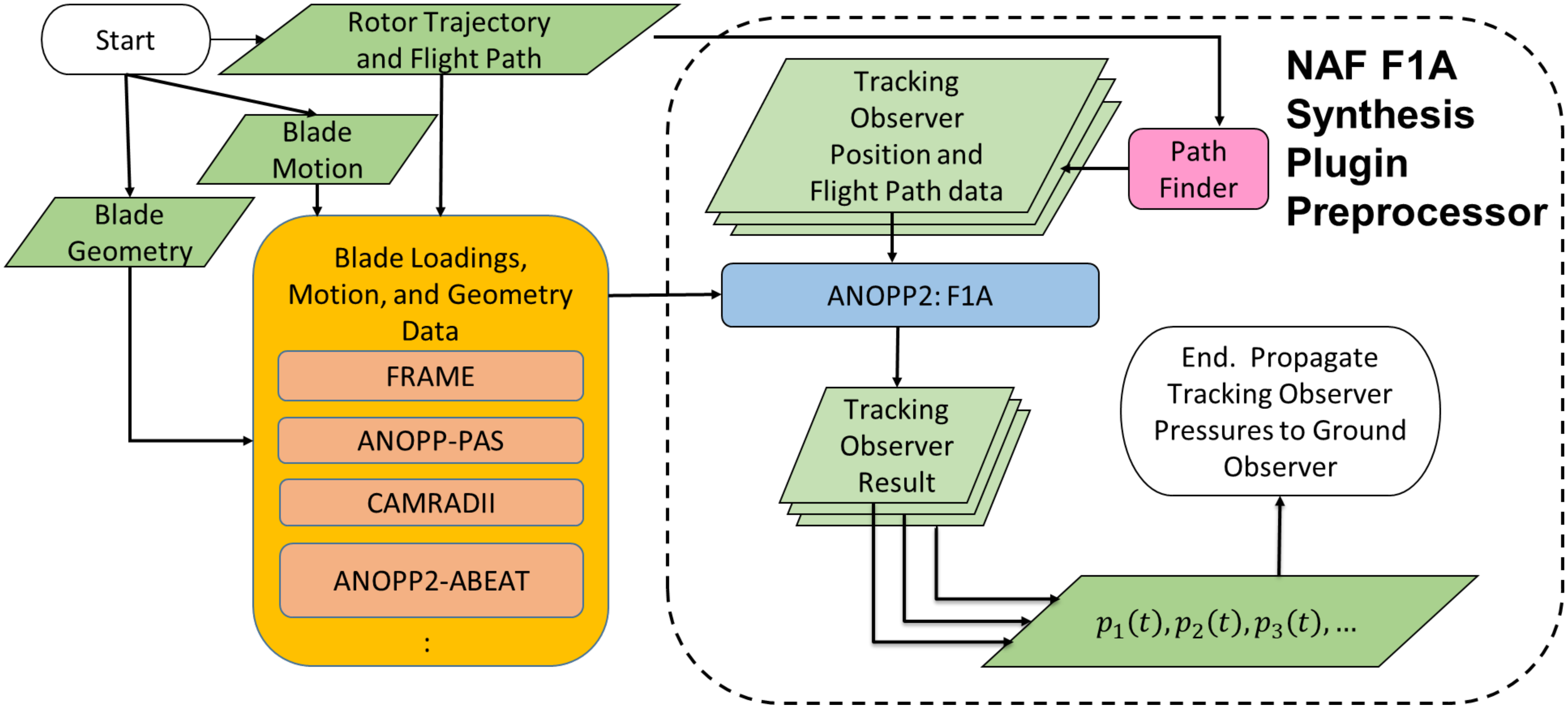
Single Rotor Harmonic Noise

- Acoustic pressure time history generated sample by sample using ANOPP2 F1A (AFFIFM).
- No harmonic magnitude or phase interpolation.

Can be applied to steady and unsteady periodic and unsteady aperiodic sound synthesis.

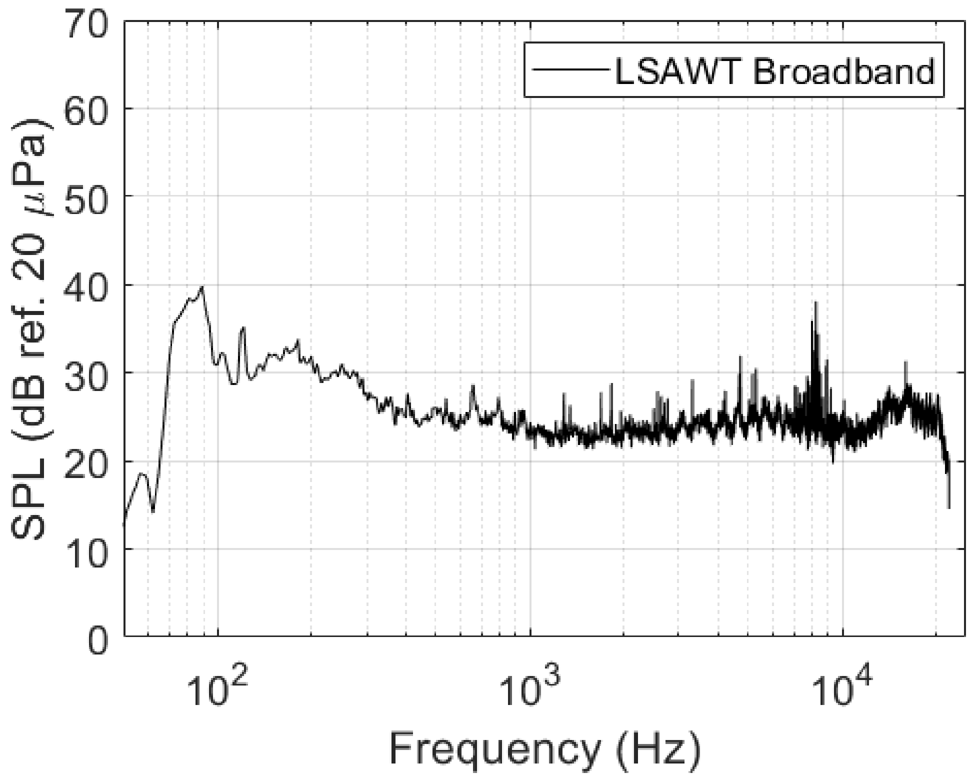
NAF F1A Synthesis Plugin

Krishnamurthy, Tuttle, Rizzi, "A Synthesis Plug-in for Steady and Unsteady Loading and Thickness Noise Auralization," 26th AIAA/CEAS Aeroacoustics Conference, AIAA-2020-2597, Virtual Meeting, 2020, https://arc.aiaa.org/doi/10.2514/6.2020-2597.



Modulated Broadband Noise

Rizzi, Zawodny, Pettingill, "On the use of Acoustic Wind Tunnel Data for the Simulation of sUAS Flyover Noise", 25th AIAA/CEAS Aeroacoustics Conference, AIAA-2019-2630, Delft, 2019, https://doi.org/10.2514/6.2019-2630.

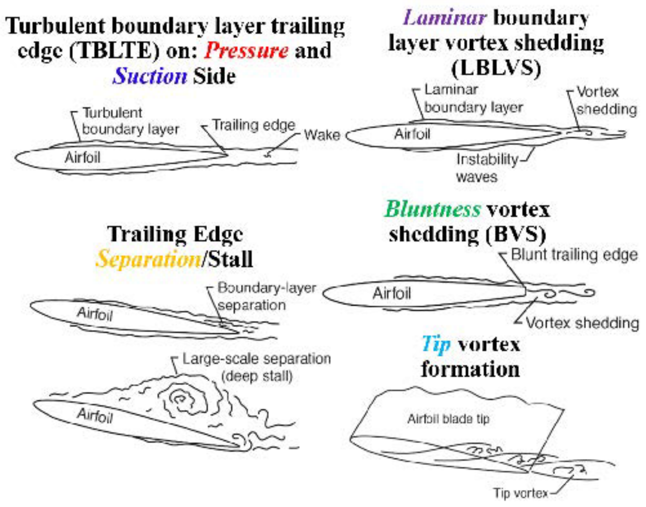


Synthesis

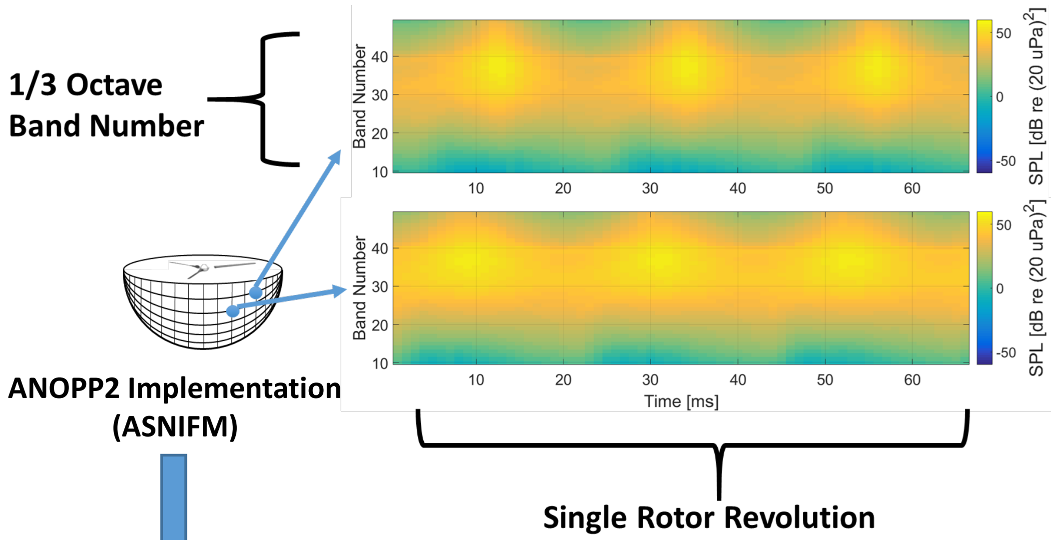
LSAWT

Modulations (at BPF) in tunnel data not captured in time-averaged SPL data.

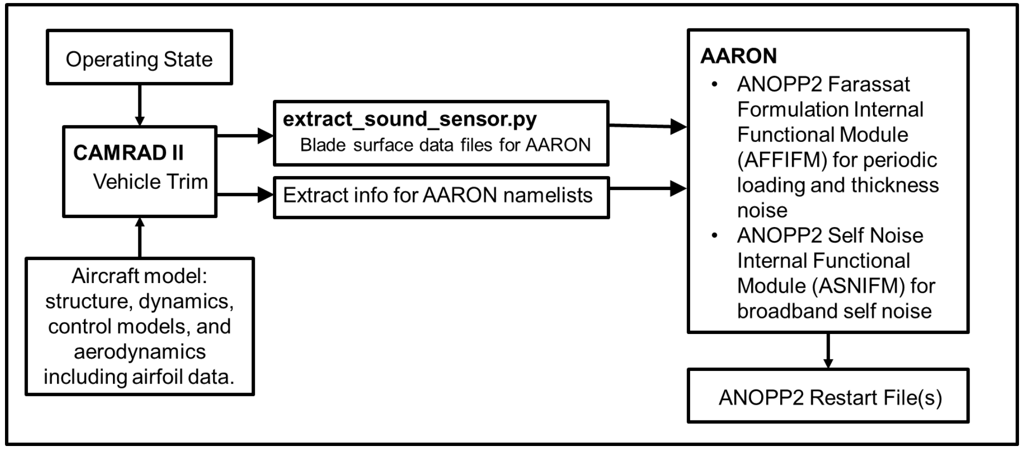
ANOPP2 and AARON Development & Lab Validation



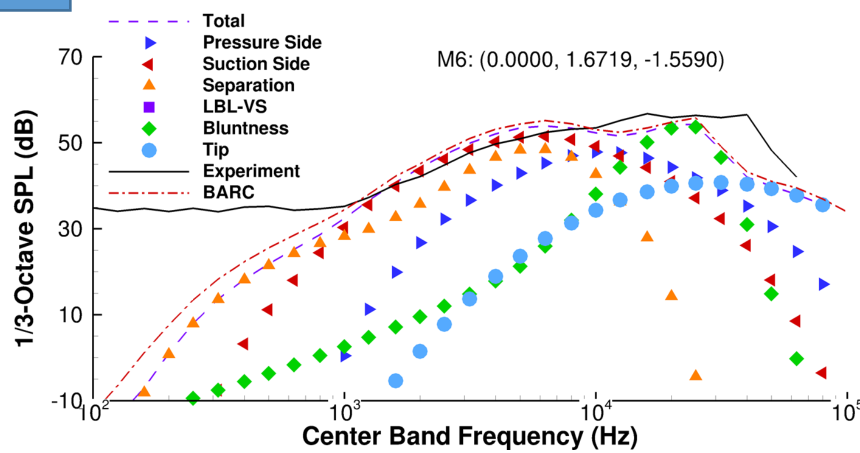
Brooks, Pope, Marcolini, “Airfoil Self-Noise and Prediction,” NASA-RP-1218, 1989, https://ntrs.nasa.gov/citations/19890016302.

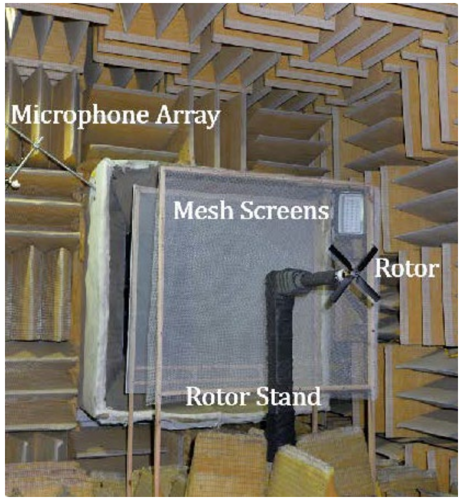


pyaaron



Lab Validation

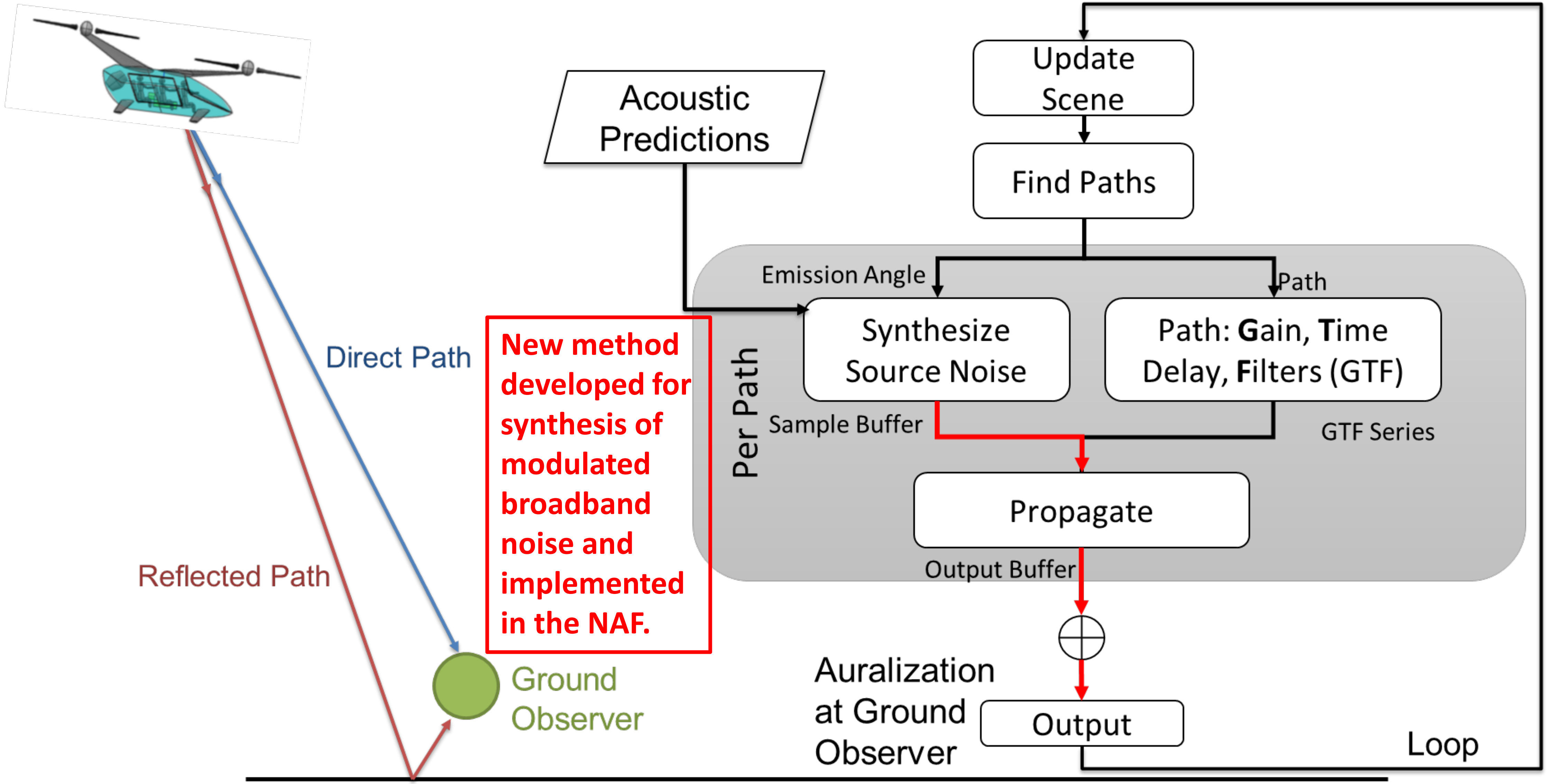




Pettingill, Zawodny, Thurman, Lopes, "Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover," 2021 AIAA SciTech Forum, AIAA 2021-1928, Virtual Meeting, 2021, https://doi.org/10.2514/6.2021-1928.

NAF Modulated Broadband Plugin

Krishnamurthy, Aumann, Rizzi, "A Synthesis Plugin for Auralization of Rotor Self Noise," 27th AIAA/CEAS Aeroacoustics Conference, AIAA 2021-2211, Virtual Meeting, 2021, https://doi.org/10.2514/6.2021-2211.



New method developed for synthesis of modulated broadband noise and implemented in the NAF.

Quadrotor Flyover

Single Rotor Self Noise

Psychoacoustic Studies Utilizing Auralizations

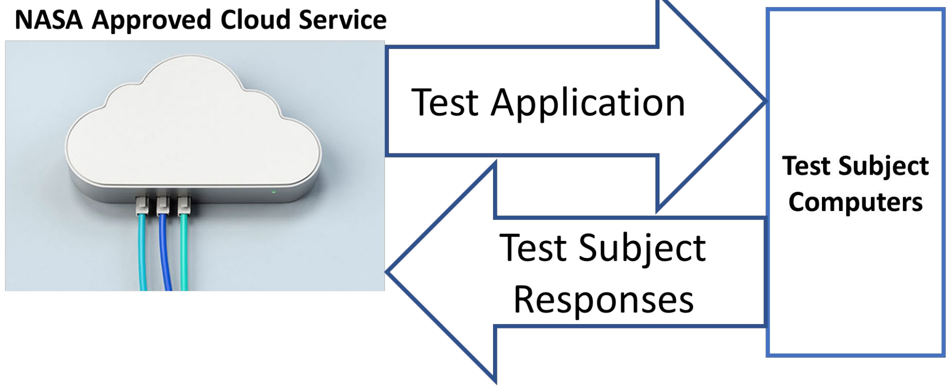
* Boucher, et al., “A Psychoacoustic Test for Urban Air Mobility Vehicle Sound Quality,” SAE TP 2023-01-1107, 2023

** Krishnamurthy, et al. , "Remotely Administered Psychoacoustic Test for sUAS Noise to Gauge Feasibility of Remote UAM Noise Study," SAE TP 2023-01-1106, 2023.

- Test of UAM Sound Quality (completed July 2022*)
  - Objective: Investigate how annoyance varies with sound quality.
  - Main Finding: UAM sounds more annoying than reference sound at same level → loudness is not the only factor affecting annoyance.
- Test of Noise and Numbers (completed January 2023)
  - Objective: Investigate how annoyance varies with number of operations and spacing between operations.
  - Main Finding: Scenarios of same average sound level over some time period do not produce equal annoyance → number of events also affects annoyance.
- Test of Detection, Noticeability, and Annoyance (Sept-Oct 2023)
  - Objective: Investigate how annoyance varies in presence of masking noise, e.g., a city soundscape.
  - Main Finding: Most subjects have to notice the sound well above their detection thresholds before they become annoyed.
- Cooperative Human Response Study
  - Objectives: Verify consistency of remote test platform with prior lab results, determine effects of contextual cues, determine response differences by geographic region (Oct 2022**).
  - Objectives: Focus on UAM sounds using anonymized recordings and auralizations to determine differences in annoyance between aircraft, operations, and situational factors (2025).

Exterior Effects Room (EER)

Remote Psychoacoustic Testing Platform



Psychoacoustic Annoyance Models

- Zwicker:

$$PA = N_5\left(1 + \sqrt{w_S^2 + w_{FR}^2}\right)$$

$$w_S = (S - 1.75) \times 0.25 \log_{10}(N_5 + 10), S > 1.75\ Acum$$

$$w_{FR} = \frac{2.18}{N_5^{0.4}}(0.4F + 0.6R)$$

- More:

$$PA = N_5\left(1 + \sqrt{-0.16 + 11.48w_S^2 + 0.84w_{FR}^2 + 1.25w_T^2}\right) \quad w_T = \left((1 - e^{-0.29N_5})^2\left(1 - \mathrm{e}^{-5.49\mathrm{T}}\right)^2\right)$$

- Di:

$$PA = N_5\left(1 + \sqrt{w_S^2 + w_{FR}^2 + w_T^2}\right) \quad w_T = \frac{6.41T}{N_5^{0.52}}$$

- Torija:

$$PA = N_5\left(1 + \sqrt{103.08 + 339.49w_S^2 + 121.88w_{FR}^2 + 77.20w_T^2 + 29.29w_I^2}\right)$$

$$w_T = \left((1 - e^{-0.29N_5})^2\left(1 - \mathrm{e}^{-5.49\mathrm{T}}\right)^2\right) \quad w_I = \frac{0.975}{N_5^{-1.334}}$$

- NASA UAM:

$$PA = N_5\left(1 + \sqrt{w_S^2 + w_{FR}^2 + w_T^2}\right) \quad w_T = \frac{3.2T}{N_5}$$

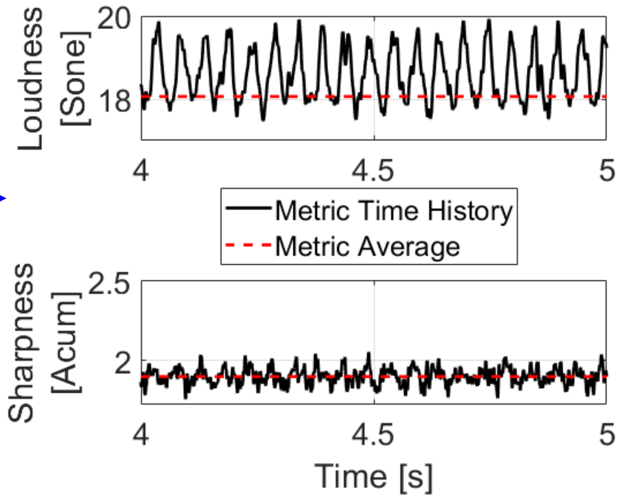
Boucher, et al. , "Toward a Psychoacoustic Annoyance Model for Urban Air Mobility Vehicle Noise," NASA TM-20240003202, 2024.

Sensitivities of Sound Quality Metrics to Rotor Noise Predictions

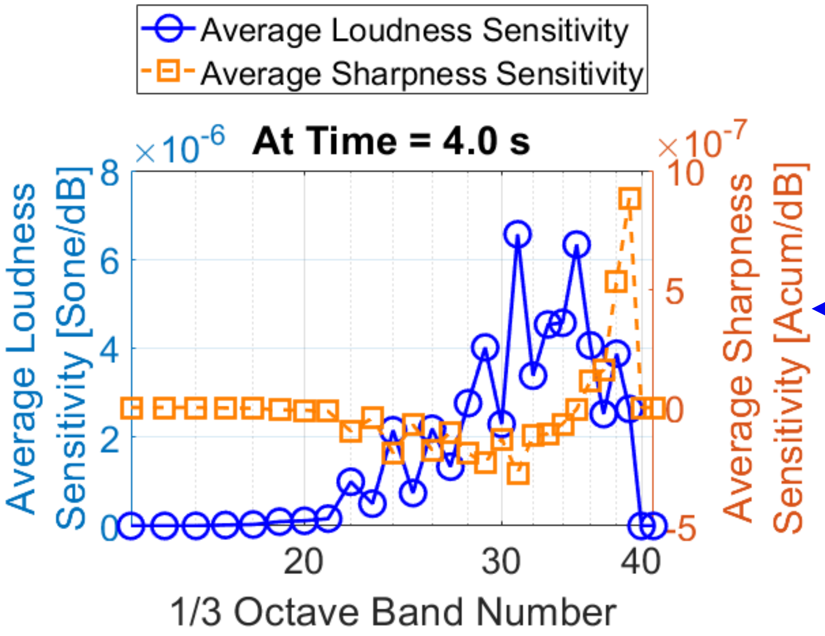
NASA Urban Air Mobility (UAM) Quadrotor Reference Vehicle

Propagate hovering rotor noise to observer 276 ft away

Rotor Noise 1/3 Octave Band Time History



Compute metric sensitivities to 1/3 octave band magnitudes through backwards differentiation



Current effort: propagate sensitivities to rotor design parameters and generate sharpness/loudness-optimized rotor

Outline

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  - Psychoacoustic Testing
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  - Contrarotating Open Rotor Propulsors
  - Advanced Subsonic Commercial Transports
  - Urban Air Mobility
- Concluding Remarks

Concluding Remarks

- Design of novel aircraft to simultaneously meet noise certification requirements and achieve desired noise attributes made possible through a perception-influenced design approach.

- Application of PID to development of low-noise operations has great future potential, especially when operations are not concentrated around an airport.

- PID is still in its infancy. It will take further development of tools and methods and successful demonstration of the approach in real-world applications before PID is widely adopted by industry.

Thank You

Selected media files are available for download at:

https://stabserv.larc.nasa.gov/flyover/

The work presented herein was primarily supported by the NASA Advanced Air Vehicles Program and Transformative Aeronautics Concepts Program.

Backup Slides

Outline

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Overcoming the Barrier to Overland Flight

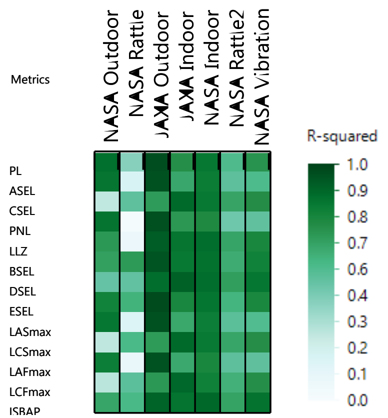
Support development of en route certification standards based on acceptable sound levels

- **New environmental standards are needed to open the market to supersonic flight**
- **An en route noise standard is the biggest challenge**
  - Requires proof of new design approaches
  - Must replace current prohibitions
  - No relevant data exists to define limits
  - Standard must be accepted internationally

Image Credit: Lockheed Martin

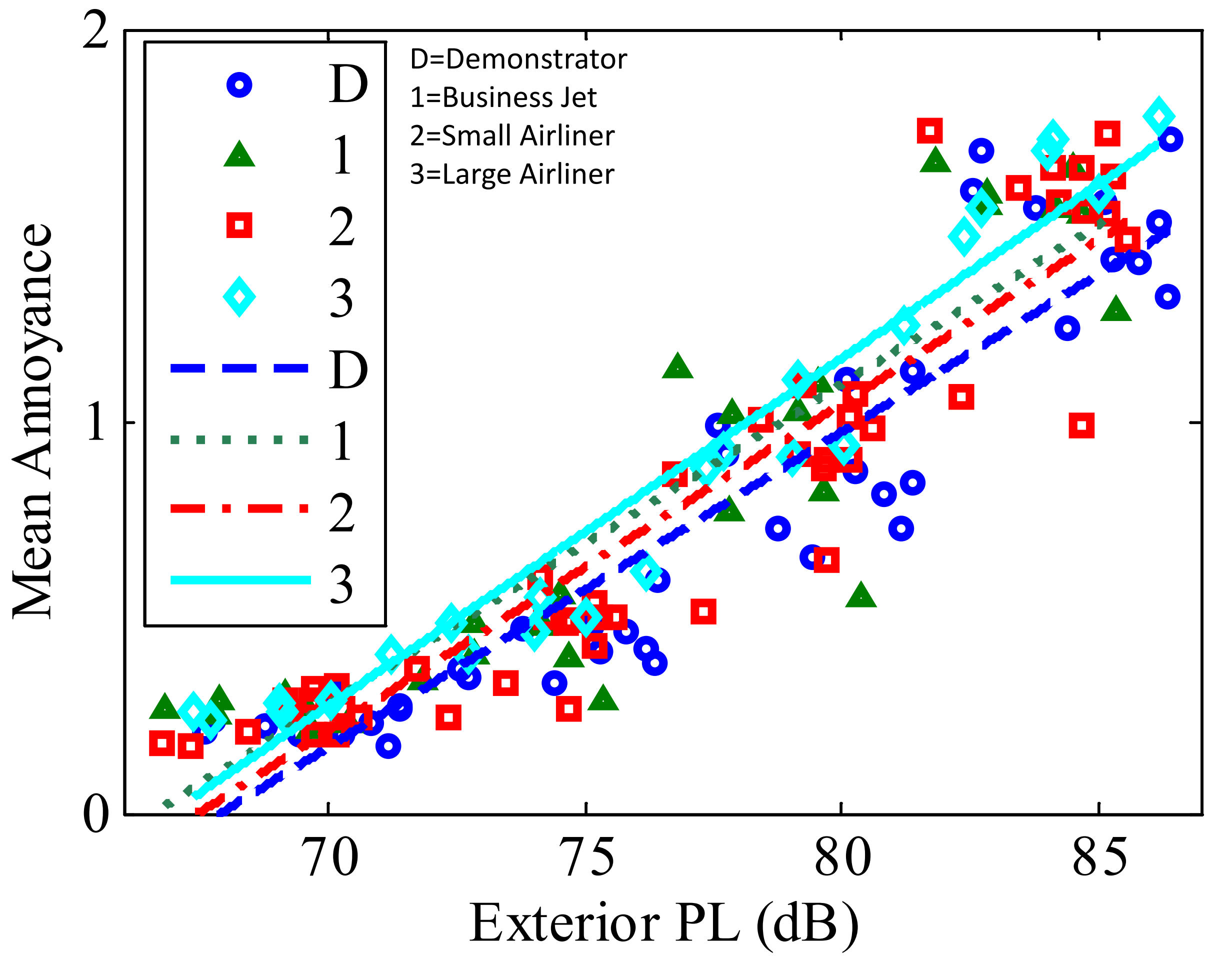
X-59 Contributions from Langley IER

Downselection of noise metrics
for aircraft noise certification



Role of vibration and rattle in annoyance

Confirm traceability of annoyance response to X-59 signature



Quesst Mission Overview

Phase 1: X-59 Aircraft Development

- Detailed design
- Fabrication, integration, ground test
- Checkout flights
- Subsonic envelope expansion
- Supersonic envelope expansion

Phase 2: Acoustic Validation

- In-flight and ground measurements
- Validation of X-59 signature and prediction tools
- Development of acoustic prediction tools for Phase 3

Phase 3: Community Response

- Ground measurements in communities
- Community response surveys
- Multiple campaigns across U.S.
- Data analysis and database delivery

NASA LaRC Acoustics has a technical role supporting planning and measurements for phase 2 and a lead role in planning and execution of data collection for phase 3.

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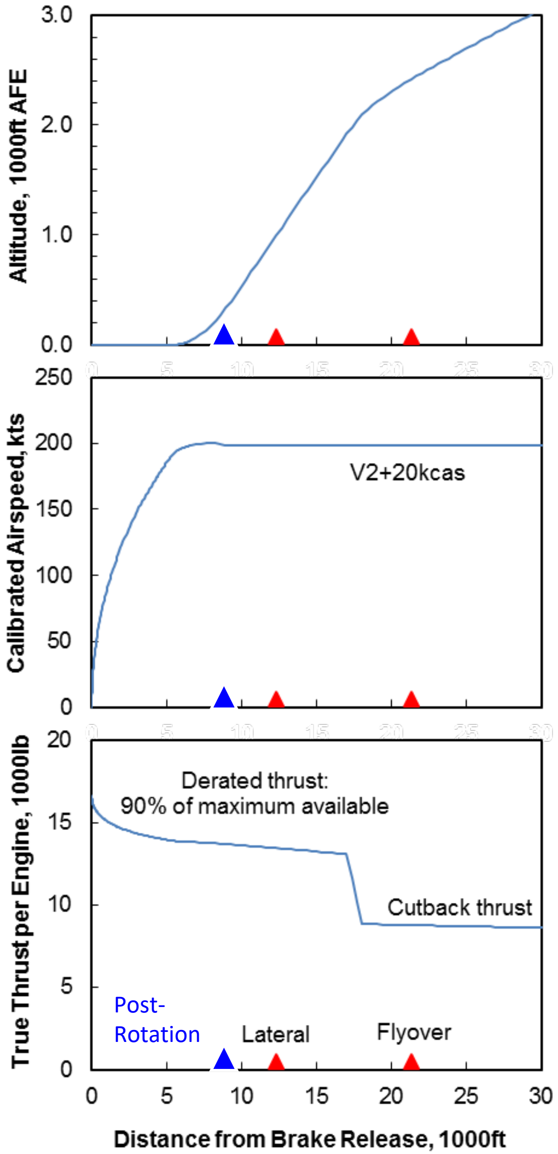
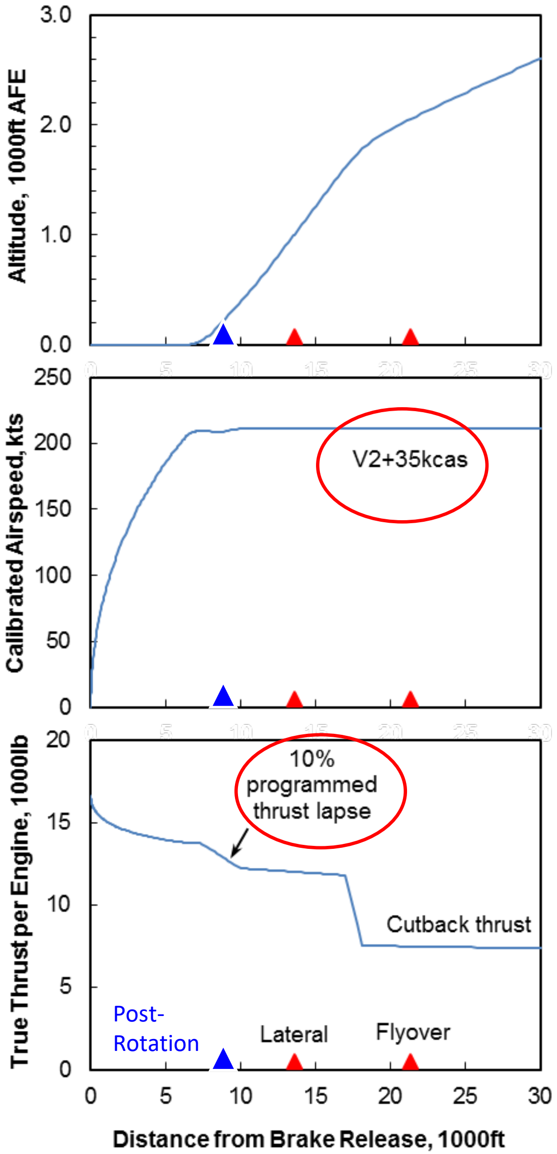
Supersonics – Takeoff Noise

Rizzi, Berton, Tuttle, "Auralization of a Supersonic Business Jet Using Advanced Takeoff Procedures," AIAA-2020-0266, 2020 AIAA SciTech Forum, Orlando, 2020, https://doi.org/10.2514/6.2020-0266.

Standard takeoff reference procedure

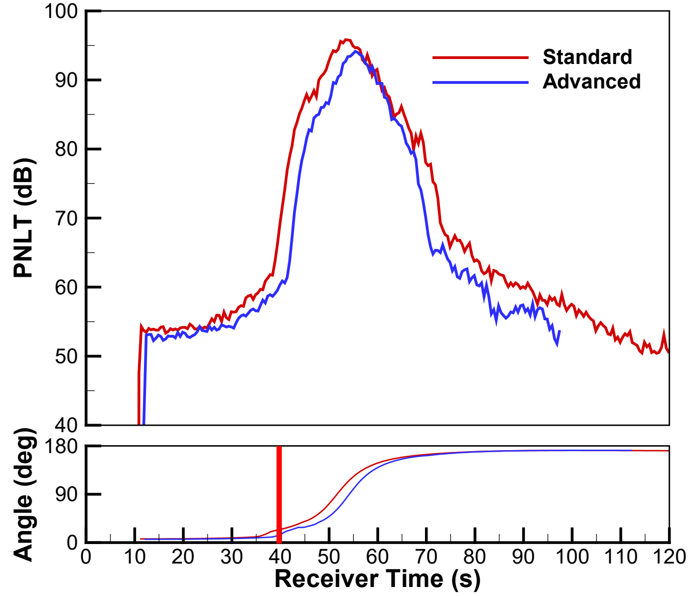




Advanced takeoff procedure uses:

- Higher-speed climbout
- Programmed thrust lapse

Standard vs Advanced Takeoff Procedures

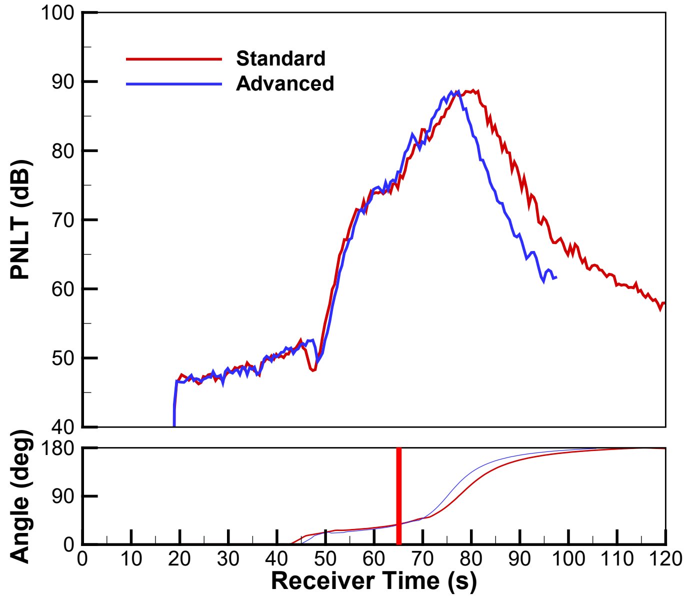


Lateral

Std

Adv

Std/Adv

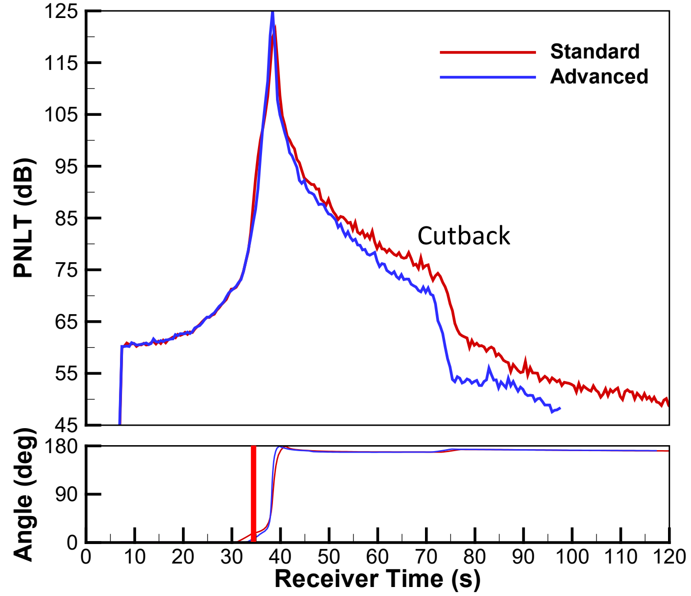


Flyover

Std

Adv

Adv/Std



Post-Rotation

Std

Adv

Measurement Point	Standard / Advanced		
	$PNLT_{max}$ (dB)	Duration (s)	EPNL (dB)
Lateral	95.7 / 94.1	17.0 / 15.5	95.0 / 92.9
Flyover	88.2 / 87.6	21.5 / 17.5	88.6 / 87.1
Post-Rotation	122.4 / 127.1	1.8 / 0.9	111.5 / 113.3

Noise at certification points goes down while noise at other points (post-rotation and in the community) may go up.

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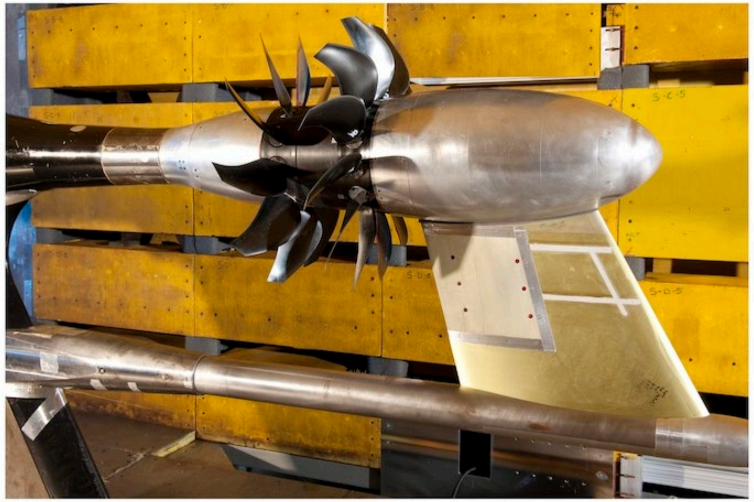
Contrarotating Open Rotor Propulsors

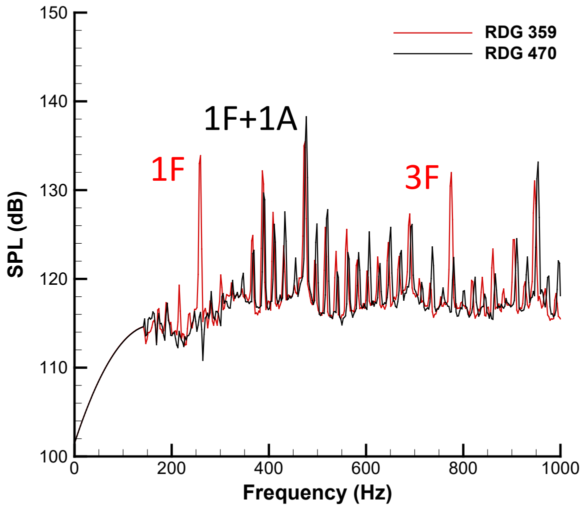
Rizzi, Stephens, Berton, Van Zante, Wojno, Goerig, "Auralization of Flyover Noise from Open-Rotor Engines Using Model-Scale Test Data," AIAA Journal of Aircraft, 2016 https://arc.aiaa.org/doi/10.2514/1.C033223.

Isolated open rotor (RDG 470)

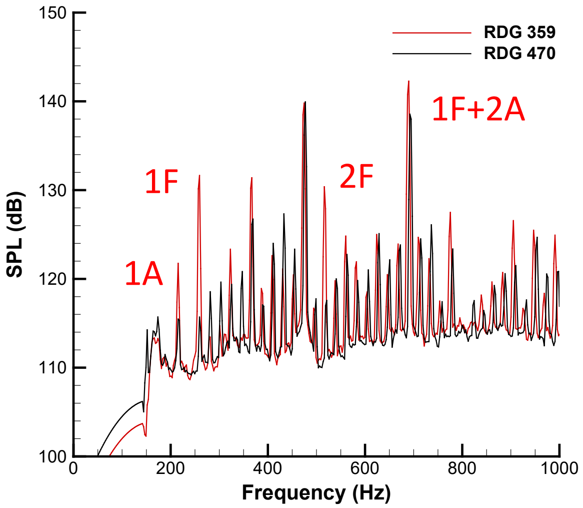
Open rotor with pylon (RDG 359)

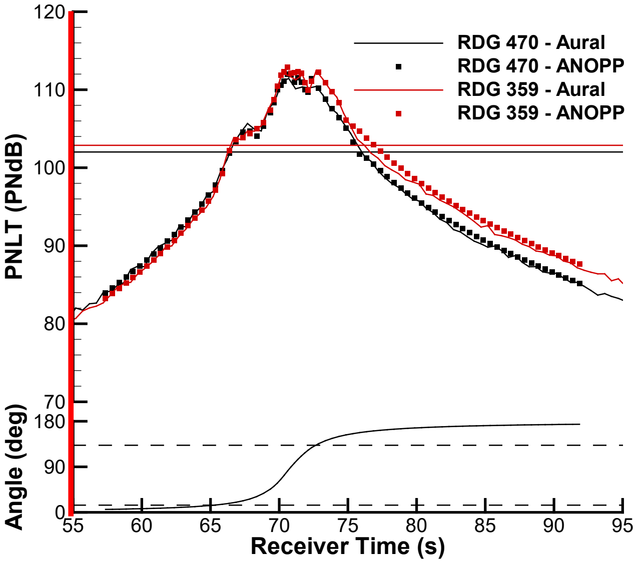


Forward Emission Angle



Aft Emission Angle





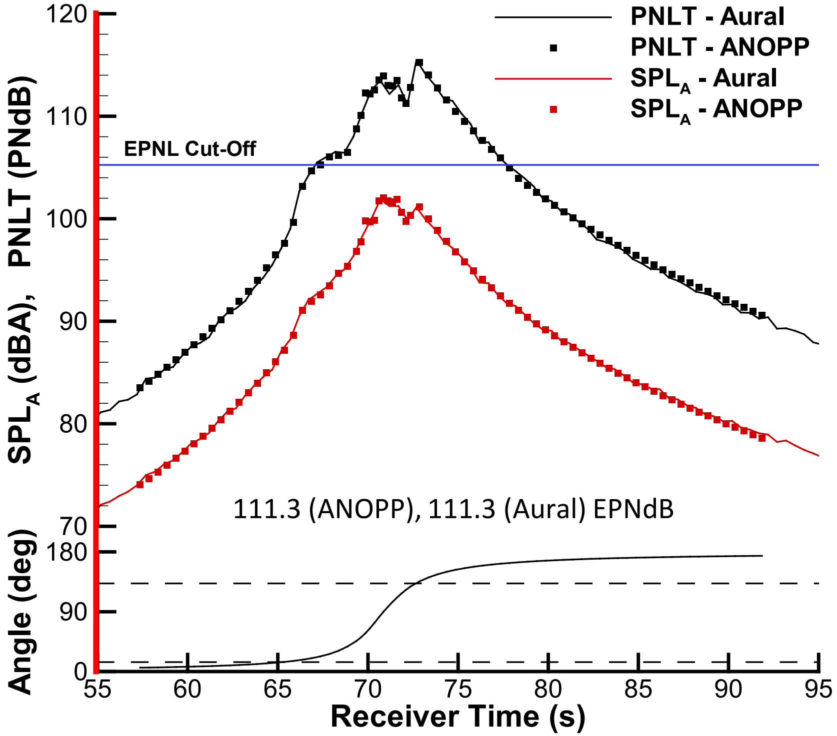
PNLT for two flyovers

108.1 (ANOPP), 108.0 (Aural) EPNdB

109.3 (ANOPP), 109.0 (Aural) EPNdB

Contrarotating Open Rotor – Effect of Blade Set

Historical Blade Set



A-weighted SPL & PNLT
(flush receiver)

Gen-2 Blade Set

100.5 (ANOPP), 100.2 (Aural) EPNdB – Flush
97.6 (ANOPP), 97.5 (Aural) EPNdB – Elevated

Solo
(flush receiver)

Interleaved
with RDG 361
(flush receiver)

Solo
(elevated receiver)

Interleaved
with RDG 361
(elevated receiver)