Characterization of Urban Air Mobility Vehicle Operational Noise and Community Noise Impact

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AIAA Hampton Roads Section
Technical Talk
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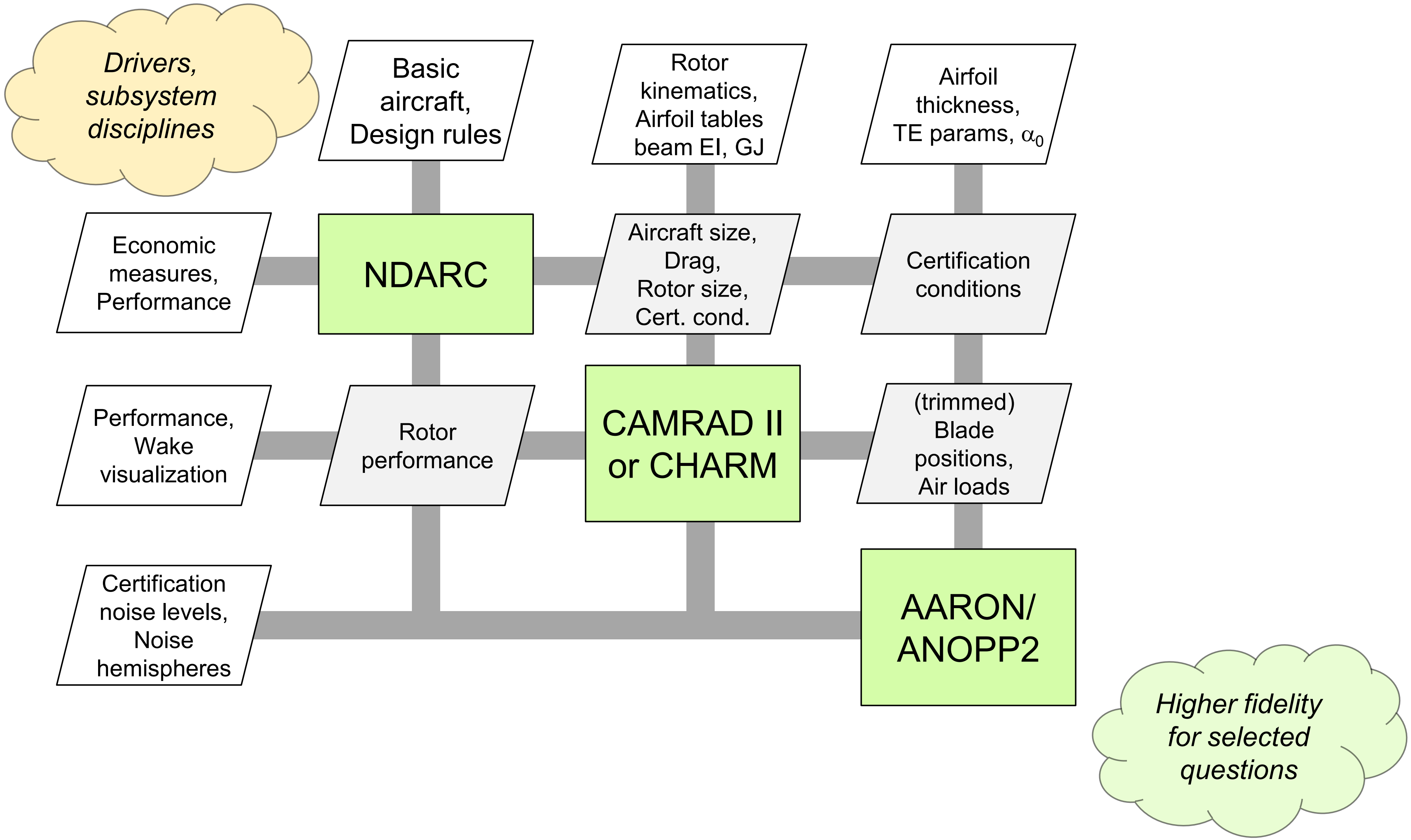
AAM and UAM

- Advanced Air Mobility (AAM) missions characterized by < 300-500 nm range
- Vehicles require increased automation and are likely electric or hybrid-electric
- Rural and urban operations are included
- Missions can be public transportation, cargo delivery, air taxi, or emergency response
- Urban Air Mobility (UAM) is a subset of AAM and is a segment that is projected to have high economic benefit and be the most difficult to develop
  - UAM requires an airspace system to handle high-density operations
  - UAM requires an advanced urban-capable vehicle
  - UAM vehicle variants can target other missions

The Revolutionary Vertical Lift Technology Project and Transformational Tools and Technologies Project are two of seven NASA projects that support the AAM Mission.

NASA Toolchain for Analysis of Noise and Performance of VTOL Vehicles



Example Concept Vehicles

Quadrotor†

- All-electric variant
- 3-bladed rotors
- 6469 lb. GTOW
- V_{max} 109 KTAS

Lift Plus Cruise†

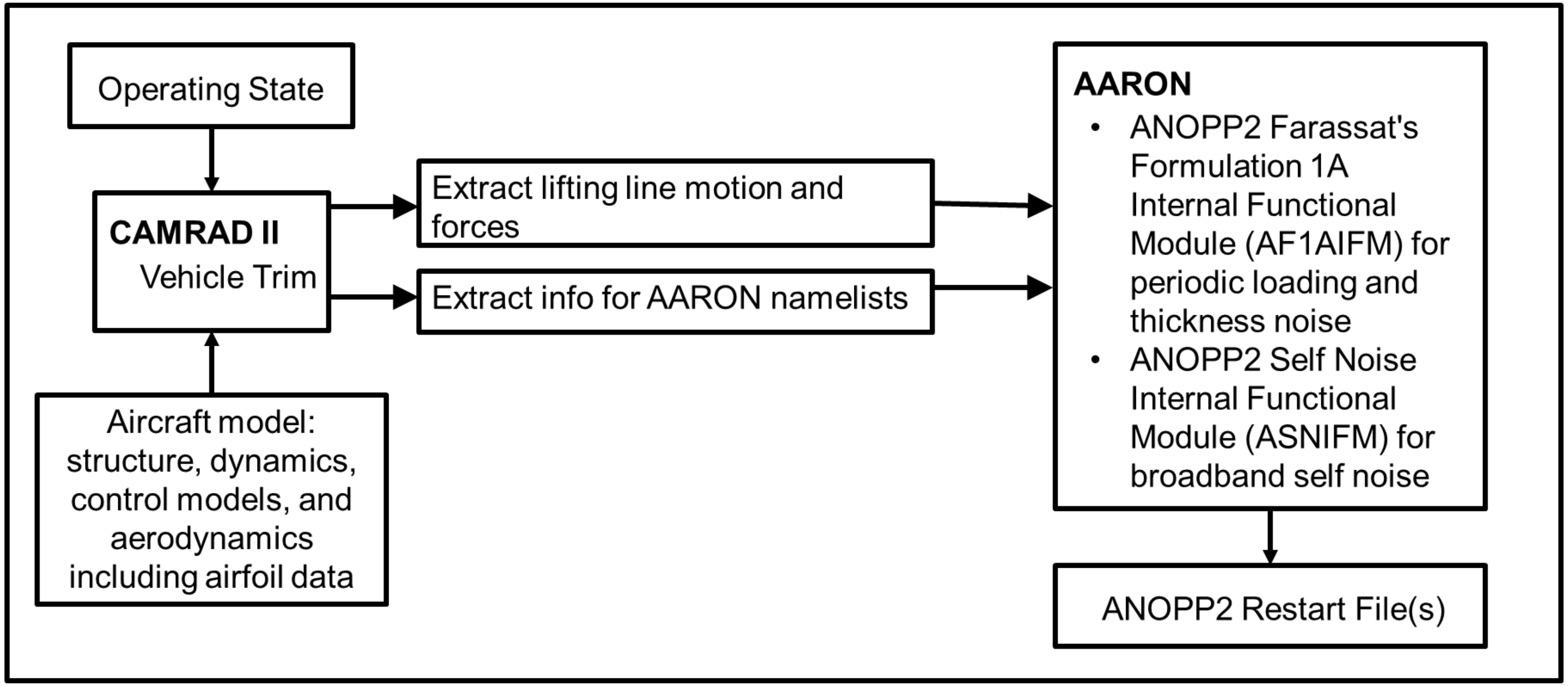
- Turboelectric variant
- (8) 2-bladed lifting rotors
- 3-bladed pusher propeller
- 5903 lb. GTOW
- V_{max} 123 KTAS

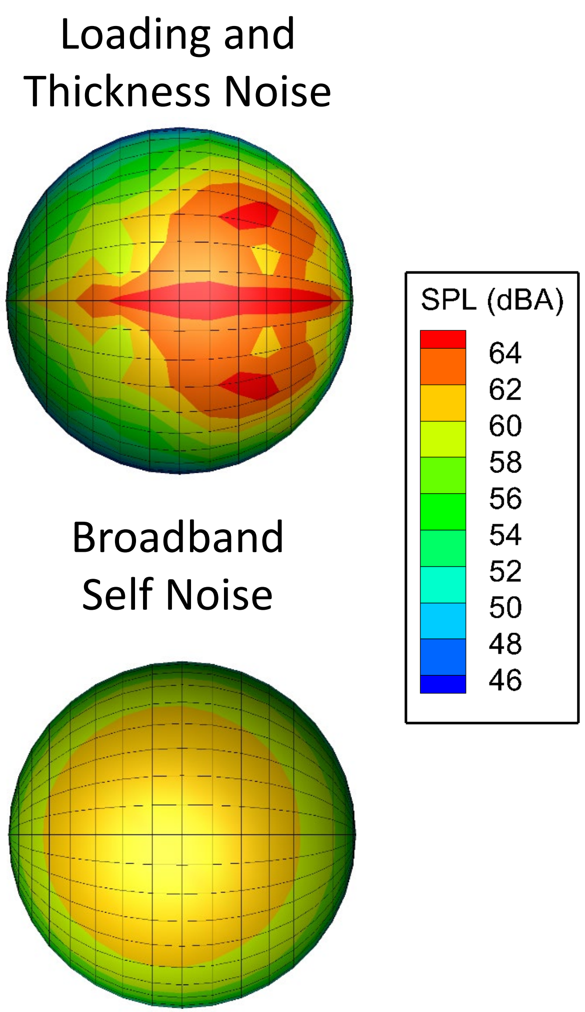
- Both vehicles sized for 1200 lb. payload (up to six passengers) executing a representative mission profile.‡

† Silva et al., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," AIAA Aviation Forum, Atlanta, GA, June 2018, AIAA-2018-3847, https://doi.org/10.2514/6.2018-3847.

‡ Patterson et al., "A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements," *AHS International 74th Annual Forum,* Phoenix, AZ, May 2018

Source Noise Prediction

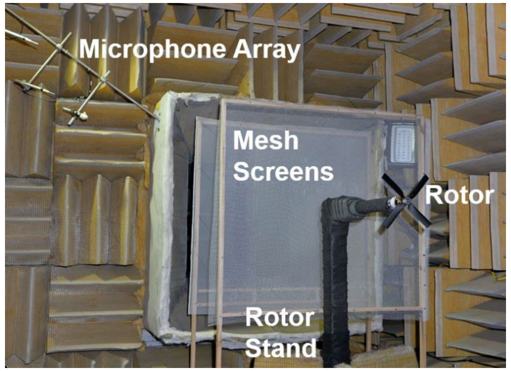




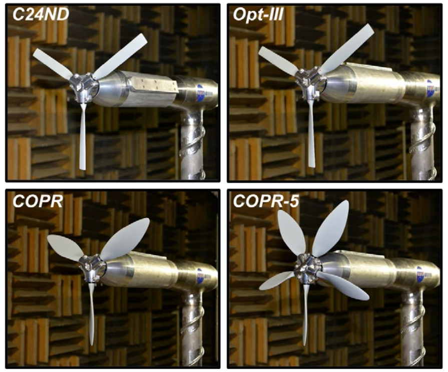
- Quadrotor was trimmed utilizing collective pitch control and constant RPM. The same trim mode was used for all speeds.
- Lift plus Cruise was trimmed utilizing collective pitch control with constant RPM. Three different trim modes used for low, moderate, and high speeds.

Experimental Databases for Validation of Noise Prediction Models

- Recent isolated propellers and rotors



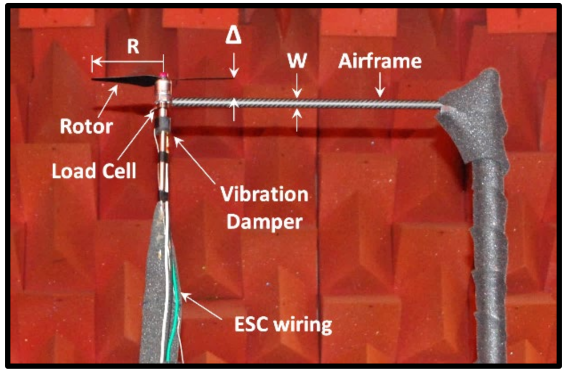
Ideally Twisted Rotor
AIAA-2021-1928



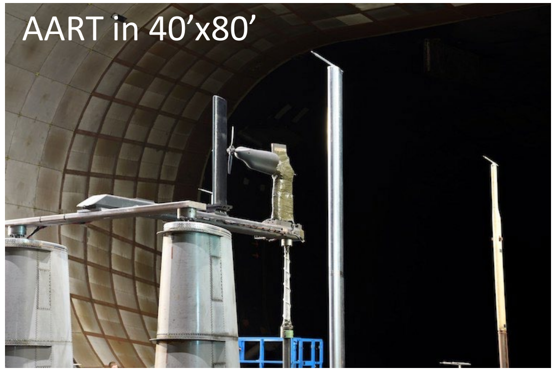
Optimized Proprotor
NASA ATWG Spring and Fall 2022

Cruise and High Lift Propellers
AIAA-2018-3448

- Recent installed propellers and rotors



Rotor-Airframe Interaction
73rd AHS Forum 2017

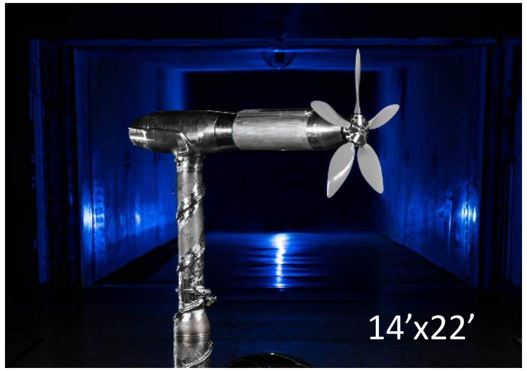


Pusher Configuration
77th VFS Forum 2021

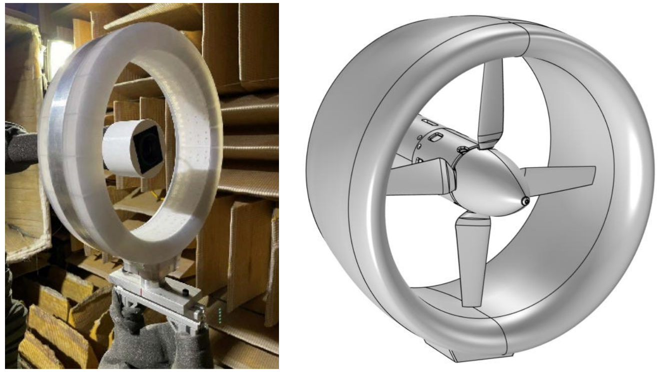
Tractor Configuration
AIAA-2021-0714

Experimental Databases for Validation of Noise Prediction Models

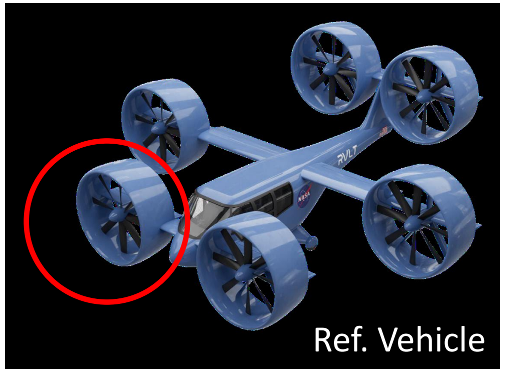
… more installed propellers, rotors, ducted rotors and tiltrotors



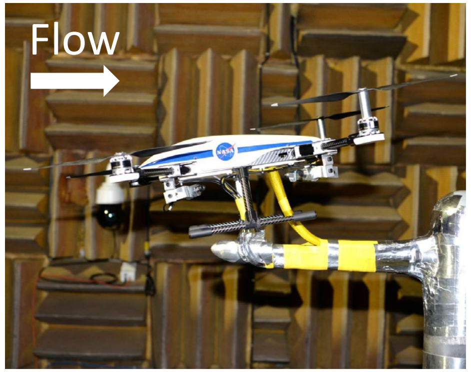
Tilting Proprotor
Aero Performance - Summer 2022
Acoustic Test – 2025



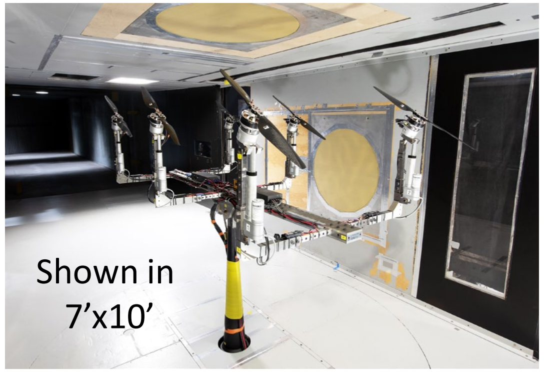
Ducted Speaker & Rotor
NASA ATWG Spring 2022



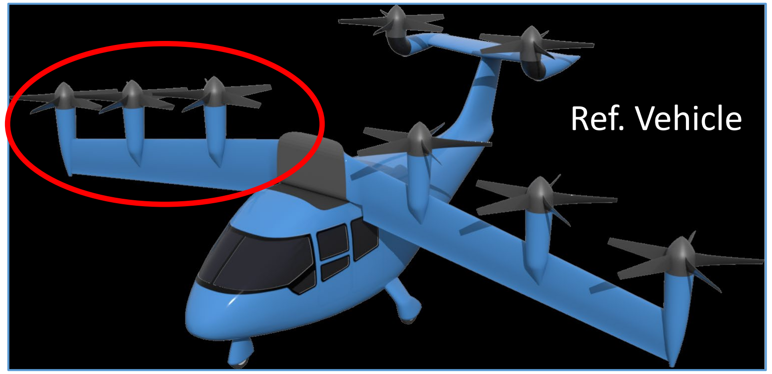
Tilt Duct Acoustic Test (40’x80’)
FY 23-25



Quadrotor – Blade Sets & Standoffs
AIAA-2022-3110 & InterNoise 2022

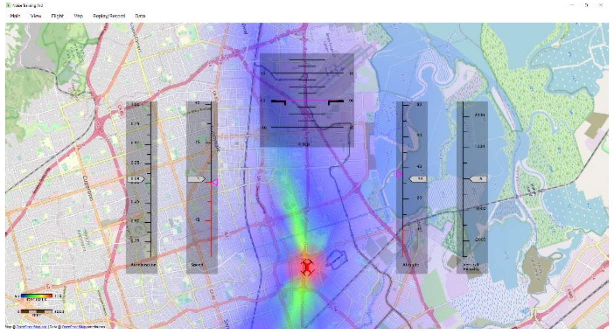


Multirotor Test Bed Acoustic Test (40’x80’)
FY 23-25

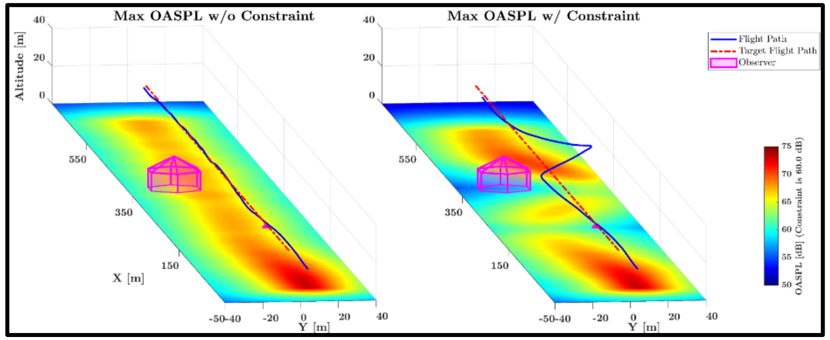


Tiltwing Acoustic Test (14’x22’)
FY 23-25

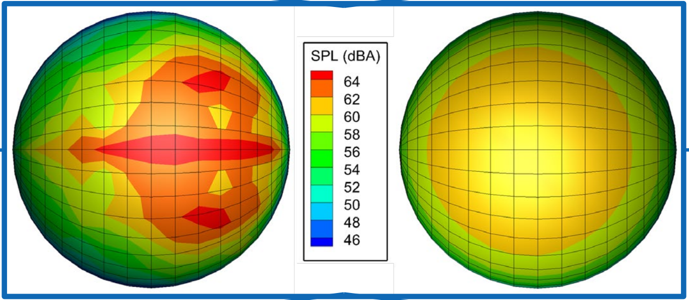
Utilization of Source Noise Predictions



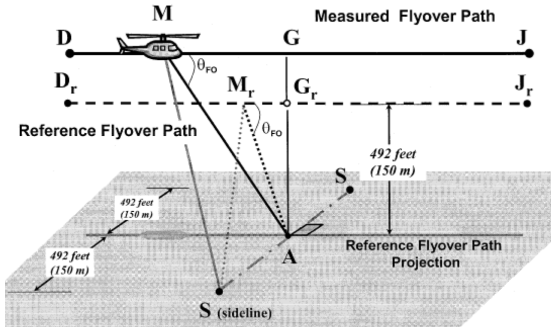
Acoustic Flight Simulator



Acoustically Aware Flight Control

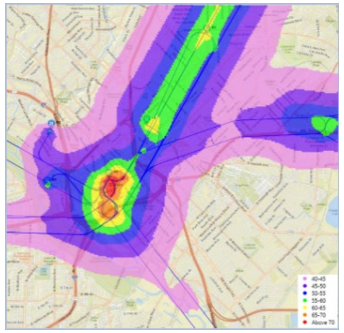


Noise Certification Analyses



https://federalregister.gov/a/04-12069

Operational Fleet Noise Assessments

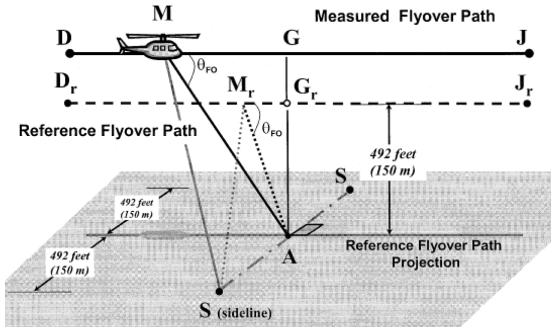


Perception-Influenced Design

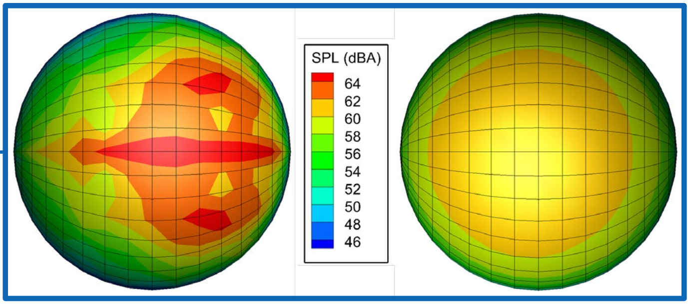
Auralization & Psychoacoustics

Utilization of Source Noise Predictions

Noise Certification Analyses

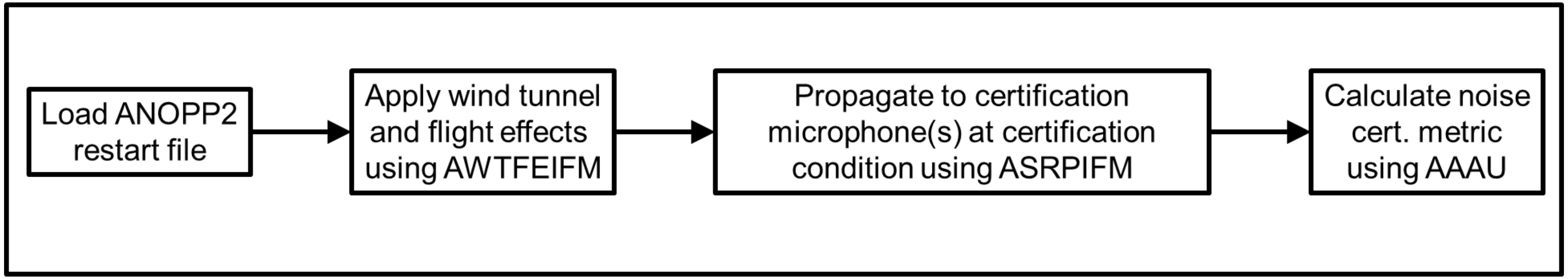


https://federalregister.gov/a/04-12069



Noise Certification

- 14 CFR Part 135 Air Carrier and Operator Certification requires noise type certification
  - 14 CFR Part 36 is the U.S. equivalent to ICAO Annex 16
- Noise certification applicability for AAM
  - Limited to “fitting” vehicle types into existing Part 36
  - Statutory requirement (U.S.C. 44715) to develop noise a noise certification process for all aircraft
  - Long term approach: develop updated certification process informed by research to better understand unique noise characteristics and flight profiles
  - Interim approach: certification on case-by-case basis (rules of particular applicability - RPA) via G-3 Issue Paper and followed by rulemaking actions (notice of proposed rulemaking and final rule)
- NASA process for noise certification analyses



Noise Certification Standards for Helicopters (Appendix H)

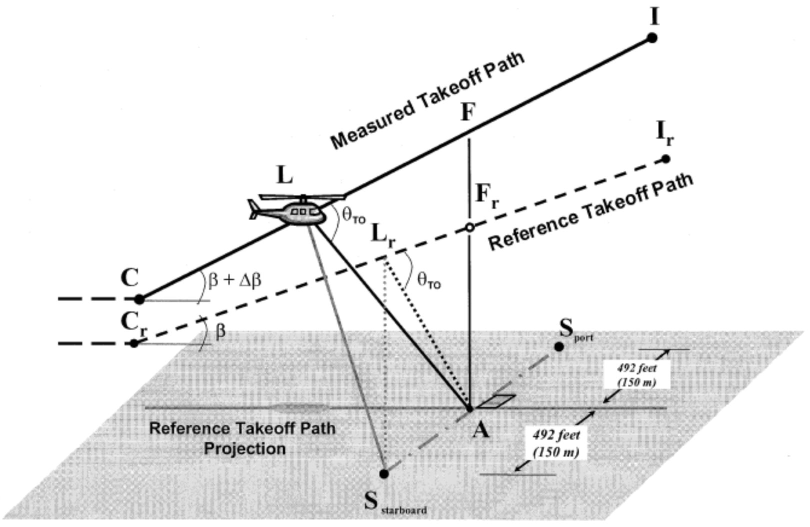


Figure H1.
Comparison of Measured and Reference Takeoff Profiles

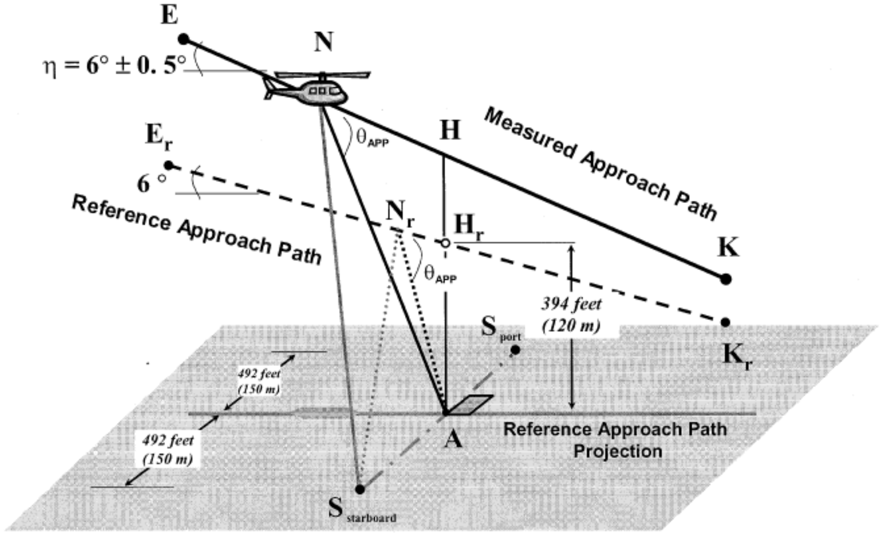


Figure H3.
Comparison of Measured and Reference Approach Profiles

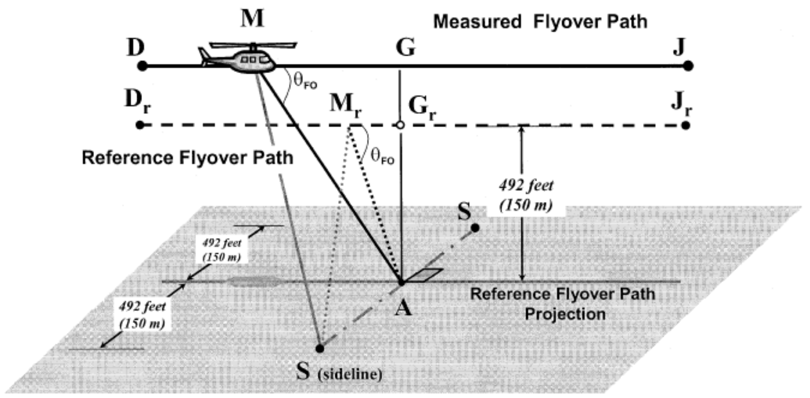
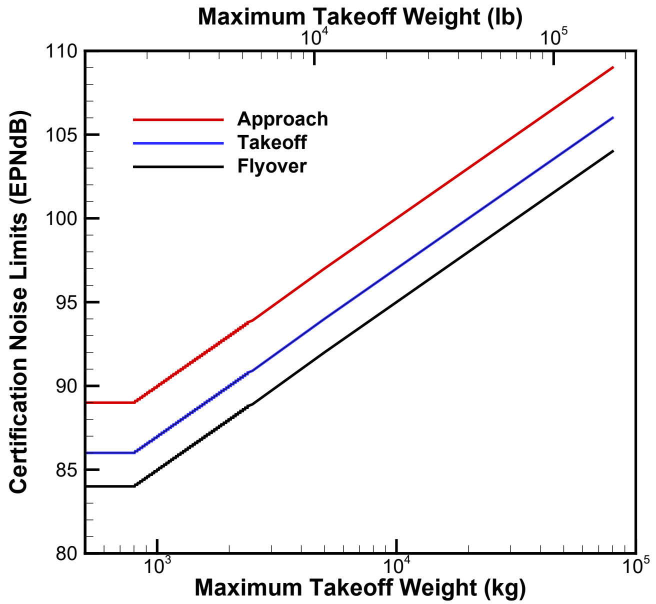


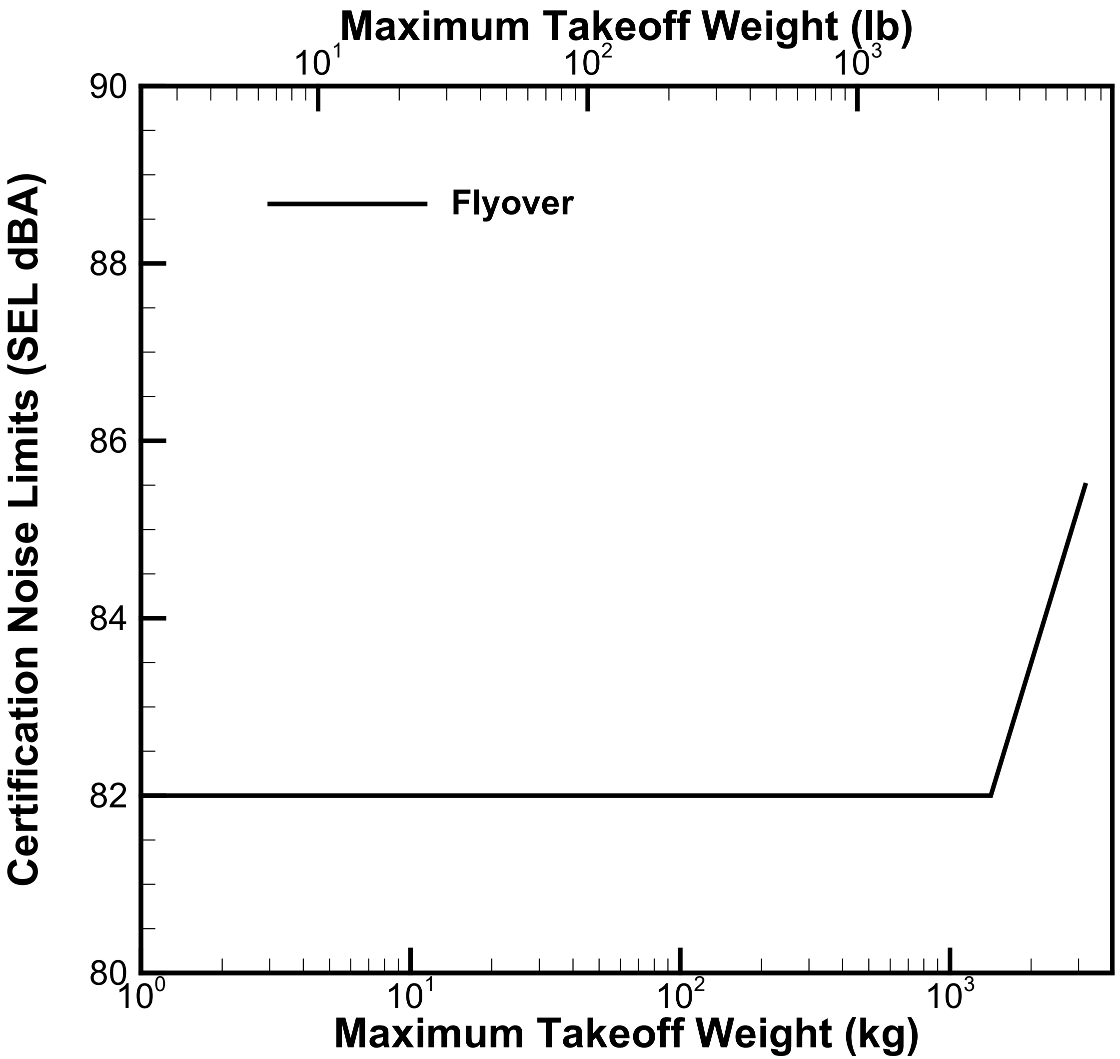
Figure H2.
Comparison of Measured and Reference Flyover Profiles



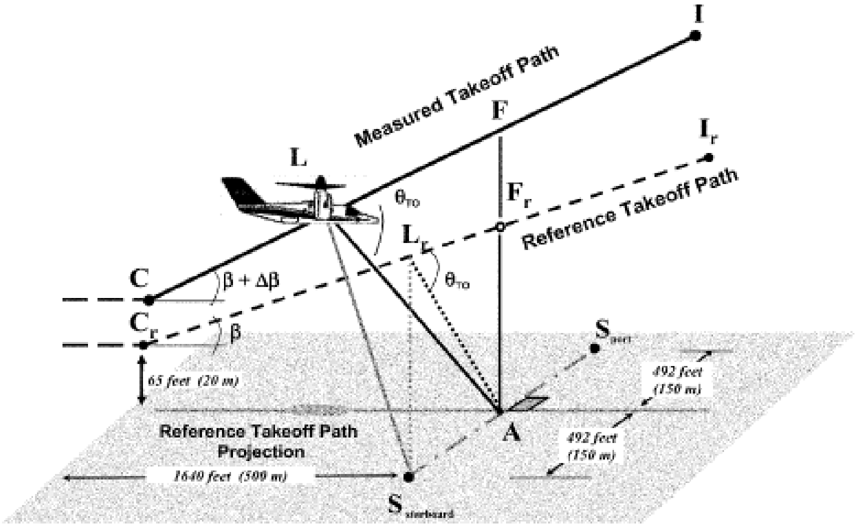
Source: https://federalregister.gov/a/04-12069

Noise Certification Standard for Light (< 7000 lbs) Helicopters (App J)

- Level overflight at 492 ft (150 m) altitude
- Single 4-ft microphone directly below flight path
- No lower weight limit
  - Matternet delivery drone (29 lbs) recently certified under RPA based on Appendix J.



Noise Certification Standards for Tiltrotors (Appendix K)



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Comparison of Measured and Reference Takeoff Profiles

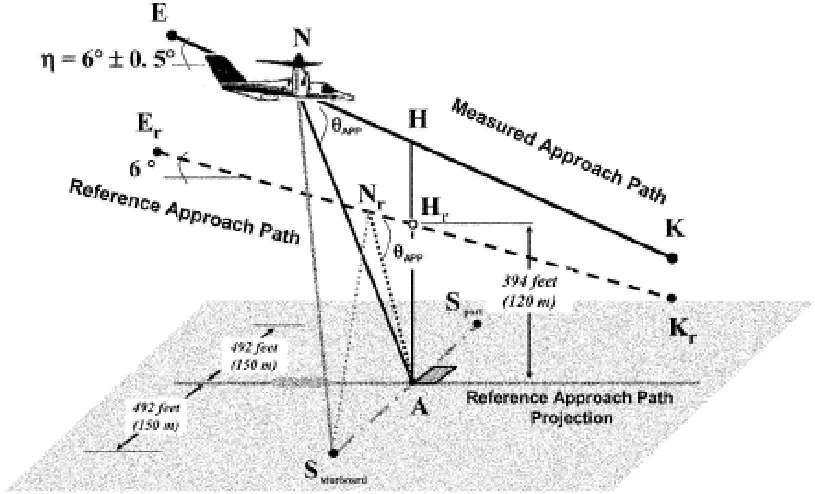
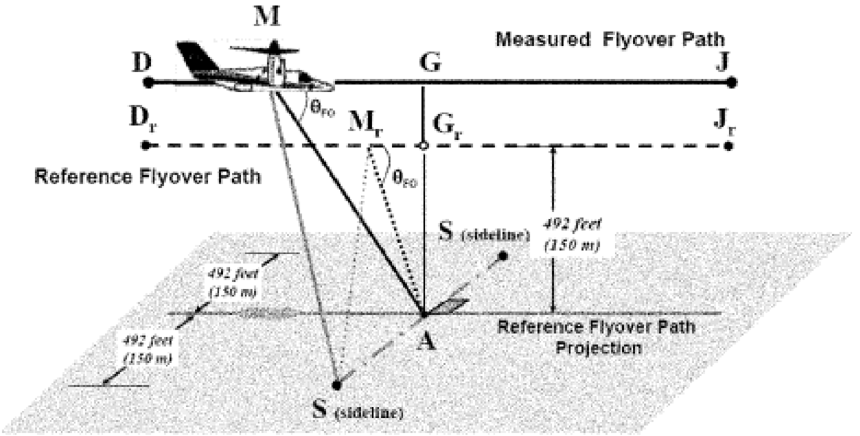


Figure K3.
Comparison of Measured and Reference Approach Profiles



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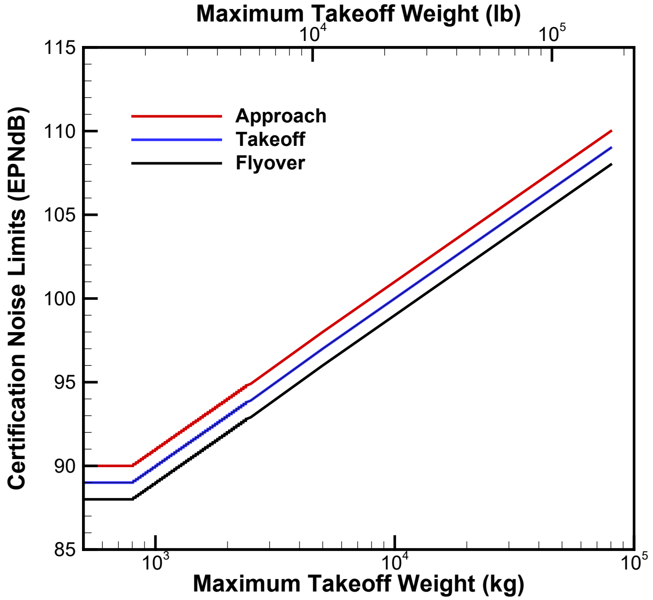
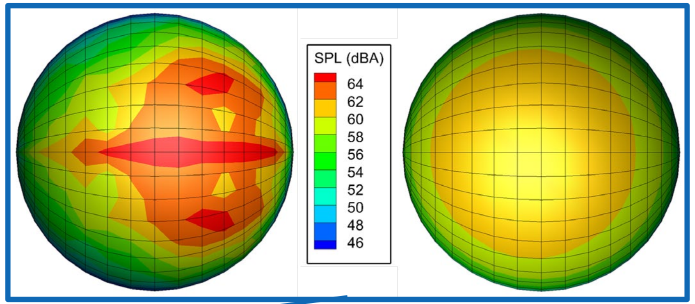


Source: https://federalregister.gov/a/2013-00111

Utilization of Source Noise Predictions



Perception-Influenced Design

Perception-Influenced Acoustic Design

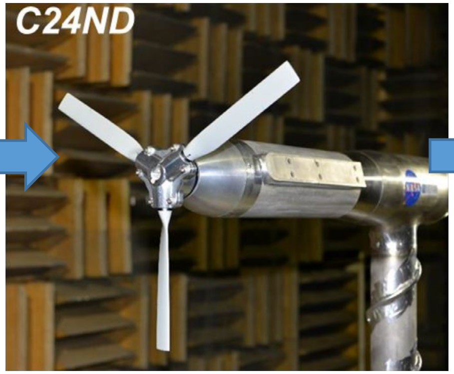
Measured
Background
Predictions

Baseline Geometry

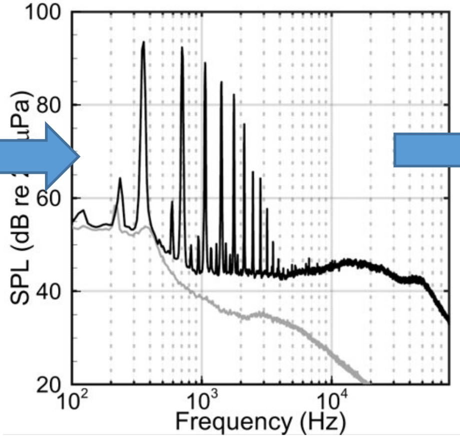
$$\phi = \mathrm{TAN}^{-1}\left(\frac{P}{\pi D}\frac{R}{r}\right)$$

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

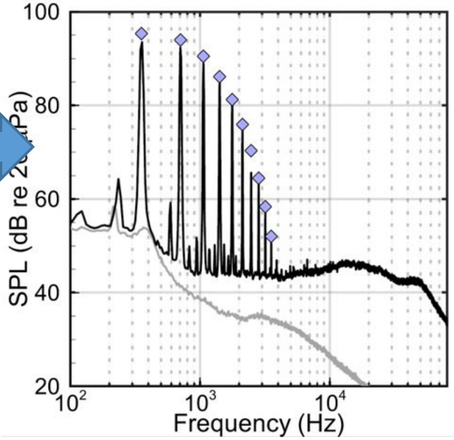
Baseline Tunnel Entry



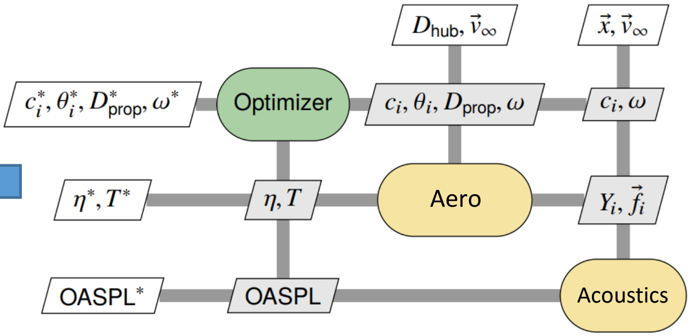
Baseline Data



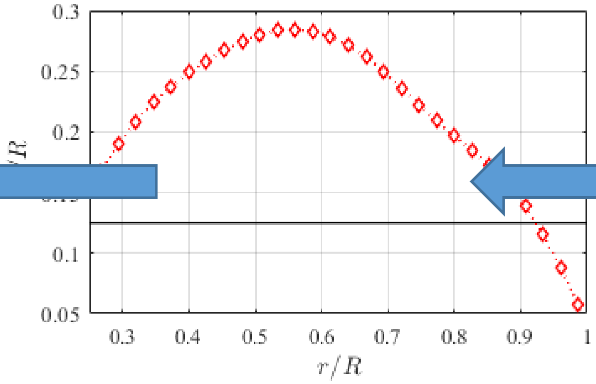
Analysis Using Optimization Tools



Design Optimization

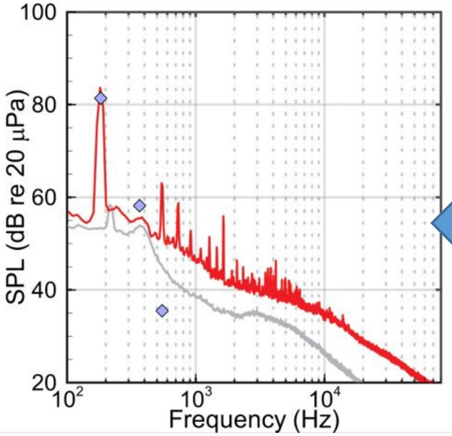


Optimized Geometry



Optimization Tunnel Entry

Validation Data

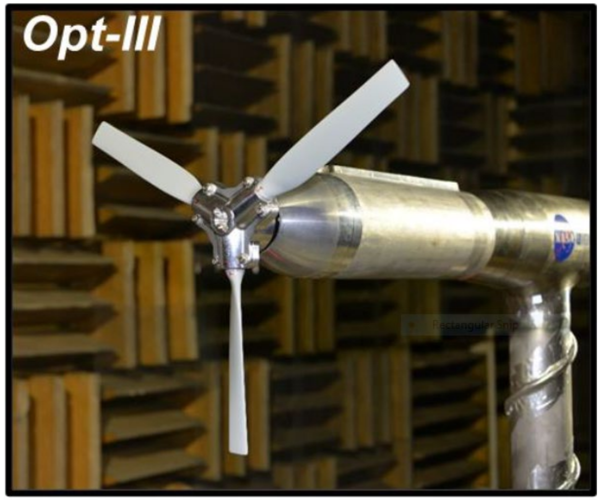


Lopes, Ingraham, Zawodny, "Status of UAM Proprotor Design Validation Campaign: Available Data and Computational Tools," NASA Acoustics Technical Working Group Meeting, Oct 2022

Perception-Influenced Acoustic Design – Isolated Proprotor

Baseline

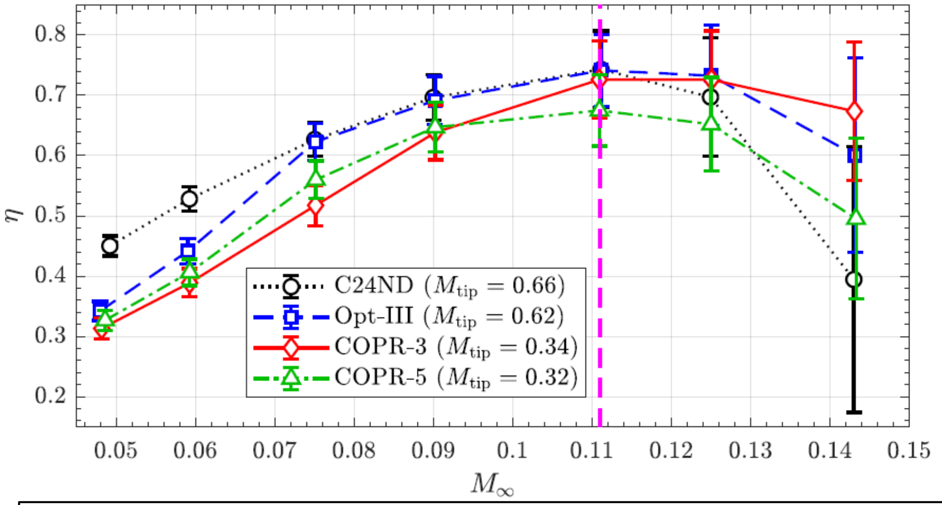
SU2



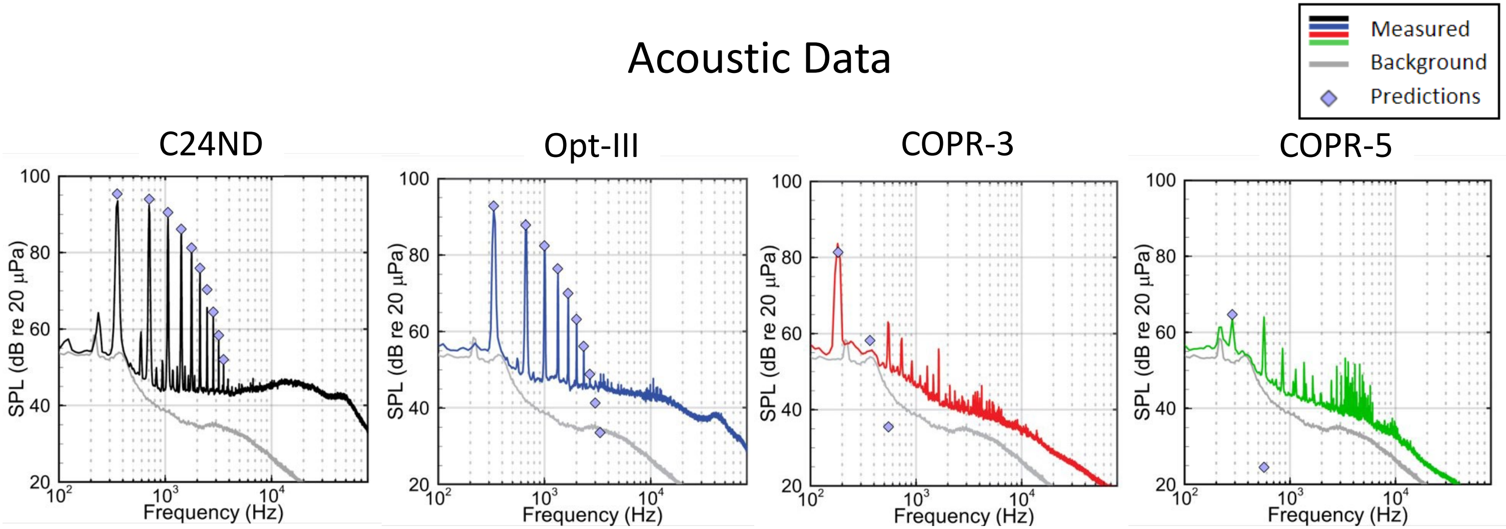
ccblade.jl

ccblade.jl blade design x5

Performance Data

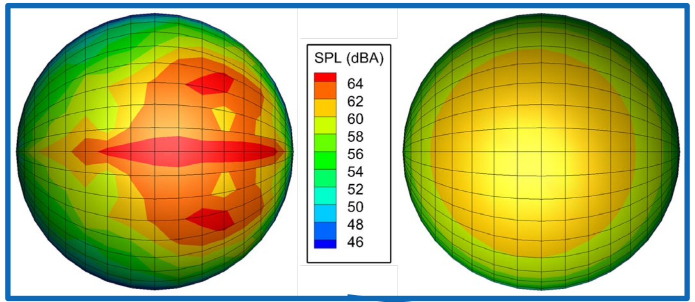


Acoustic Data



Lopes, Ingraham, Zawodny, "Status of UAM Proprotor Design Validation Campaign: Available Data and Computational Tools," NASA Acoustics Technical Working Group Meeting, Oct 2022

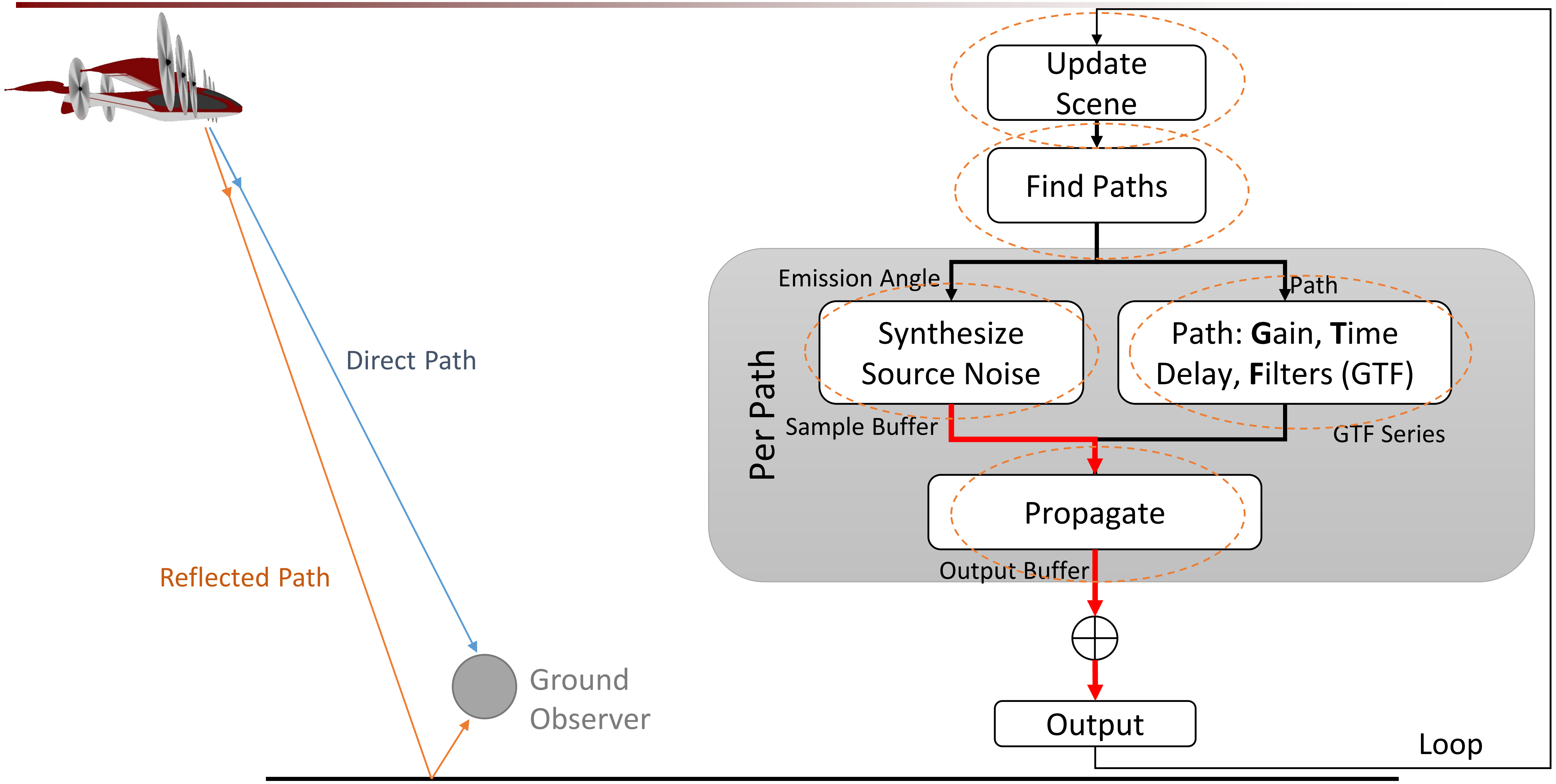
Utilization of Source Noise Predictions



Auralization & Psychoacoustics

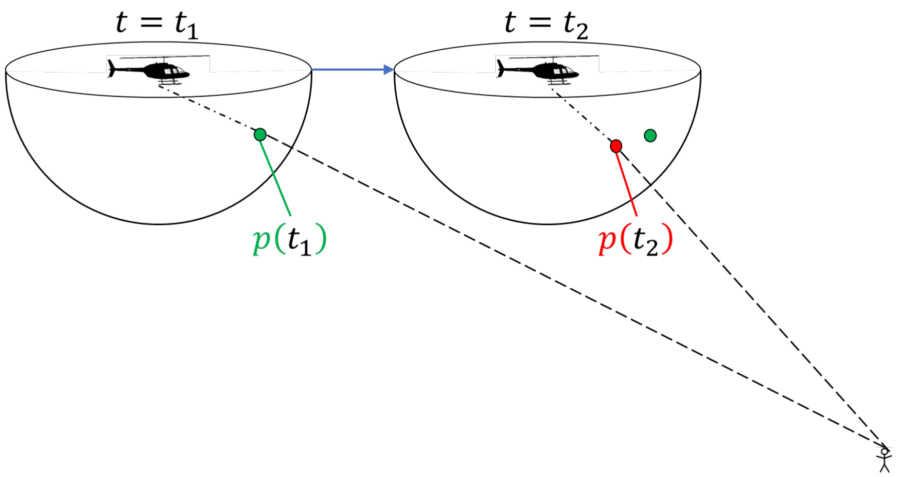
Auralization

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



Rotary-Wing Source Noise Synthesis

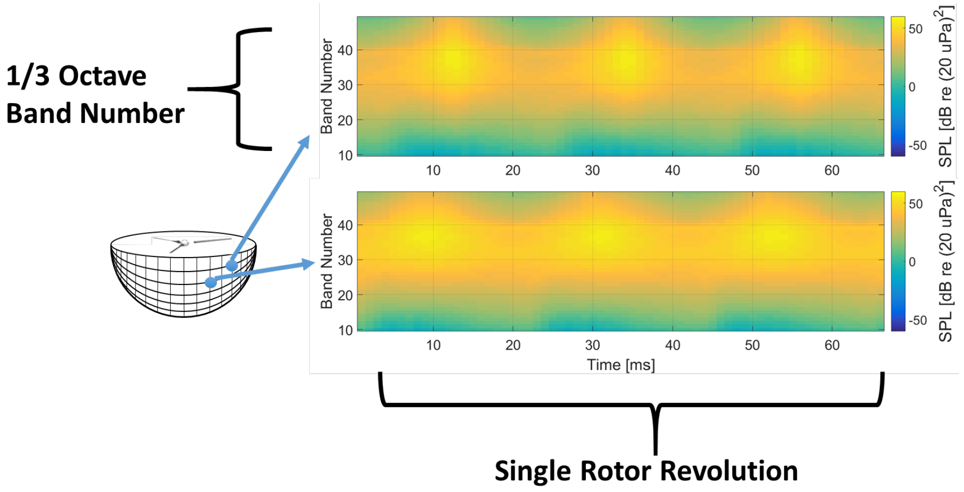
Synthesis of Loading and Thickness Noise using ANOPP2 Farassat's Formulation 1A Internal Functional Module (AF1AIFM)



Quadrotor Periodic

Krishnamurthy, Tuttle, Rizzi, "A Synthesis Plugin for Steady and Unsteady Loading and Thickness Noise Auralization", AIAA AVIATION 2020, AIAA-2020-2597, June 2020. https://doi.org/10.2514/6.2020-2597

Self Noise Sound Pressure Predictions from ANOPP2 Self Noise Internal Functional Module (ASNIFM)



1.8mm TE

7.2mm TE

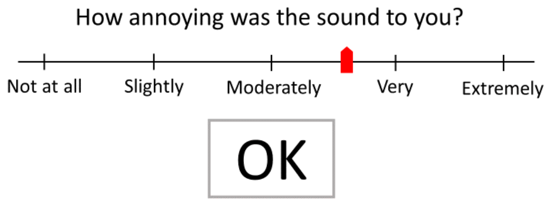
Krishnamurthy, Aumann, Rizzi, "A Synthesis Plugin for Auralization of Rotor Self Noise", AIAA AVIATION 2021, AIAA-2021-2211, August 2021. https://doi.org/10.2514/6.2021-2211

Level Flyover

Psychoacoustic Studies Utilizing Auralizations

- Test of UAM Sound Quality (completed July 2022)
  - Objective: Investigate how annoyance varies with sound quality.
  - Generated test stimuli spanning a range of loudness, sharpness, tonality, fluctuation strength, and impulsiveness.

Christian, Boucher, Begault, Rafaelof, Rizzi, Krishnamurthy, “Initial Results from a Psychoacoustic Test for UAM Sound Quality,” NASA Acoustics Technical Working Group Meeting, Oct 2022



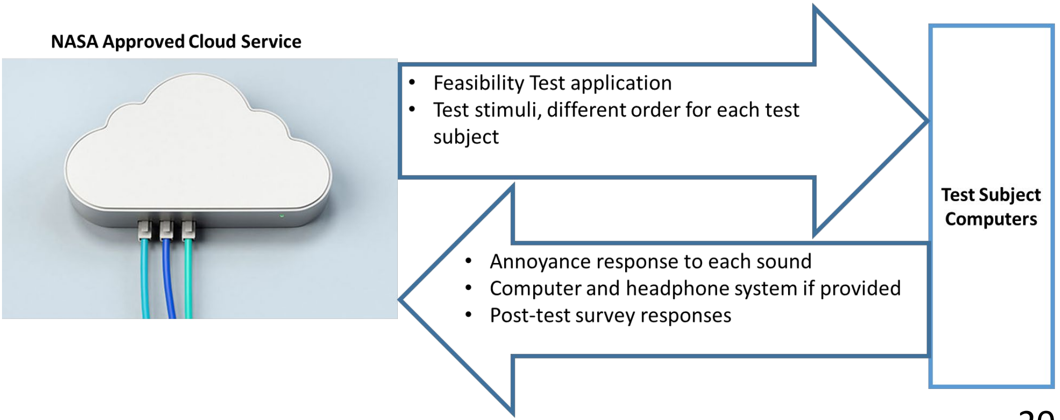
- Test of Noise and Numbers (January 2023)
  - Objective: Investigate how annoyance varies with number of operations, spacing between operations, and makeup of the fleet.

- Test of Detection, Noticeability, and Annoyance (Sept 2023)
  - Objective: Investigate how annoyance varies in presence of masking noise, e.g., cityscape.

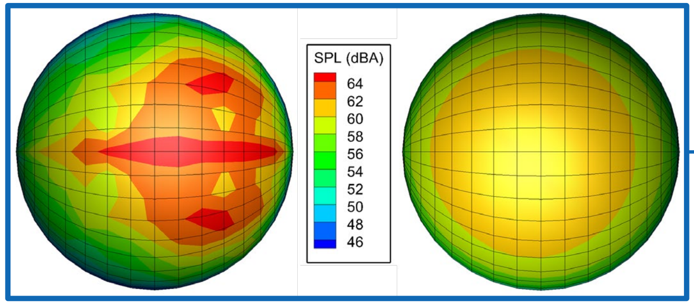
- Cooperative Human Response Study
  - Objective: Verify consistency of remote test platform with prior lab results (Oct 2022).
  - Objectives under consideration include annoyance between geographically distinct communities, near vertiports, number of events, different soundscapes, relative to existing aircraft noise sources (2024).

Exterior Effects Room (EER) at NASA Langley

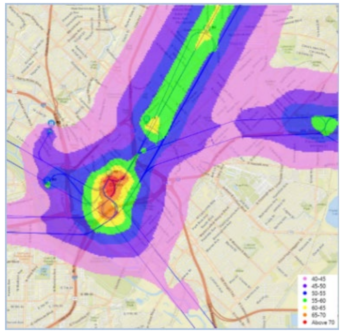
Remote Psychoacoustic Testing Platform



Utilization of Source Noise Predictions



Operational Fleet Noise Assessments



UAM Operational Fleet Noise Assessments

- FAA Aviation Environmental Design Tool (AEDT) is the required tool to assess aircraft noise and other environmental impact due to federal actions at a civilian airport or vertiport, or in the U.S. airspace for commercial flight operations
- Obstacles to using AEDT for assessing UAM operations include:
  - No available noise-power-distance data for UAM vehicles (whether modeled as fixed-wing or rotary-wing aircraft in AEDT)
  - When modeled as fixed-wing aircraft, there are no performance data available to determine engine power, and unclear if engine power is a good predictor of noise
  - When modeled as rotary-wing aircraft, the number of operating modes within AEDT are limited to a few that are appropriate for typical helicopter operations, but may be insufficient for describing UAM operations
- Technical approach includes:
  - Develop means to generate fixed-wing and rotary-wing NPD data from prediction†
  - Develop means to model UAM operations in AEDT fixed-wing‡, rotary-wing, and hybrid modes
  - Identify best modeling practices through comparison using simulation methods

† Rizzi, Letica, Boyd, Lopes, “Prediction-Based Approaches for Generation of Noise-Power-Distance Data with Application to Urban Air Mobility Vehicles,” 28th AIAA/CEAS Aeroacoustics Conference, Southampton, UK, June 2022, AIAA-2022-2839, https://doi.org/10.2514/6.2022-2839.

‡ Rizzi, Rafaelof, “Community Noise Assessment of Urban Air Mobility Vehicle Operations using the FAA Aviation Environmental Design Tool,” InterNoise 2021, Virtual, 2021.

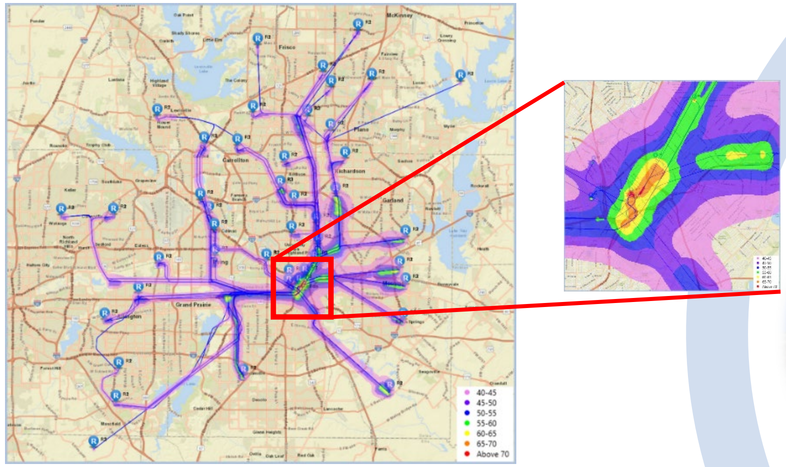
‡ Rizzi, Rafaelof, “Second Generation UAM Community Noise Assessment using the FAA Aviation Environmental Design Tool,” AIAA SciTech Forum, San Diego, CA, Jan 2022, AIAA-2022-2167, https://doi.org/10.2514/6.2022-2167.

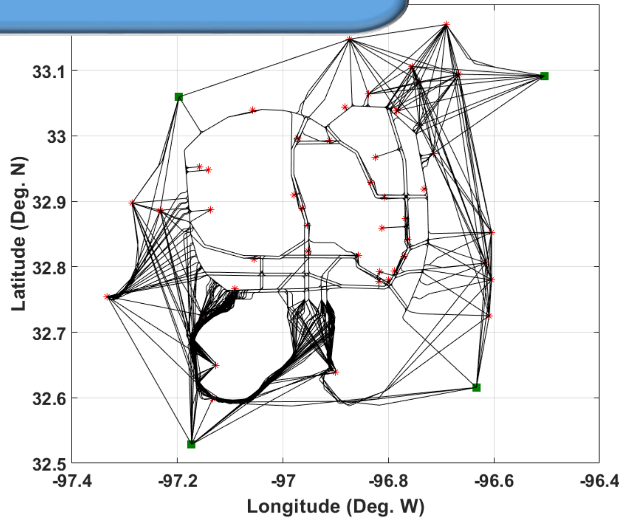
UAM Operational Fleet Noise Assessments

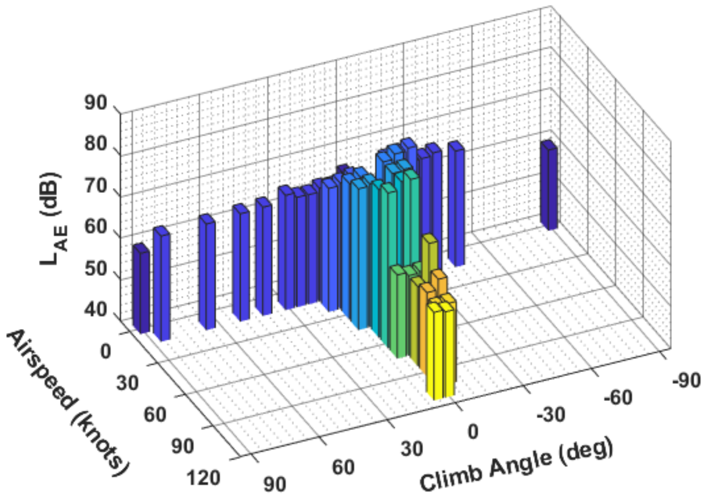
Use AEDT to evaluate community noise, combining all vehicles and operational states

https://doi.org/10.2514/6.2022-2167

Identify routes, trajectories, and aircraft flight conditions



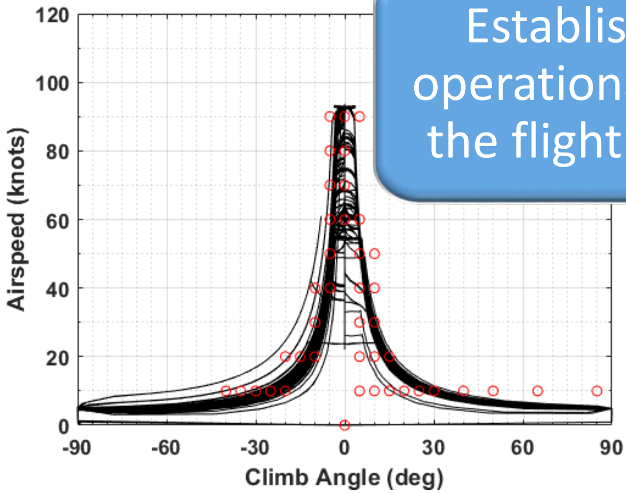




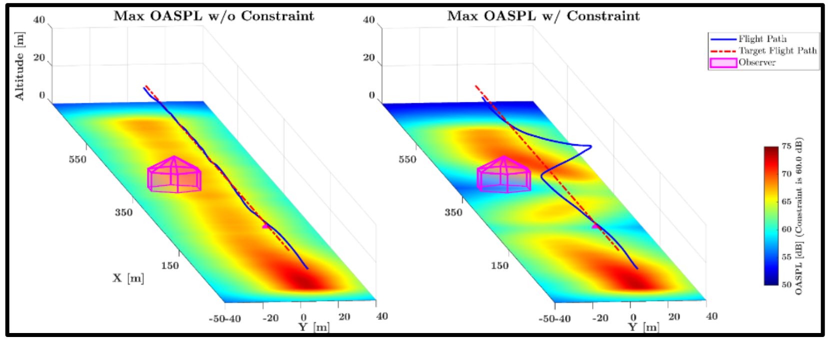
Evaluate source noise and generate noise-power-distance data using AMAT

https://doi.org/10.2514/6.2022-2839

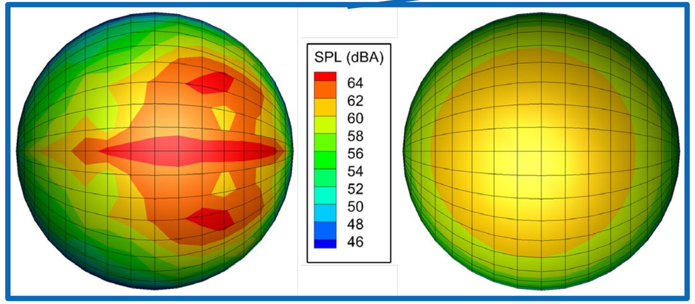
Establish aircraft operational states for the flight conditions



Utilization of Source Noise Predictions



Acoustically Aware Flight Control



Ackerman, Gregory, Theodorou, Hovakimyan, "A Model Predictive Control Approach for In-Flight Acoustic Constraint Compliance," 2021 AIAA SciTech Forum, Virtual, Jan. 2021, AIAA-2021-1958, https://doi.org/10.2514/6.2021-1958.

- Model Predictive Path Integral Control (MPPI)
  - Sample thousands of control sequences, $\boldsymbol{\nu}_t \sim \mathcal{N}(\boldsymbol{u}_t, \boldsymbol{\Sigma})$, propagate trajectories in parallel
  - Exponential cost-weighted averaging to update mean of optimal control distribution, $\boldsymbol{u}_t$
  - Propagate mean optimal control sequence to obtain nominal trajectory

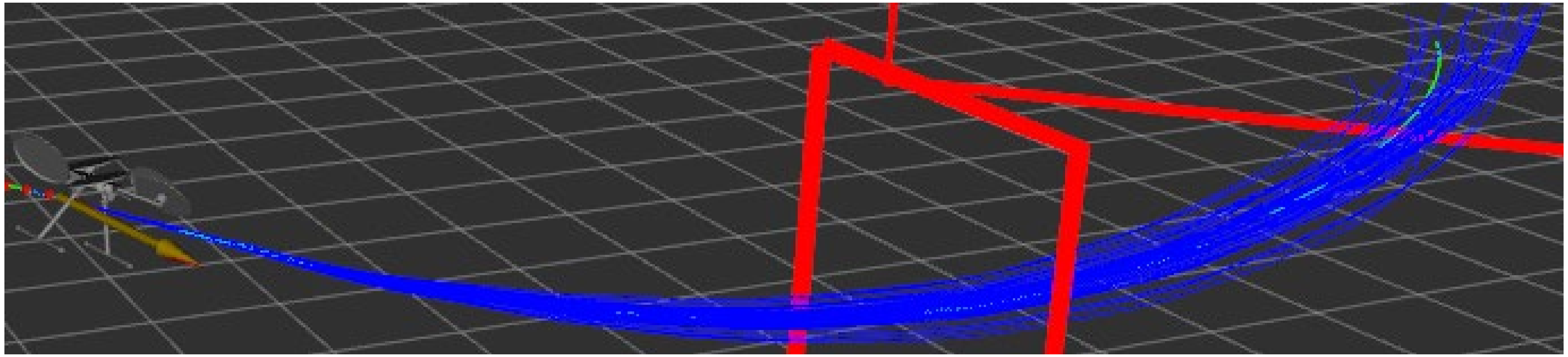
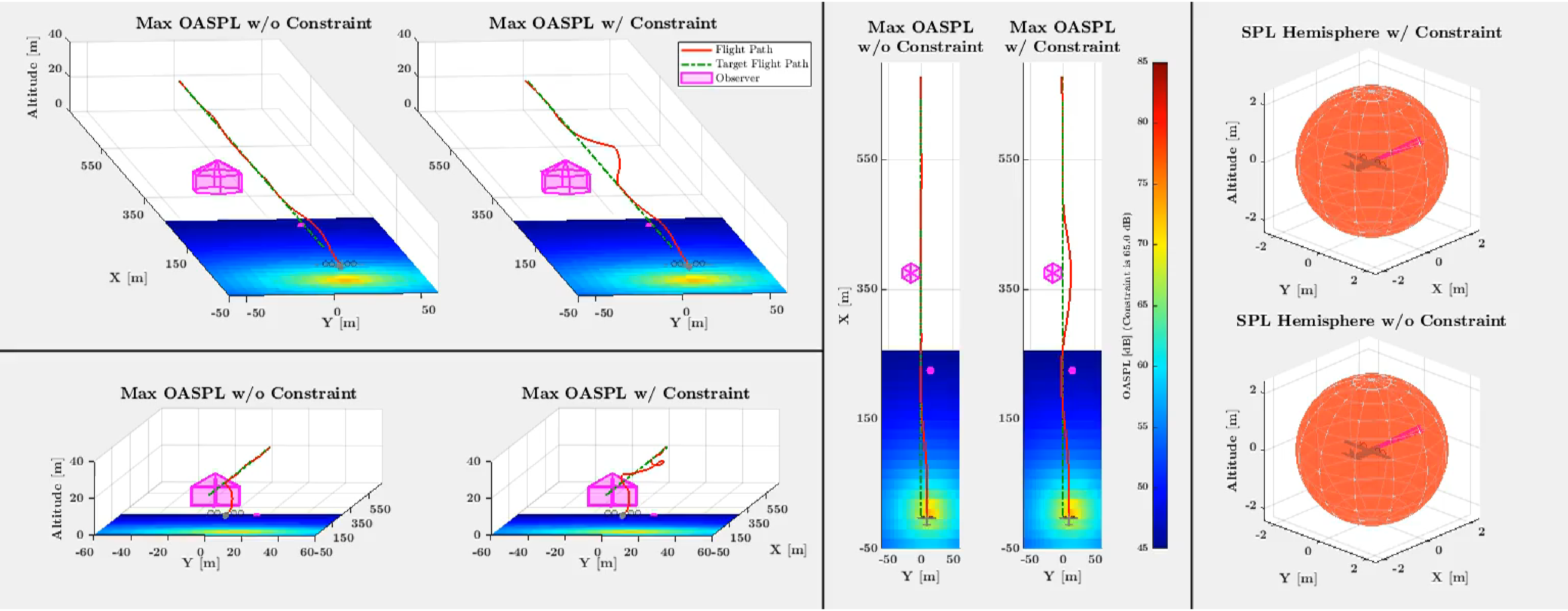


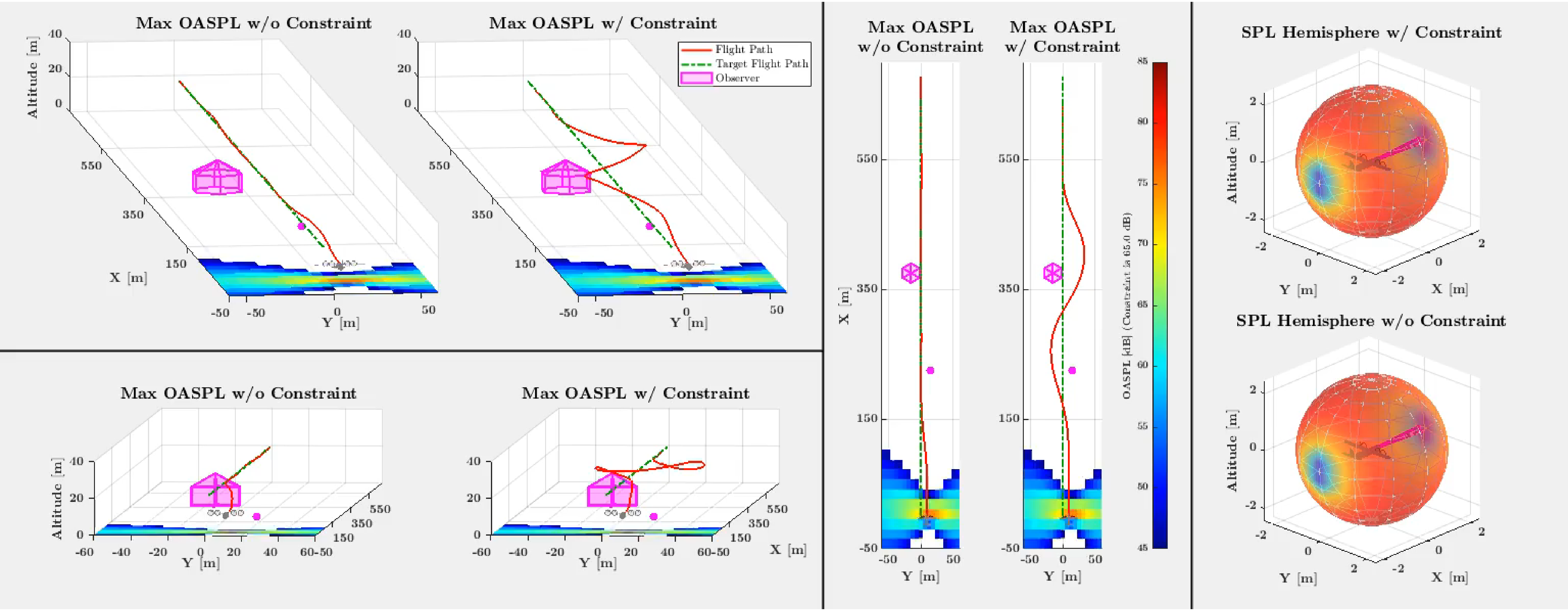
Figure credit: J Pravitra, KA Ackerman, N Hovakimyan, EA Theodorou, "L1-Adaptive MPPI Architecture for Robust and Agile Control of Multirotors," IROS, 2020.

Simulation Results – Video (monopole source)



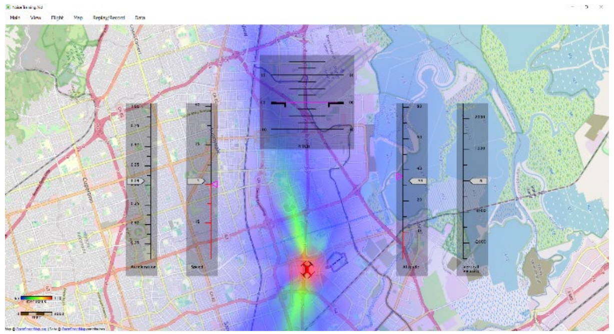
*Aircraft is animation only, not to scale or representative

Simulation Results – Video (directive source)

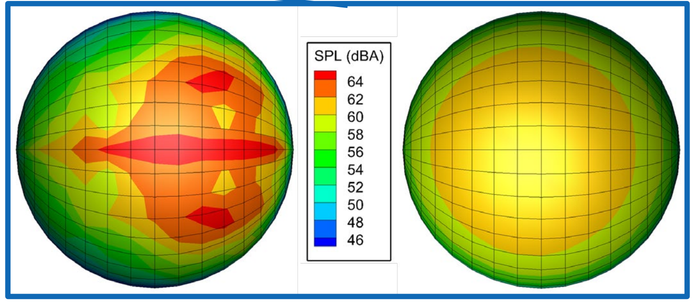


*Aircraft is animation only, not to scale or representative

Utilization of Source Noise Predictions

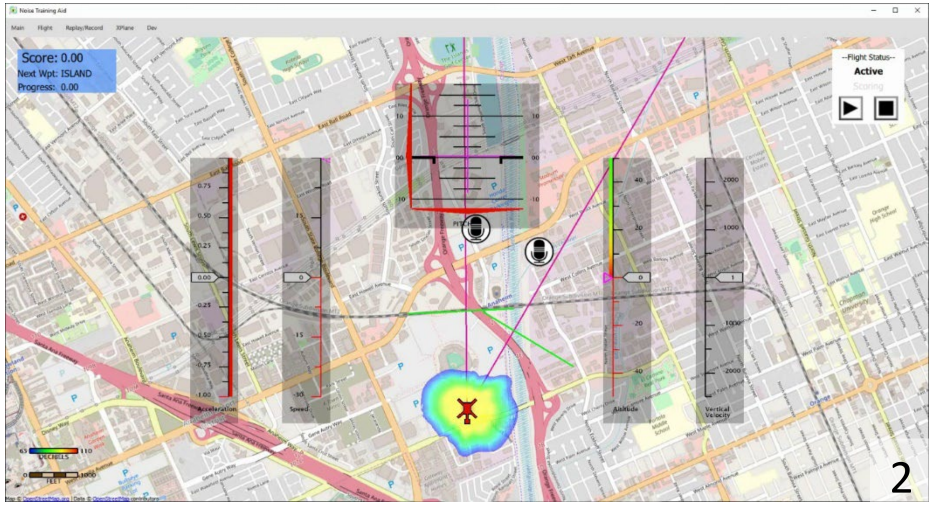


Acoustic Flight Simulator



Generate predicted helicopter ground noise footprint based on:

- Vehicle attitude in real time
- Flight-test-generated vehicle noise spheres[1]



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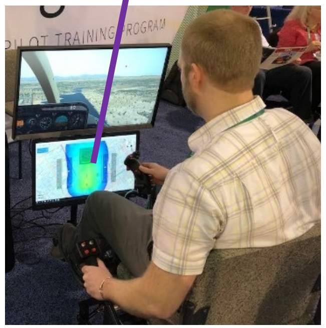
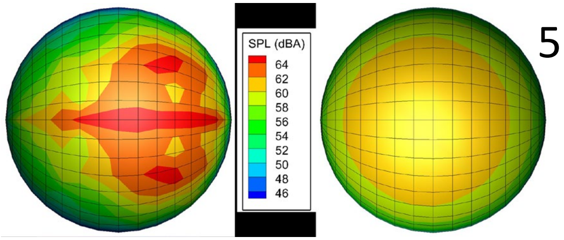


Generate predicted **UAM** ground noise footprint at each timestamp based on:

- Detailed trajectory from simulation[3]
- Generated UAM noise spheres
- Extrapolated to ground using modeling techniques[4]



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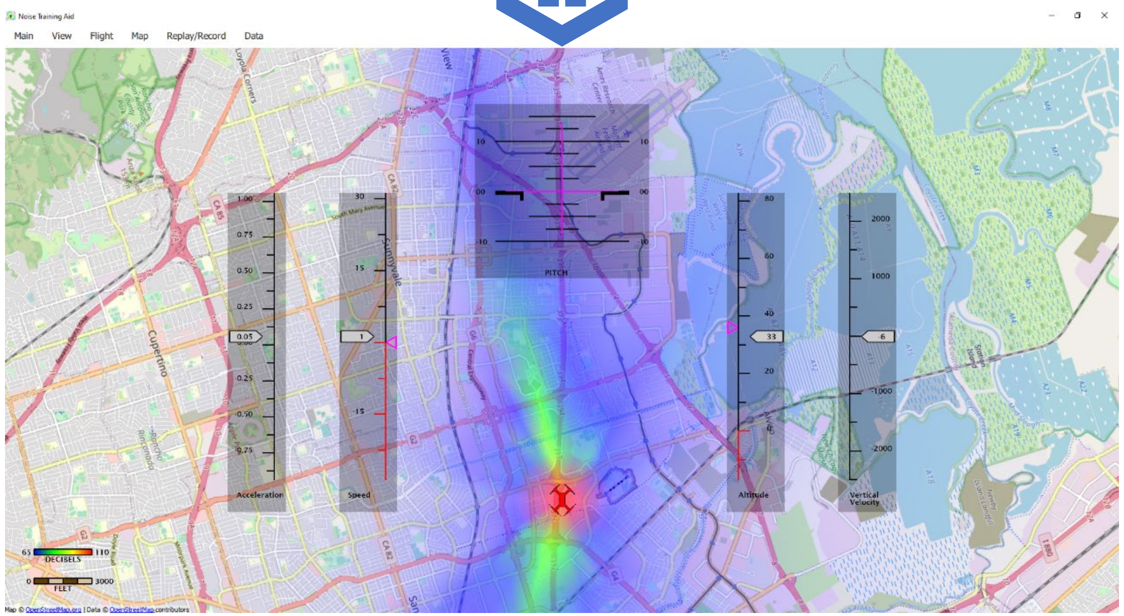
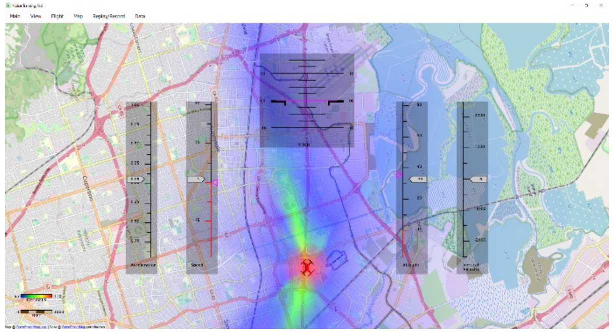
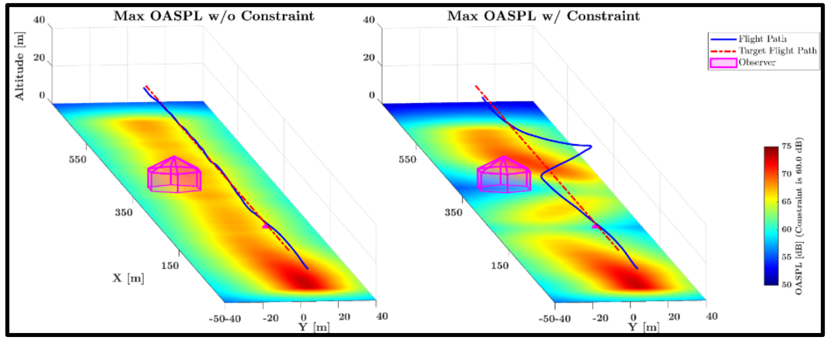


1. Helicopter noise spheres: Eric Greenwood, “Real time helicopter noise modeling for pilot community noise awareness,” in *Noise-Con 2017,* June 2017.
2. Acoustic flight simulator: A. C. Trujillo and D. R. Hill, “Acoustic Flight Simulator Architecture, Noise Training Aid Manual, and Its Training Benefits,” NASA-TM-2021-0014096, October 2021.
3. Trajectory generation: K. A. Ackerman, I. M. Gregory, E. Theodorou, and N. Hovakimyan, “A Model Predictive Control Approach for In-Flight Acoustic Constraint Compliance,” AIAA 2021-1958, *AIAA Scitech 2021 Forum*, January 2021.
4. UAM noise extrapolation to ground: *Advanced Acoustic Model (AAM)*, Volpe, December 2020
5. Rizzi, Letica, Boyd, Lopes, “Prediction-Based Approaches for Generation of Noise-Power-Distance Data with Application to Urban Air Mobility Vehicles,” AIAA-2022-2839, 28th AIAA/CEAS Aeroacoustics Conference, Southampton, UK, June 2022.

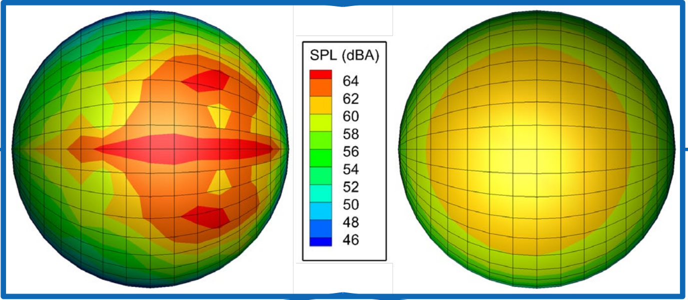
Utilization of Source Noise Predictions





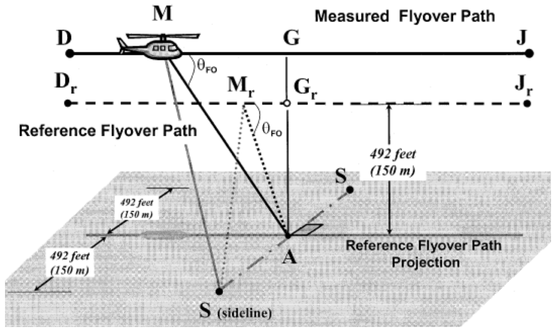
Acoustic Flight Simulator

Acoustically Aware Flight Control

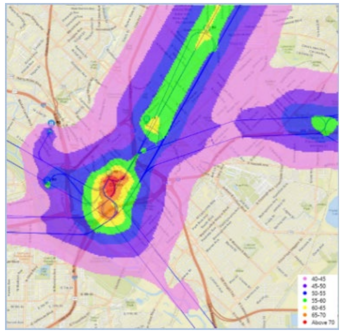


Noise Certification Analyses

Operational Fleet Noise Assessments



https://federalregister.gov/a/04-12069



Perception-Influenced Design

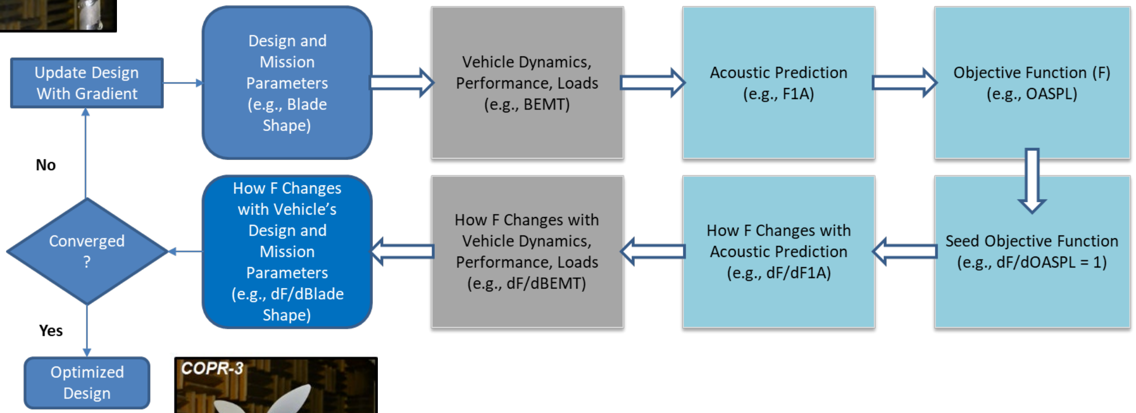
Auralization & Psychoacoustics

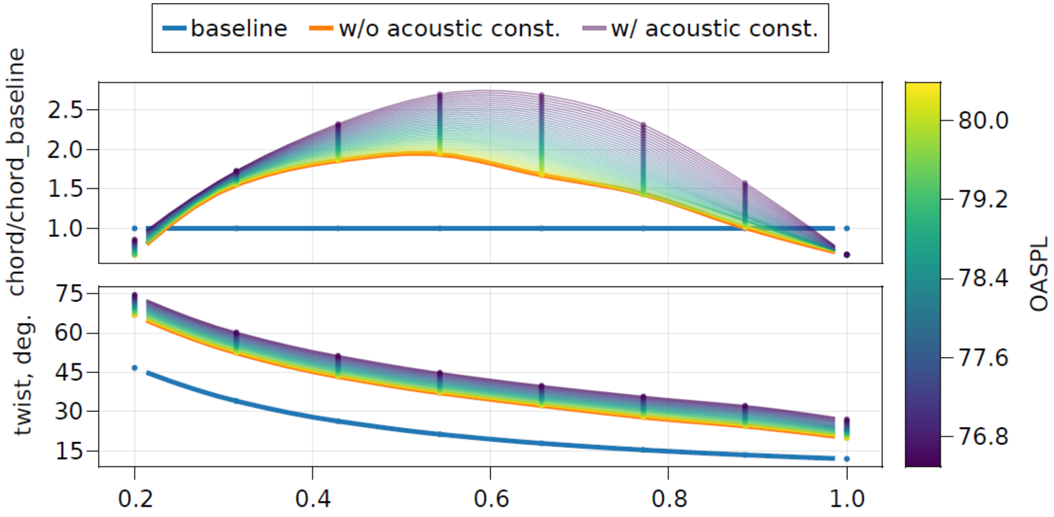
The work presented herein was primarily supported by the NASA Revolutionary Vertical Lift Technology Project and the Transformational Tools and Technologies Project.

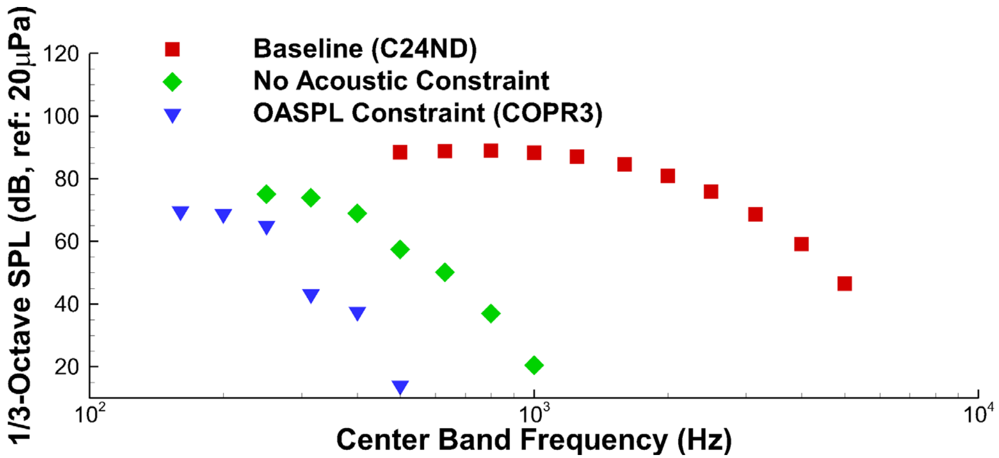
Backup Slides

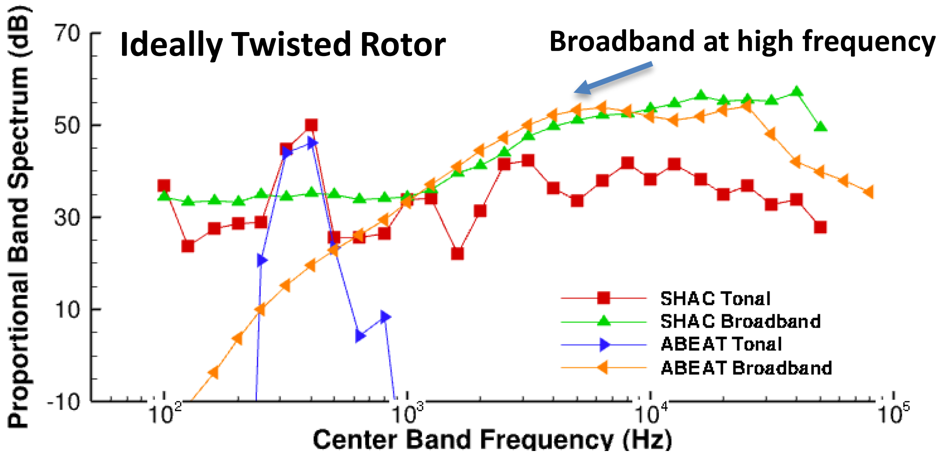
Perception-Influenced Acoustic Design

Zawodny, Lopes, Ingraham, "Preliminary Results of Adjoint-Based Proprotor Designs," NASA Acoustics Technical Working Group Meeting, April 2022









Simulation Results

- Overall sound pressure level (OASPL) at both observers