Community Noise Impact of Urban Air Mobility Vehicle Operations

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Aeroacoustics of Electrically Driven Air Vehicles: Towards a Green and Quiet Aviation
12-13 October 2023, Budapest

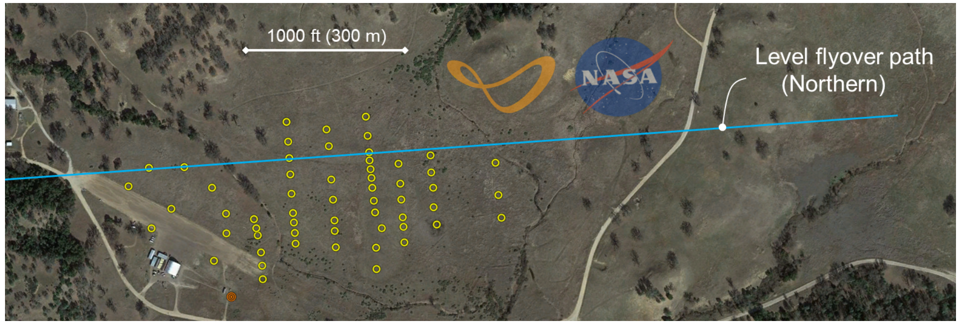
AAM and UAM

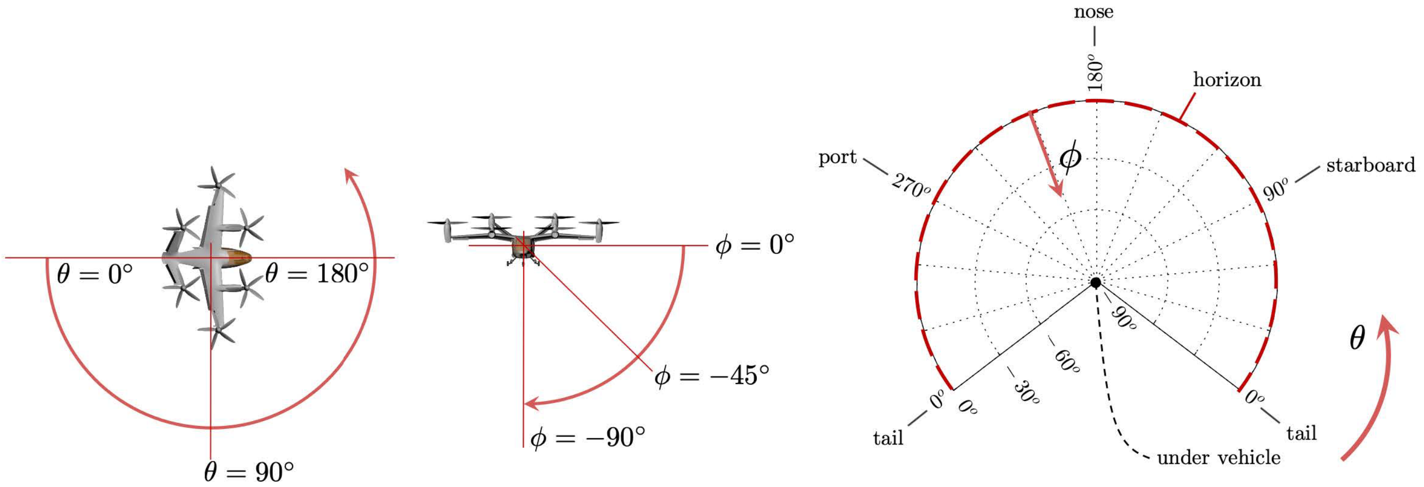
- Advanced Air Mobility (AAM) missions characterized by < 300-500 nm range
- Vehicles require increased automation and are likely electric or hybrid-electric
- Rural and urban operations are included
- Missions can be public transportation, cargo delivery, air taxi, or emergency response
- Urban Air 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

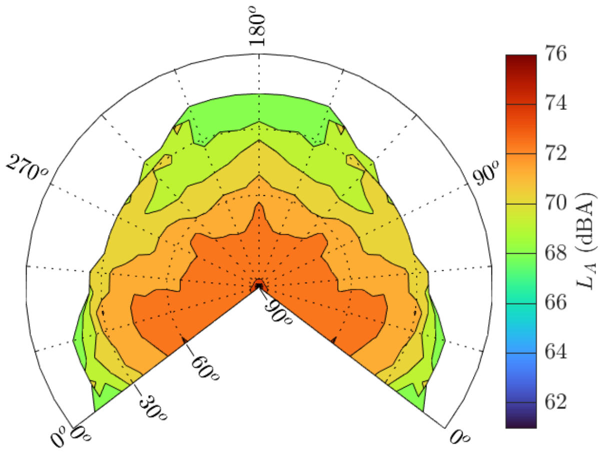
The Revolutionary Vertical Lift Technology Project and Transformational Tools and Technologies Project are two of eight NASA projects that support the AAM Mission.

Acoustic Flight Test Measurements

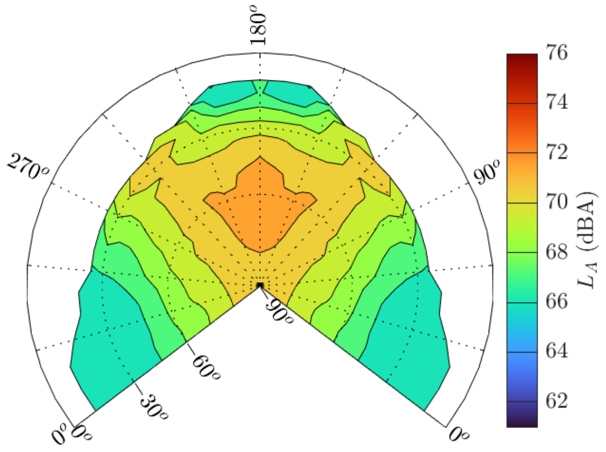
Joby Aviation preproduction prototype vehicle (Source: NASA and Joby Aviation)







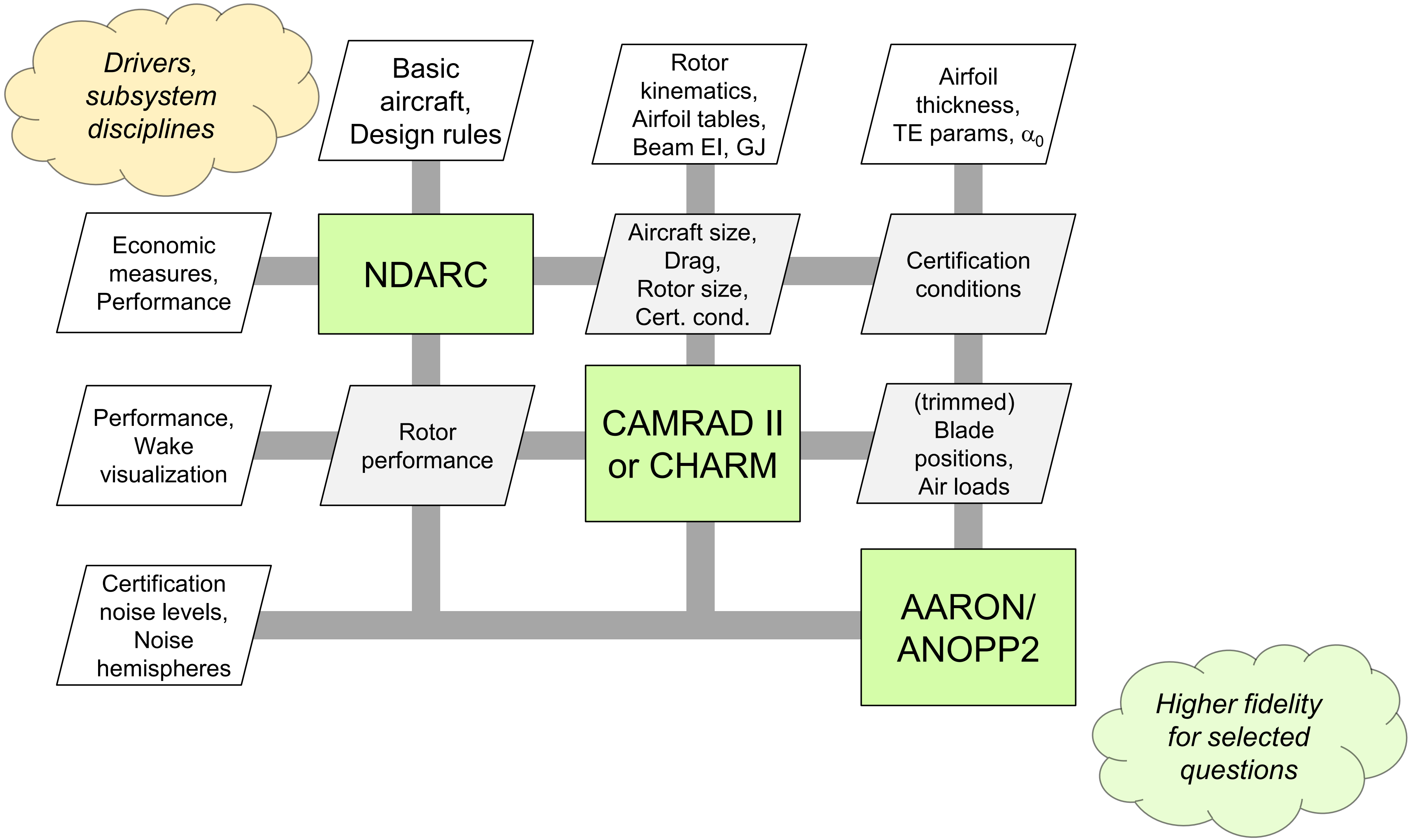
Level Flyover
(Semithrust-Borne Flight)



Level Flyover
(Wing-Borne Flight)

Pascioni, Watts, Houston, Lind, Stephenson, Bain, "Acoustic Flight Test of the Joby Aviation Advanced Air Mobility Prototype Vehicle," 28th AIAA/CEAS Aeroacoustics Conference, Southampton, UK, 2022 (https://doi.org/10.2514/6.2022-3036)

NASA Toolchain for Analysis of Noise and Performance of VTOL Vehicles



Example Concept Vehicles

Quadrotor†
- All-electric variant
- 3-bladed rotors
- 2934 kg (6469 lb.) GTOW
- V_{max} 109 KTAS

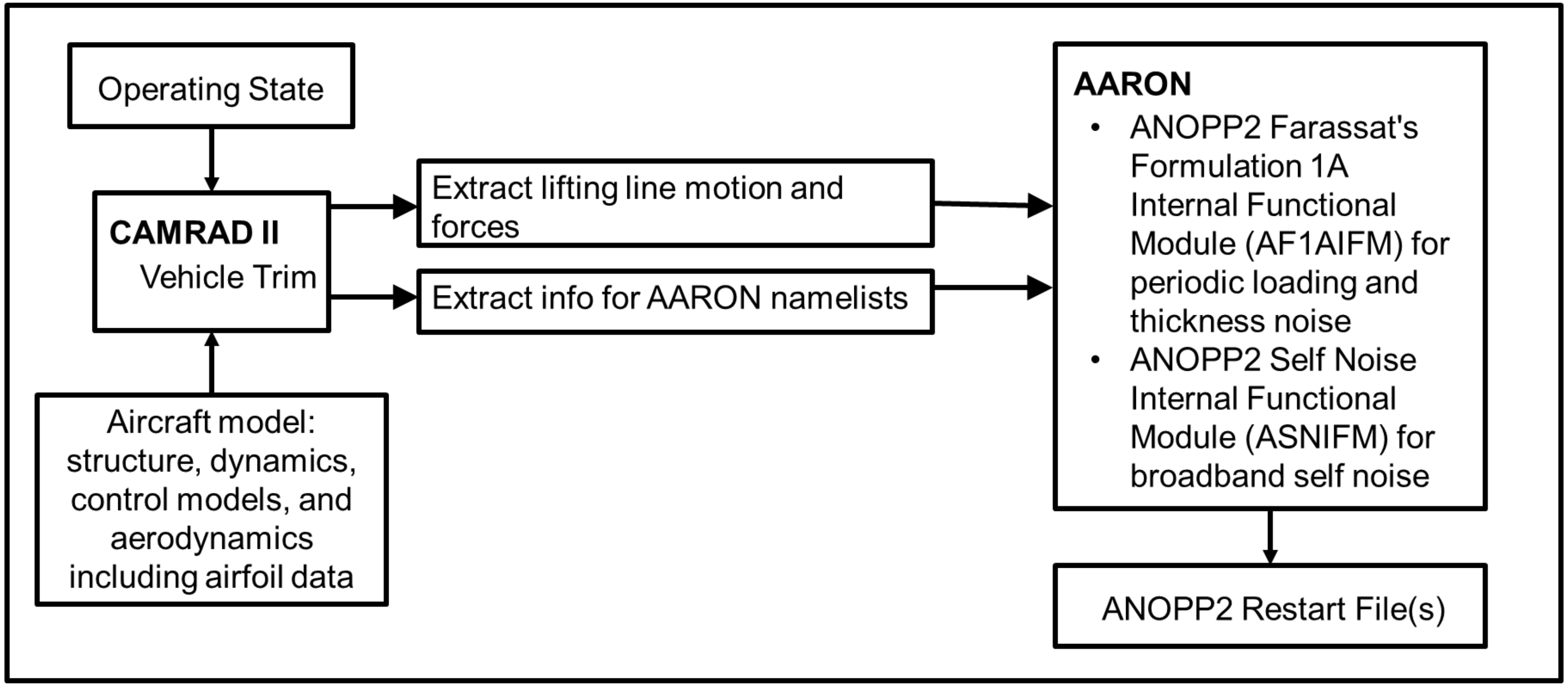
Lift Plus Cruise†
- Turboelectric variant
- (8) 2-bladed lifting rotors
- 3-bladed pusher propeller
- 2678 kg (5903 lb.) GTOW
- V_{max} 123 KTAS

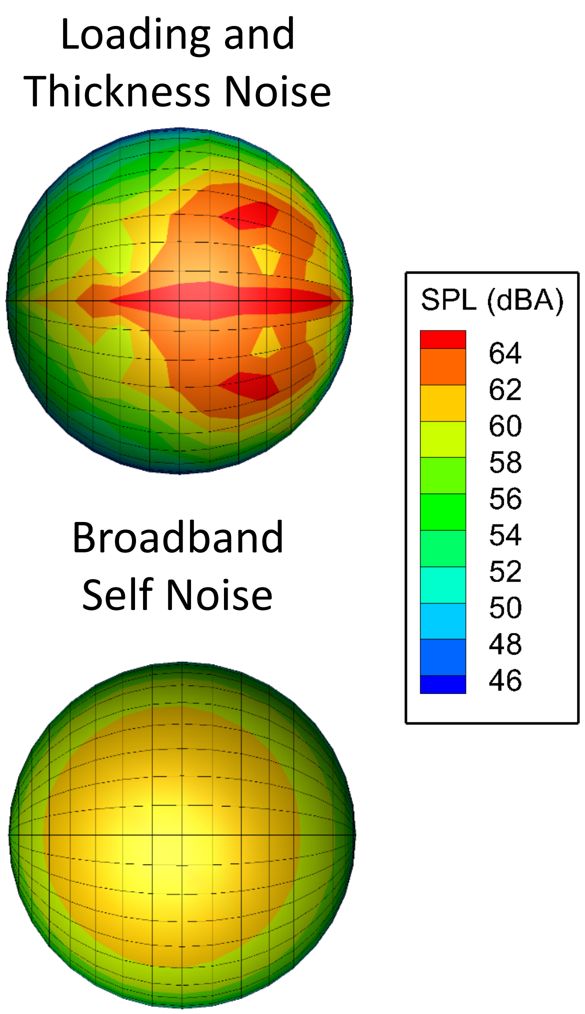
- Both vehicles sized for 544 kg (1200 lb.) payload (up to six passengers) executing a representative mission profile.‡

† Silva, Johnson, Solis, Patterson, Antcliff, "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, Antcliff, Kohlman, "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, https://ntrs.nasa.gov/citations/20190000991.

Source Noise Prediction

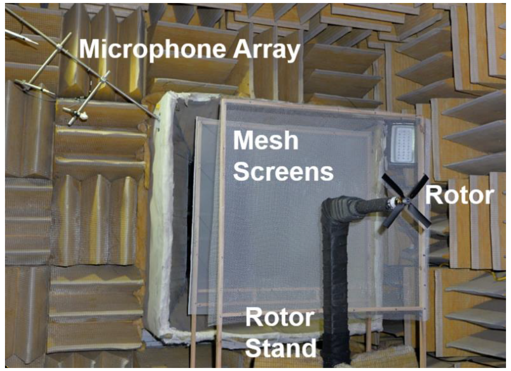




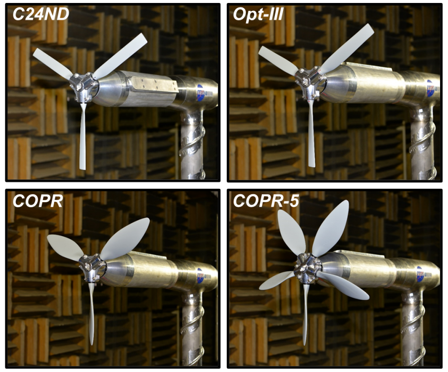
- Quadrotor was trimmed utilizing collective pitch control and constant RPM. The same trim mode was used for all speeds.
- Lift plus Cruise was trimmed utilizing collective pitch control with constant RPM. Three different trim modes used for low, moderate, and high speeds.

Experimental Databases for Validation of Noise Prediction Models

- Recent isolated propellers and rotors



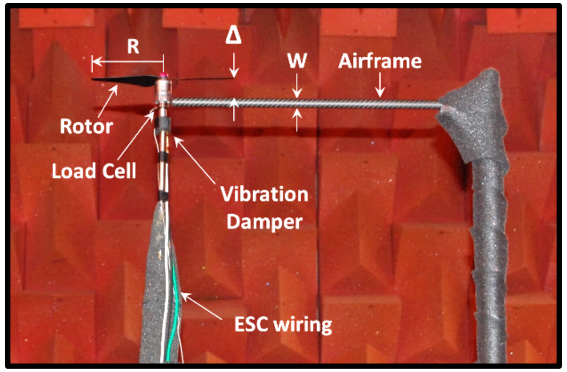
Ideally Twisted Rotor (SHAC)
AIAA-2021-1928



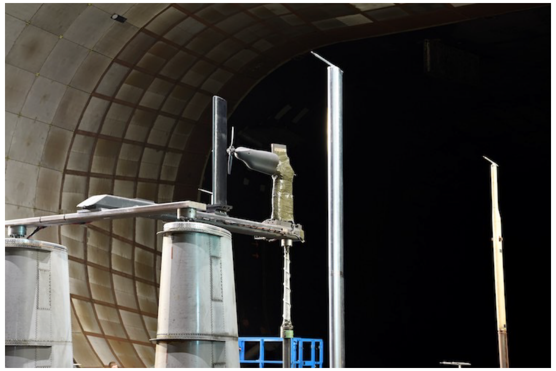
Optimized Proprotor (LSAWT)
NASA-TM-20220015637

Cruise and High Lift Propellers (LSAWT)
AIAA-2018-3448

- Recent installed propellers and rotors



Rotor-Airframe Interaction (SALT)
73rd AHS Forum 2017



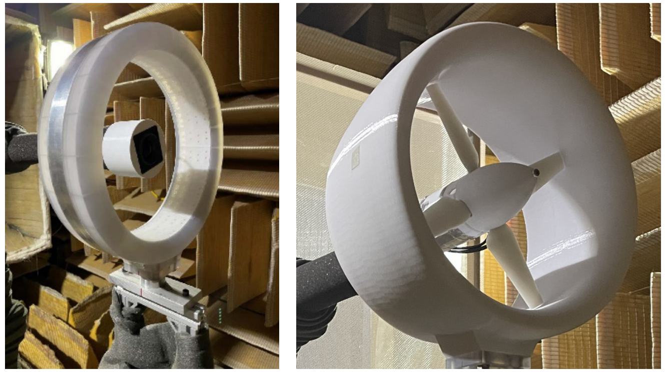
Aero & Acoustic Rotorprop Test (40'x80')
77th VFS Forum 2021

Tractor Configuration (LSAWT)
AIAA-2021-0714

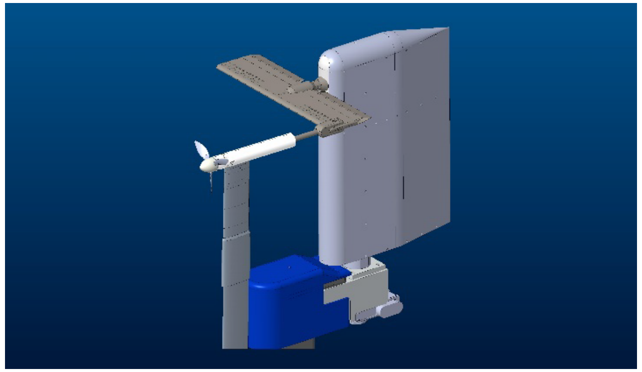
Experimental Databases for Validation of Noise Prediction Models

… more installed propellers, rotors, ducted rotors and tiltrotors

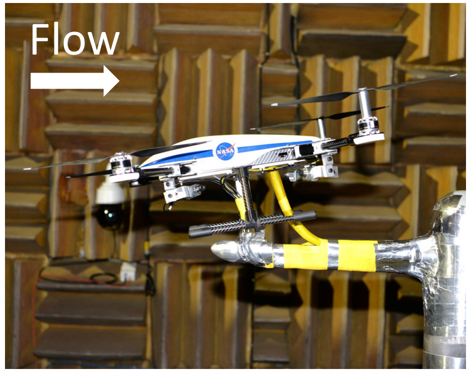
Tilting Proprotor (14’x22’)
Aero Performance - VFS 79-2023-0140
Acoustic Test – 2025



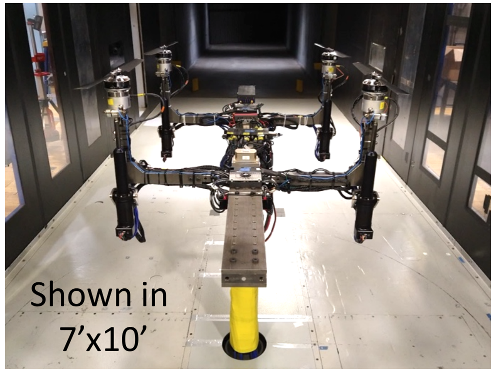
Ducted Speaker & Rotor
NASA ATWG Spring 2022



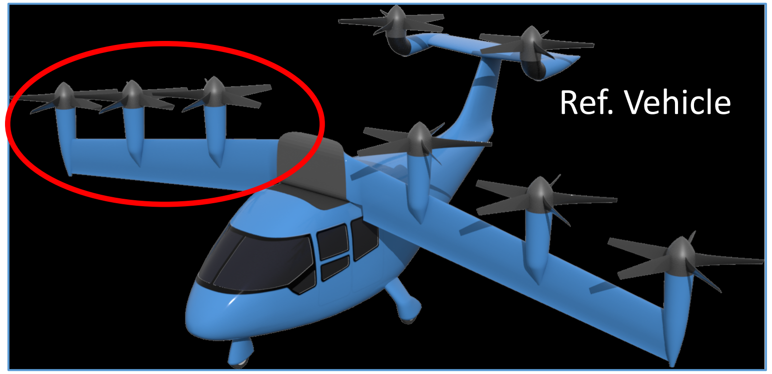
Tip-Mounted Propeller-Wing Interaction (LSAWT)
Fall 2023



Quadrotor – Blade Sets & Standoffs (LSAWT)
AIAA-2022-3110 & InterNoise 2022

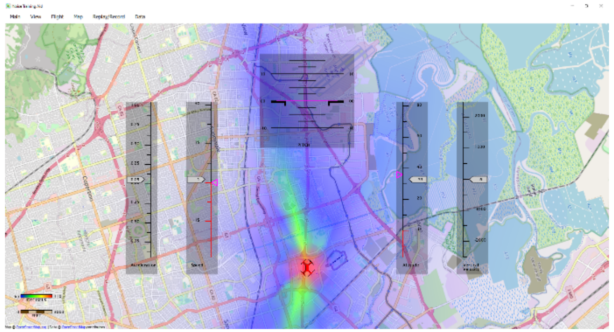


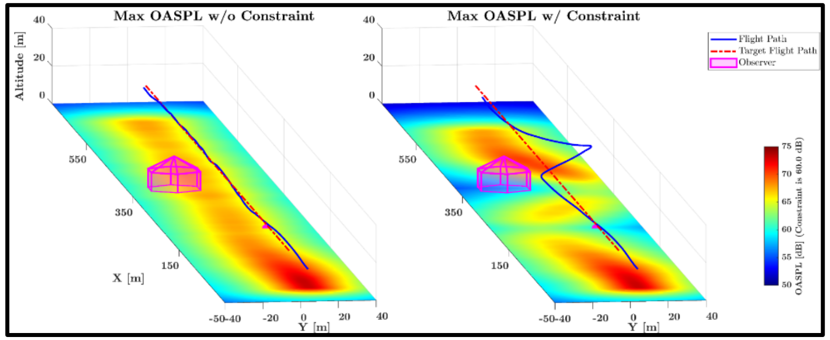
Multirotor Test Bed Acoustic Test (40’x80’)
2024-2026



Tiltwing Acoustic Test (14’x22’)
2025-2026

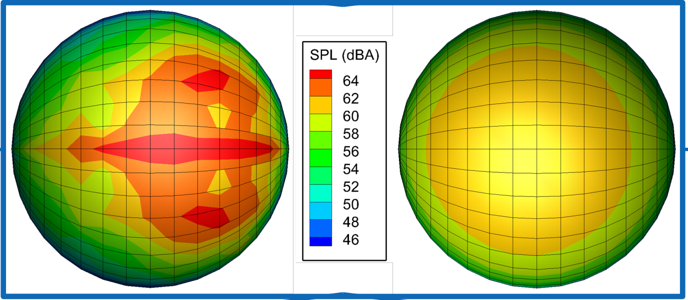
Utilization of Source Noise Predictions





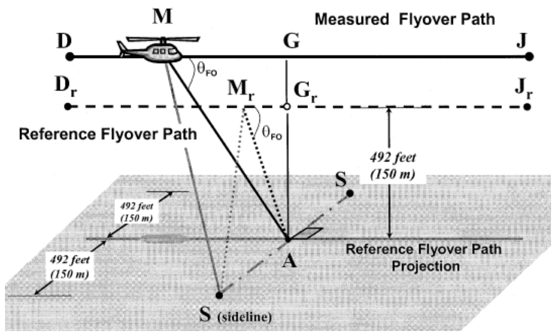
Acoustic Flight Simulator

Acoustically Aware Flight Control

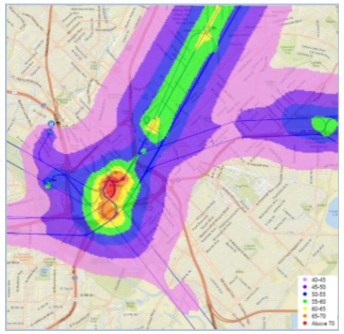


Noise Certification Analyses

Operational Fleet Noise Assessments



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

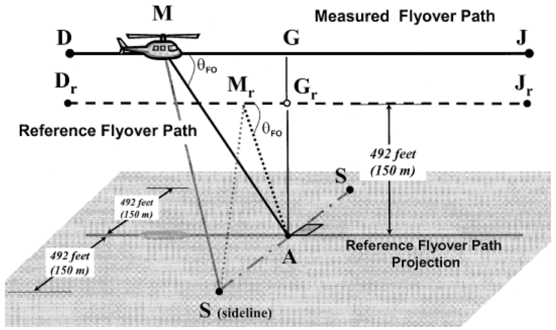


Perception-Influenced Design

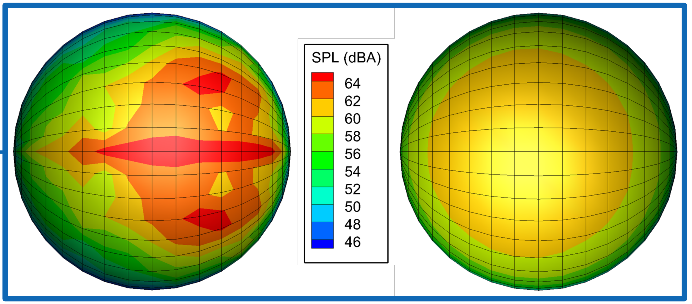
Auralization & Psychoacoustics

Utilization of Source Noise Predictions

Noise Certification Analyses



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



Noise Certification

- Aircraft noise certification is part of the aircraft type certification process
  - Noise limits specified in ICAO Annex 16, Vol 1 are in the form of Standards and Recommended Practices (SARPs)
  - SARPs exist for subsonic transport airplanes, propeller-drive airplanes, lightweight and heavy helicopters, and tiltrotors, but not specifically for UAM.

- Noise certification applicability for UAM
  - If UAM aircraft design and operational characteristics fit into an existing SARP, that SARP will be used as the certification basis.
  - Development of a noise certification process is required when new aircraft don't align with existing SARPs.
    - In the US, FAA publishes a notice of proposed rulemaking (NPRM) followed by a final rule of particular applicability (RPA). FAA may adopt same standard to similar aircraft.
    - In the EU, EASA publishes consultation paper for Environmental Compatibility Technical Specifications (EPTS) followed by a final specification. EASA may also apply to similar designs.
  - Long term approach: develop updated certification process informed by research to better understand unique noise characteristics and flight profiles

Noise Certification Standard for Tiltrotors (ICAO Chapter 13, FAR 36 Appendix K)

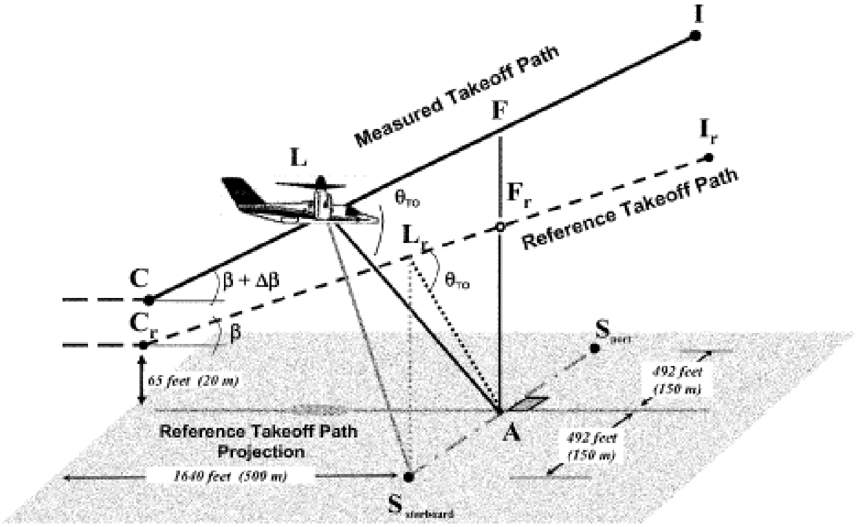


Figure K1.
Comparison of Measured and Reference Takeoff Profiles

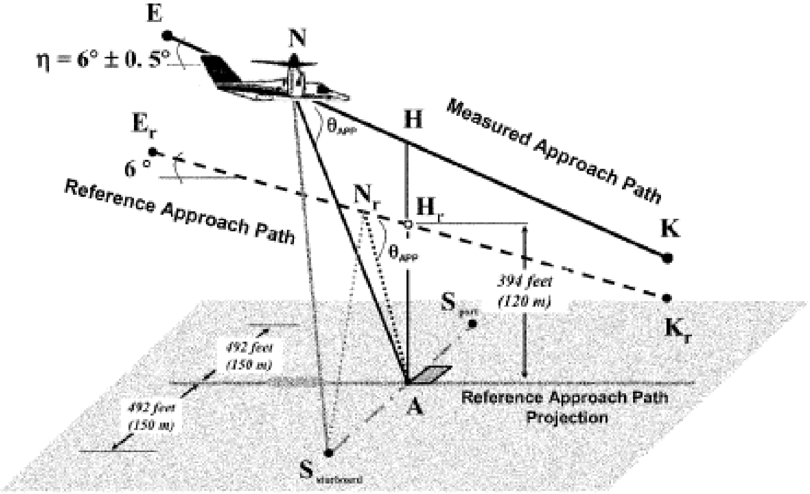


Figure K3.
Comparison of Measured and Reference Approach Profiles

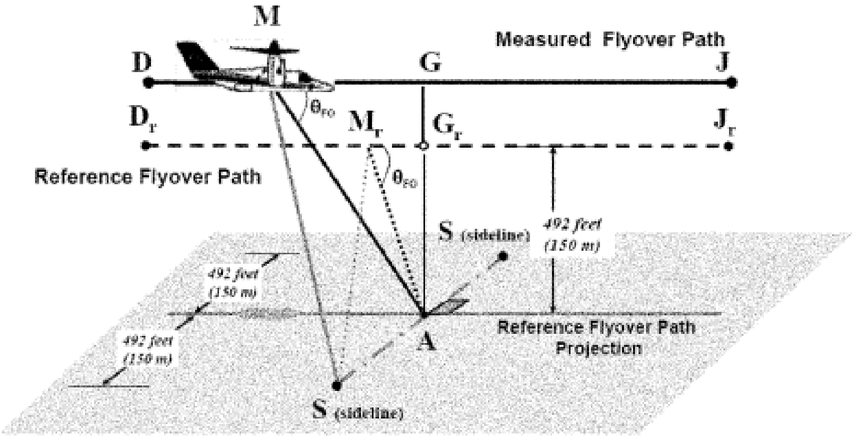
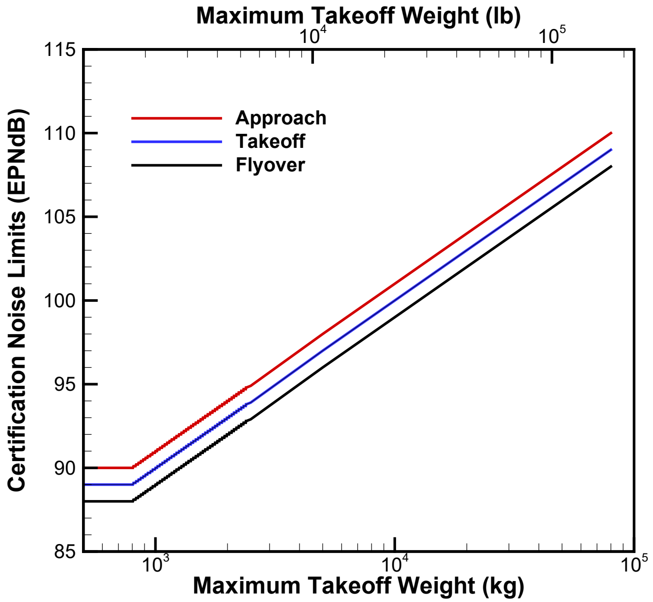


Figure K2.
Comparison of Measured and Reference Flyover Profiles



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

Noise Certification Standard for Helicopters (ICAO Chapter 8.4.2, FAR 36 Appendix H Stage 3)

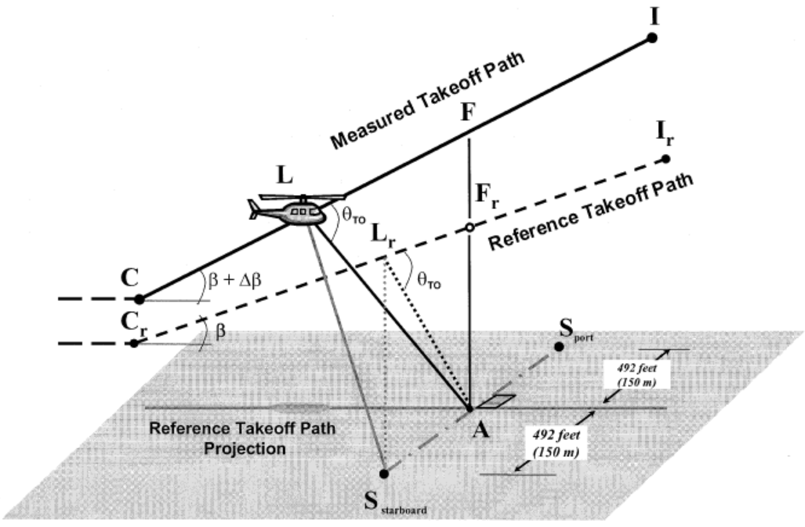


Figure H1.
Comparison of Measured and Reference Takeoff Profiles

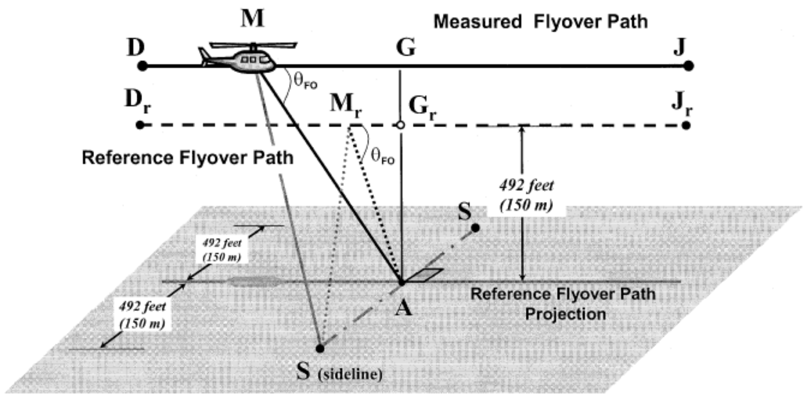


Figure H2.
Comparison of Measured and Reference Flyover Profiles

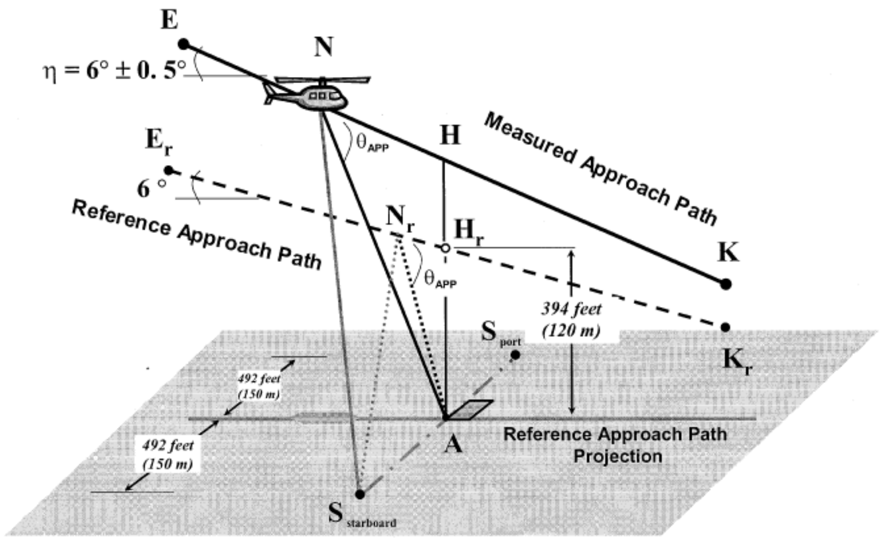
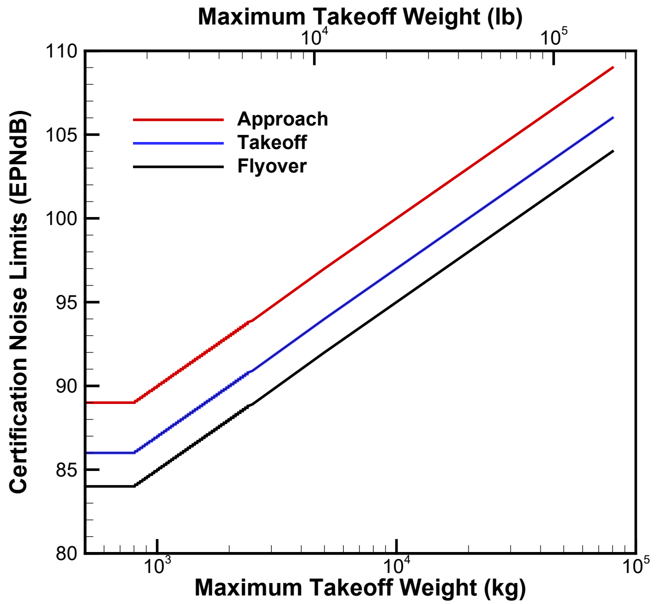


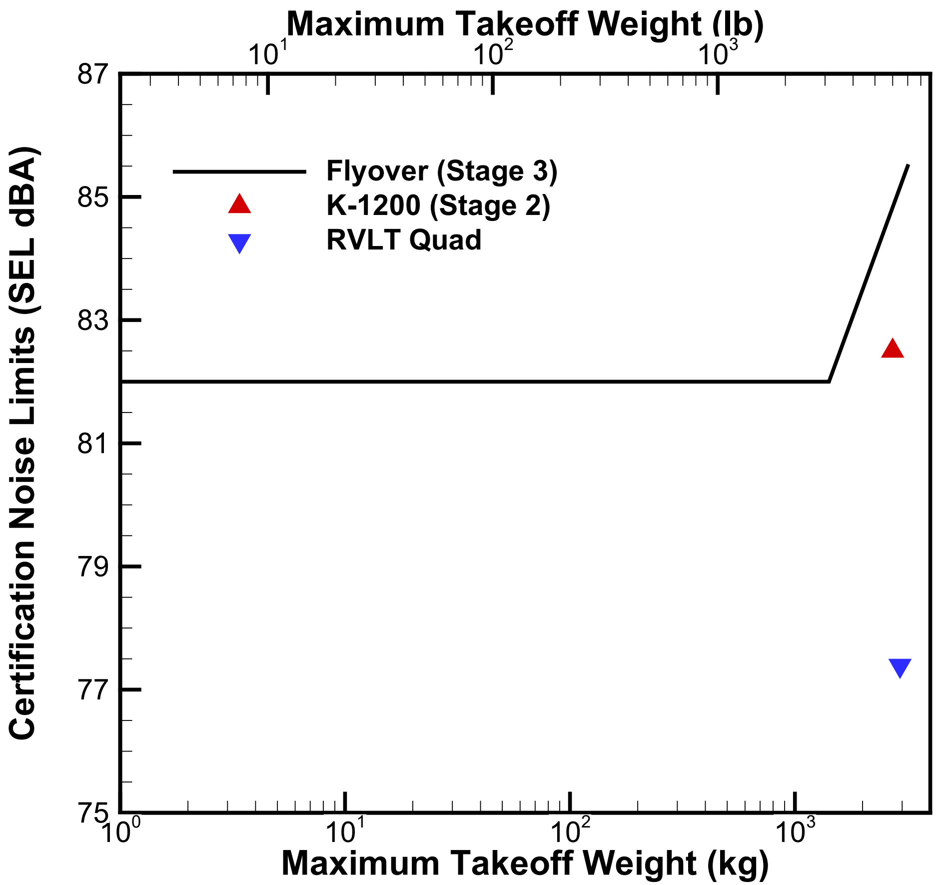
Figure H3.
Comparison of Measured and Reference Approach Profiles



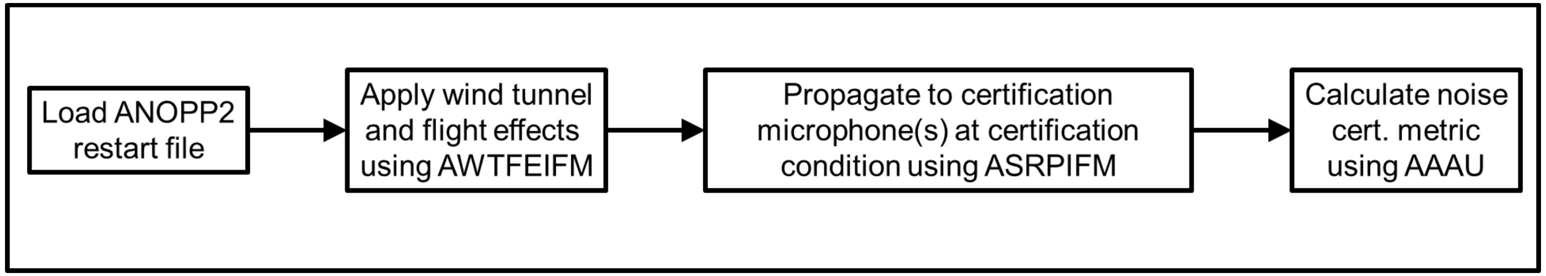
Source: https://federalregister.gov/a/04-12069

Noise Certification Standard for Light (< 3175 kg) Helicopters (ICAO Chapter 11.4.2, FAR 36 Appendix J Stage 3)

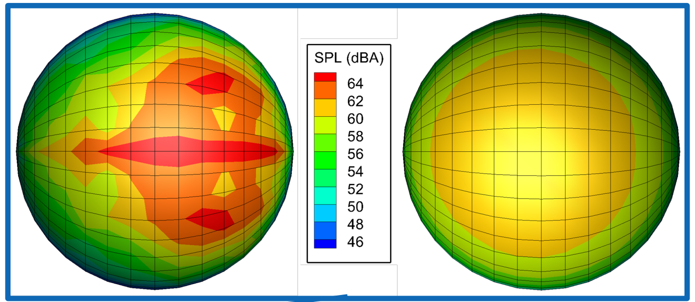
- Level overflight at 150m altitude, single 4-ft microphone directly below flight path.
- No lower weight limit
  - Matternet delivery drone (29 lbs) recently certified under RPA based on Appendix J.



NASA process for predicting UAM noise certification levels using ANOPP2 Mission Analysis Tool (AMAT)



Utilization of Source Noise Predictions



Perception-Influenced Design

Perception-Influenced Acoustic Design

Measured
Background
Predictions

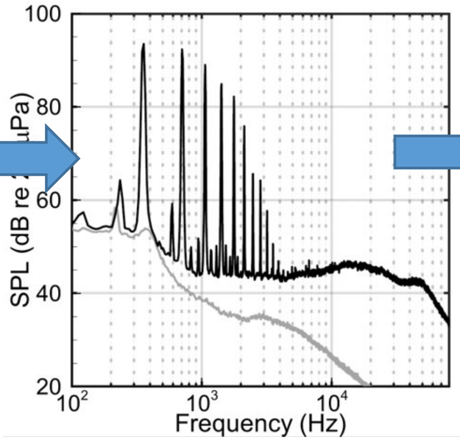
Baseline Geometry

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

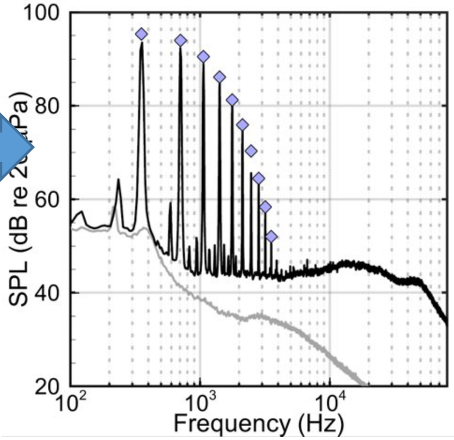
Parameter	Value
c, in. (mm)	1.5 (38.1)
P, in. (mm)	16.0 (406.4)
D_p, in. (mm)	24.0 (609.6)

Baseline Tunnel Entry

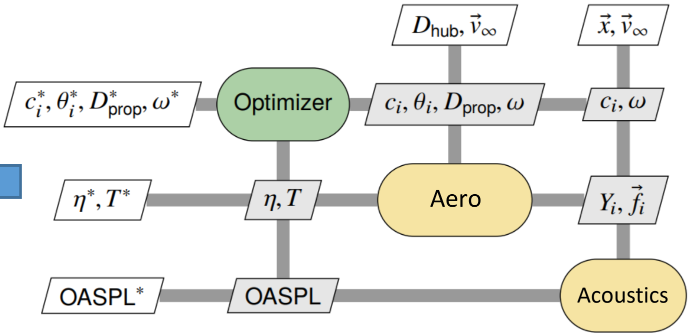
Baseline Data



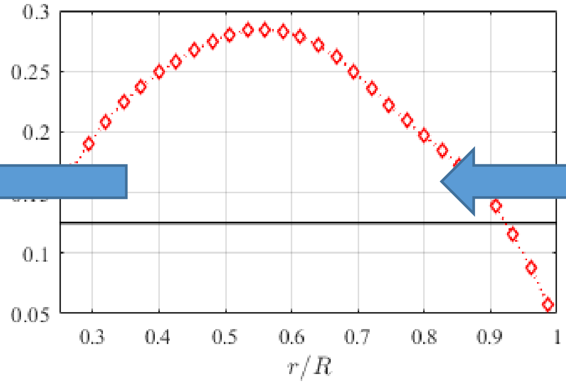
Analysis Using Optimization Tools



Design Optimization

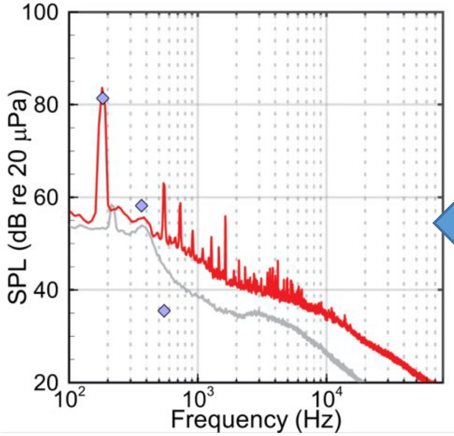


Optimized Geometry



Optimization Tunnel Entry

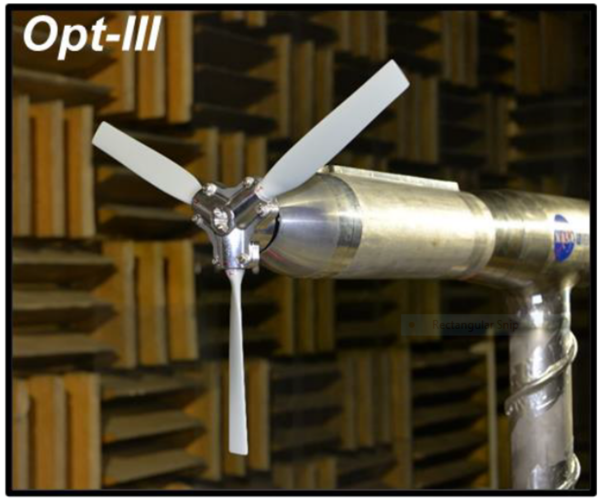
Validation Data



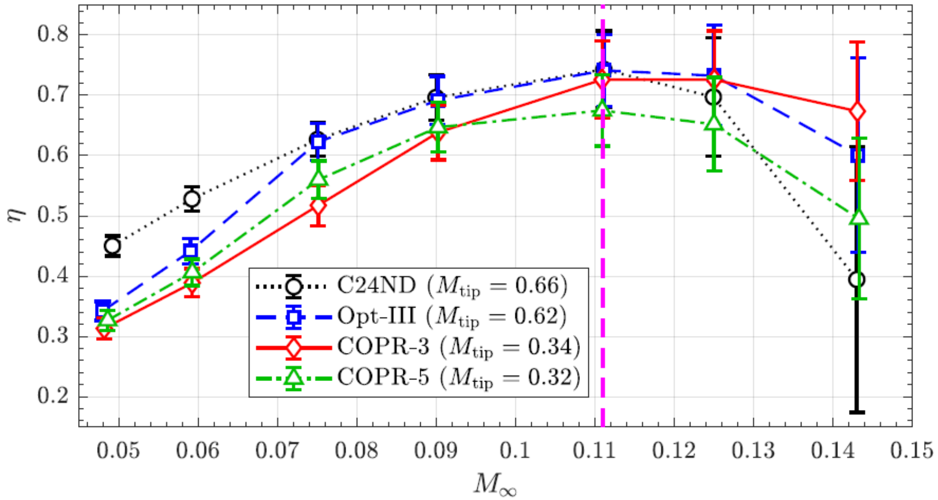
Zawodny, Pettingill, Lopes, Ingraham, "Experimental Validation of an Acoustically and Aerodynamically Optimized UAM Proprotor, Part 1: Test Setup and Results," NASA TM-20220015637, 2023, https://ntrs.nasa.gov/citations/20220015637

Perception-Influenced Acoustic Design – Isolated Proprotor

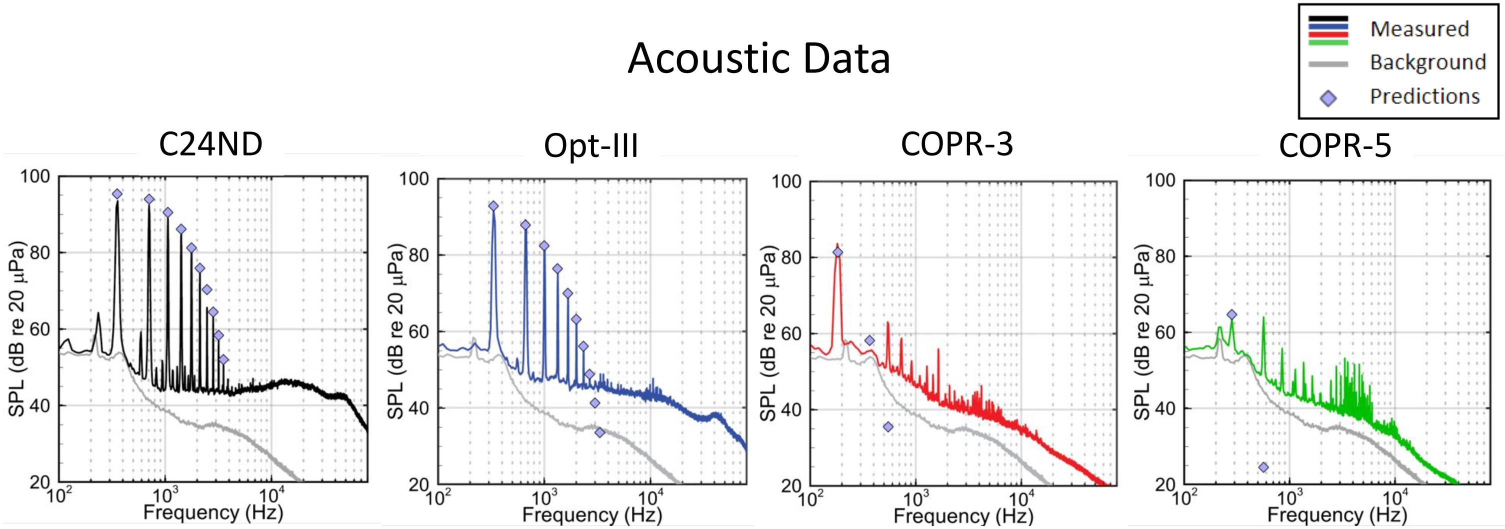
Baseline	SU2	ccblade.jl	ccblade.jl blade design x5



Performance Data

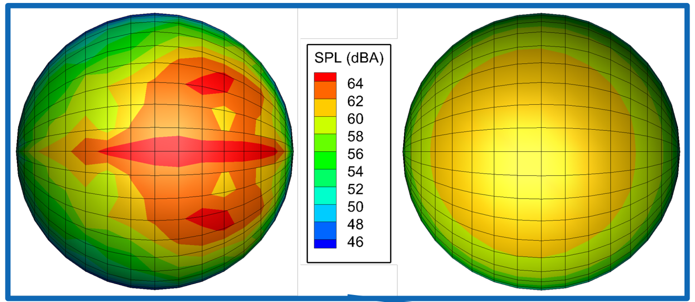


Acoustic Data



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

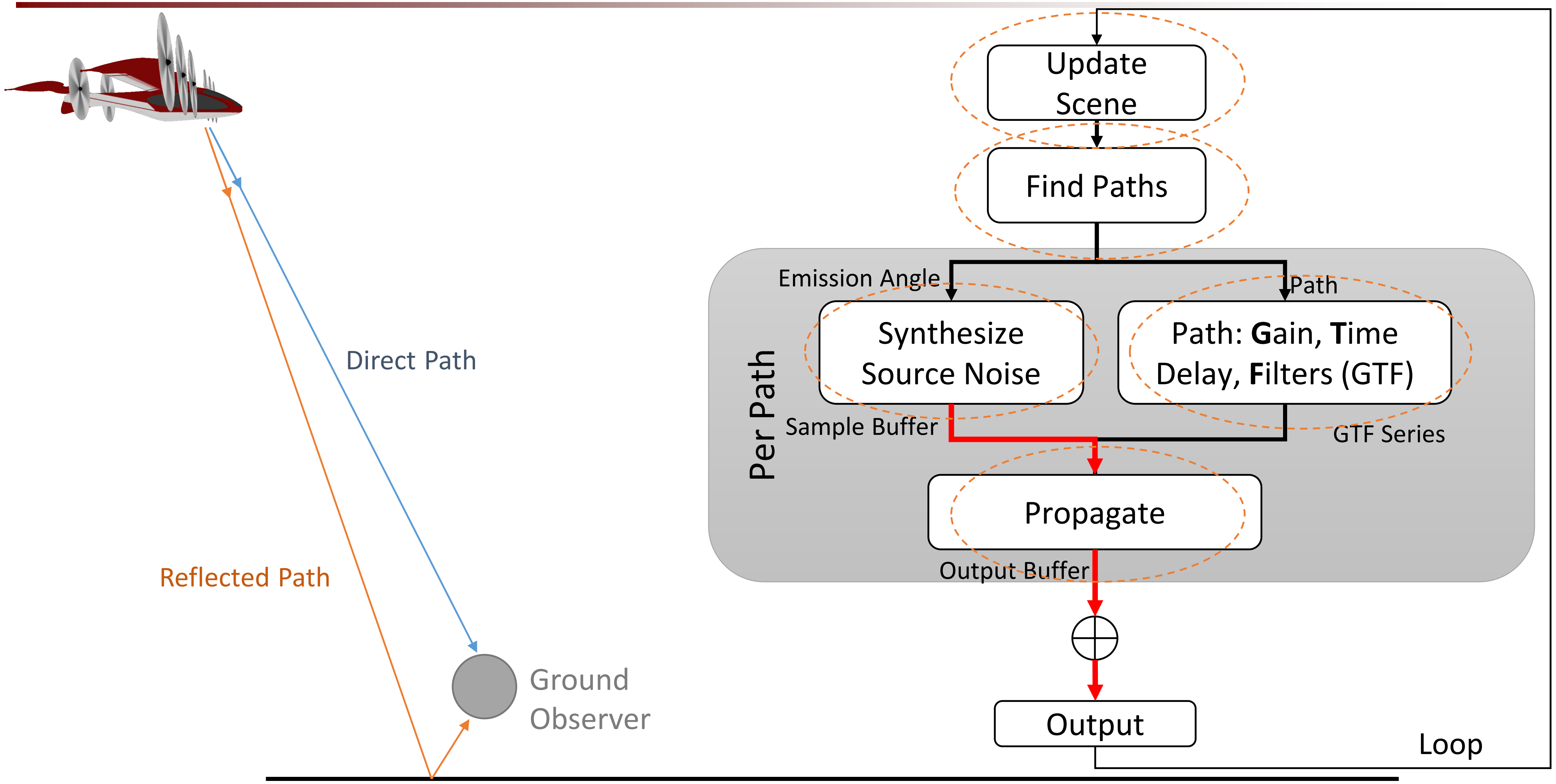
Utilization of Source Noise Predictions



Auralization & Psychoacoustics

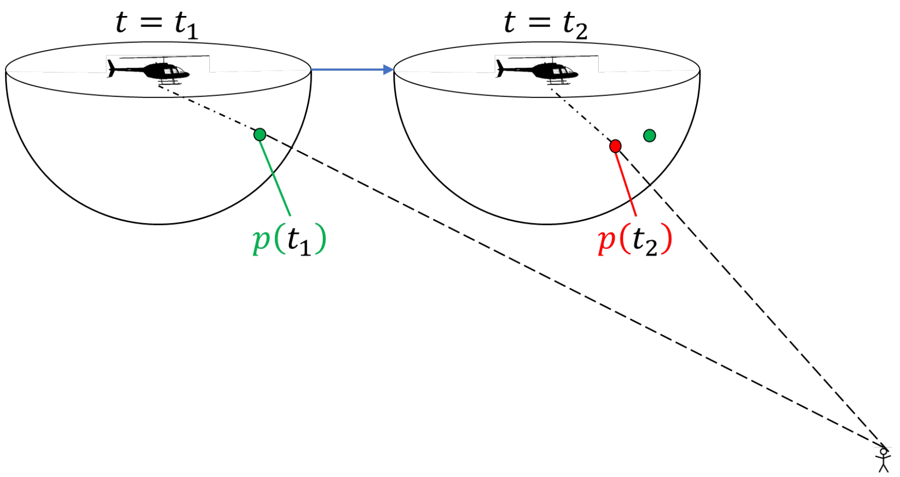
Auralization

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)

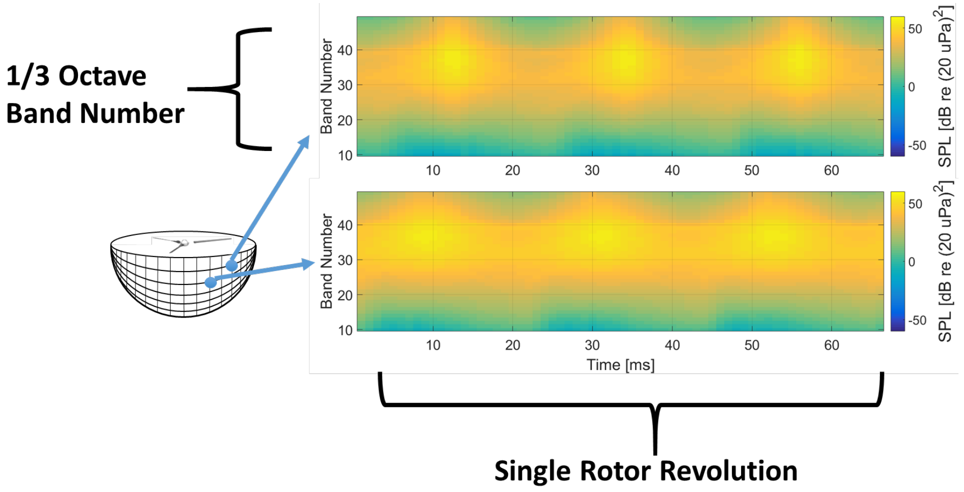


Quadrotor Periodic

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

Level Flyover

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

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.

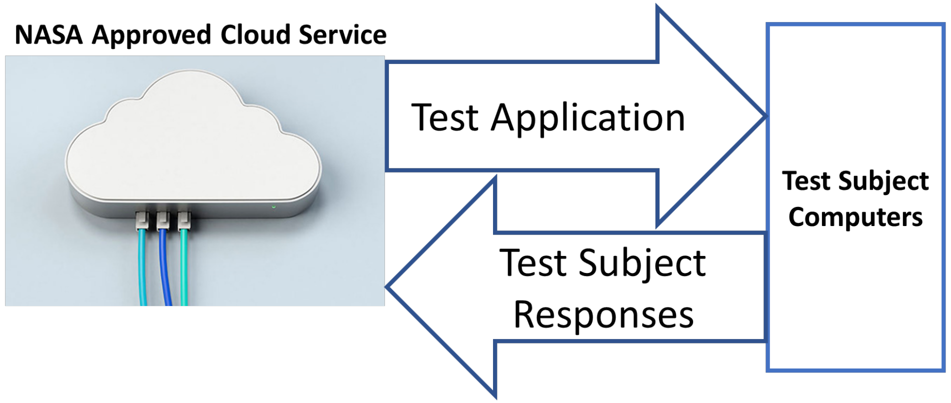
- Test of Noise and Numbers (completed January 2023)
  - Objective: Investigate how annoyance varies with number of operations, spacing between operations, and makeup of the fleet.
  - To be presented at NASA Acoustics Technical Working Group mtg., Fall 2023

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

- 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. (2024).

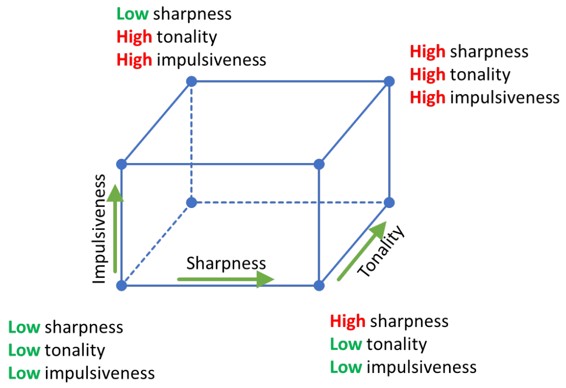
Exterior Effects Room (EER)

Remote Psychoacoustic Testing Platform

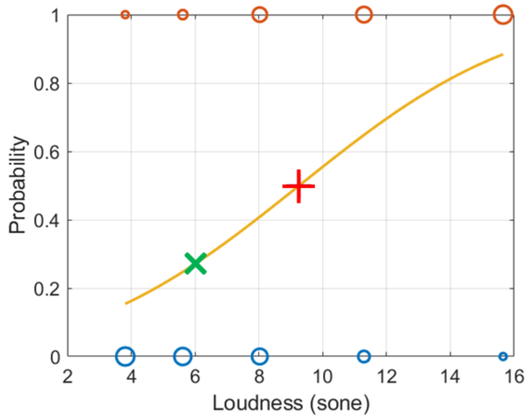


Psychoacoustic Studies

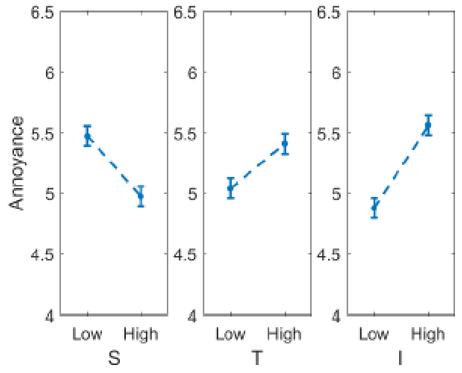
Test of UAM Sound Quality (TuSQ)



- Baseline auralizations of level cruise and descent manipulated to provide range of SQ attributes.



- Difference in loudness 3 sones (~6 dB) at equal annoyance point +
- UAM sounds more annoying than ref. sound when presented at same level x

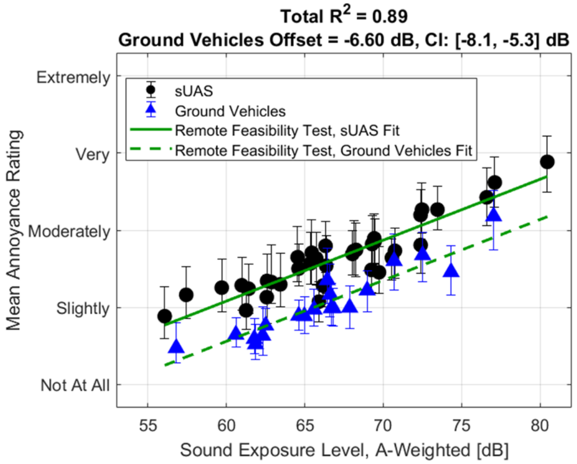


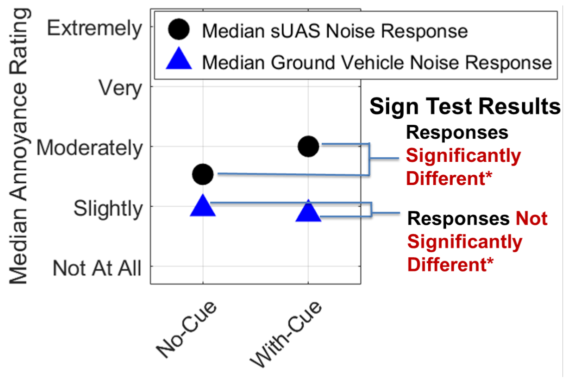
- Tonality, impulsiveness and roughness: positive correlation with annoyance.
- Sharpness: negative correlation with annoyance (at low levels)

Boucher, Rafaelof, Begault, Christian, Krishnamurthy, Rizzi, "A Psychoacoustic Test for Urban Air Mobility Vehicle Sound Quality," SAE TP 2023-01-1107, 2023, https://doi.org/10.4271/2023-01-1107.

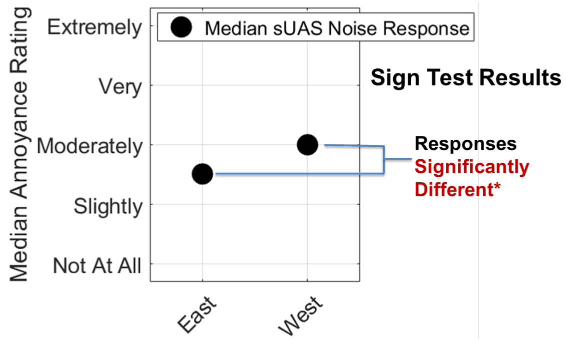
Cooperative Human Response Study (Feasibility)

- Replicated previous in-person test but found larger annoyance diff. between sUAS and ground vehicles.



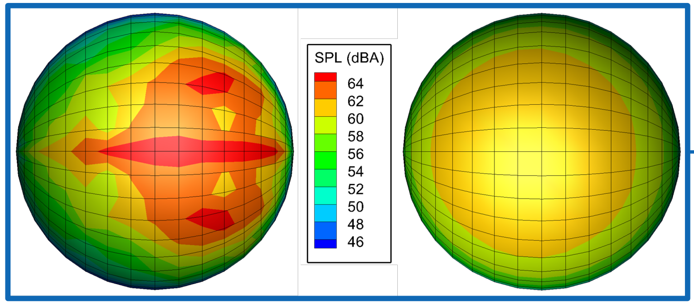


- Contextual cue affected annoyance to sUAS but not ground vehicle noise.
- Detected annoyance response differs between two geographically distinct subject groups.

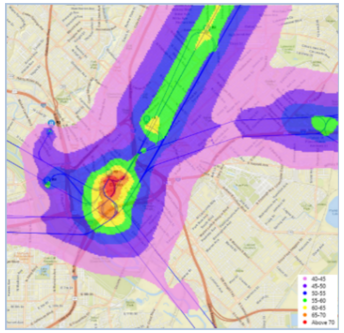


Krishnamurthy, Rizzi, Biziorek, Czech, Berg, Tannler, Bean, Ayrapetyan, Nguyen, Wivagg, "Remotely Administered Psychoacoustic Test for sUAS Noise to Gauge Feasibility of Remote UAM Noise Study," SAE TP 2023-01-1106, 2023, https://doi.org/10.4271/2023-01-1106.

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.

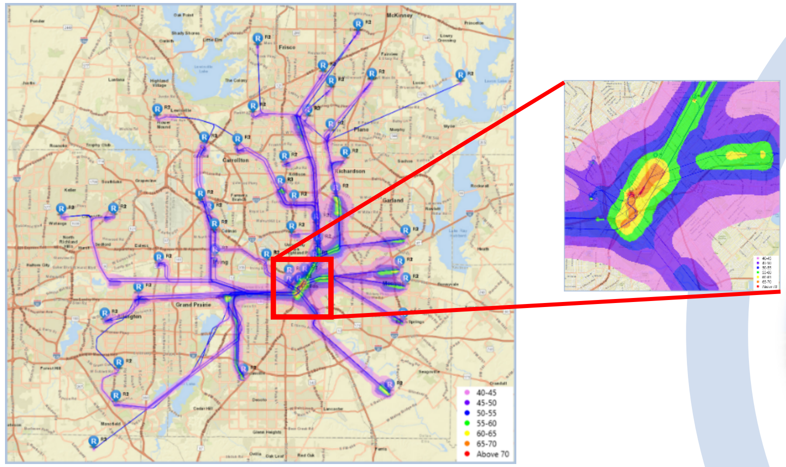
‡ Rizzi, Rafaelof, "Community Noise Assessment of Urban Air Mobility Vehicle Operations using the FAA Aviation Environmental Design Tool," InterNoise 2021, Virtual, 2021.

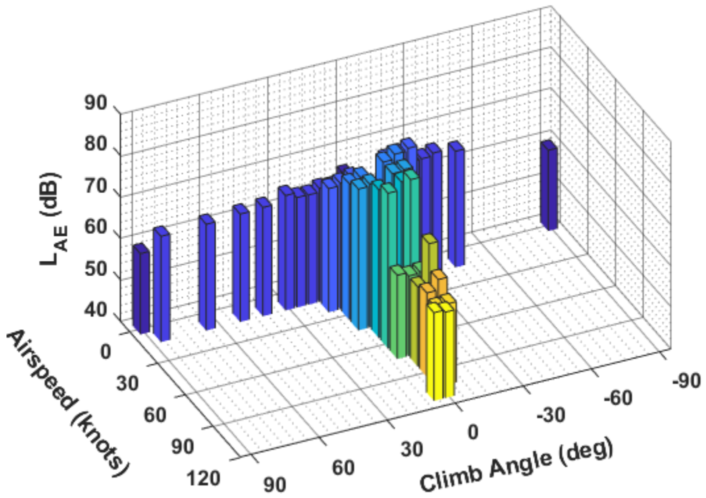
‡ Rizzi, Rafaelof, "Second Generation UAM Community Noise Assessment using the FAA Aviation Environmental Design Tool," AIAA SciTech Forum, San Diego, CA, Jan 2022, AIAA-2022-2167, https://doi.org/10.2514/6.2022-2167.

§ Rizzi, Rafaelof, "On the Modeling of UAM Aircraft Community Noise in AEDT Helicopter Mode," 29th AIAA/CEAS Aeroacoustics Conference, San Diego, CA, June 2023, AIAA-2023-3363, https://doi.org/10.2514/6.2023-3363.

UAM Operational Fleet Noise Assessments

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





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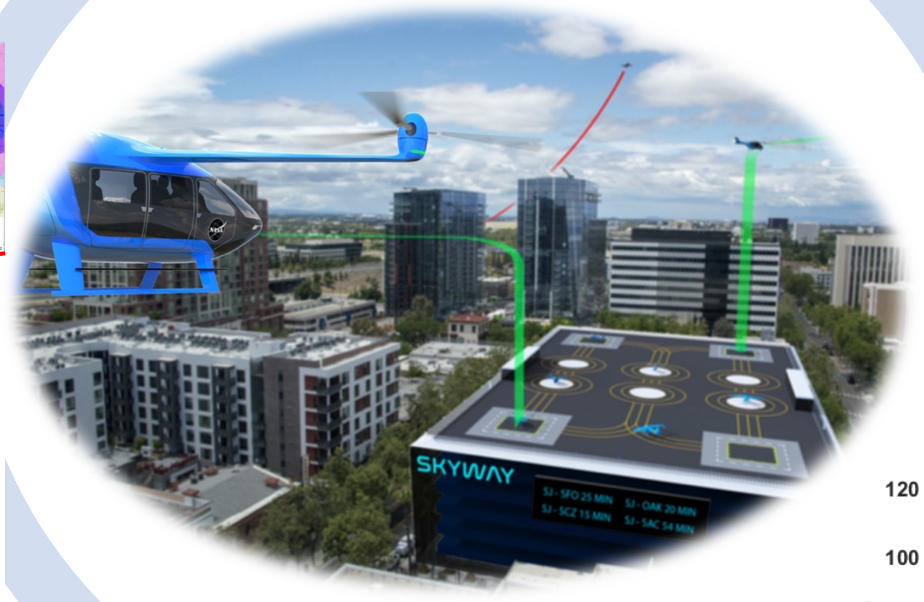
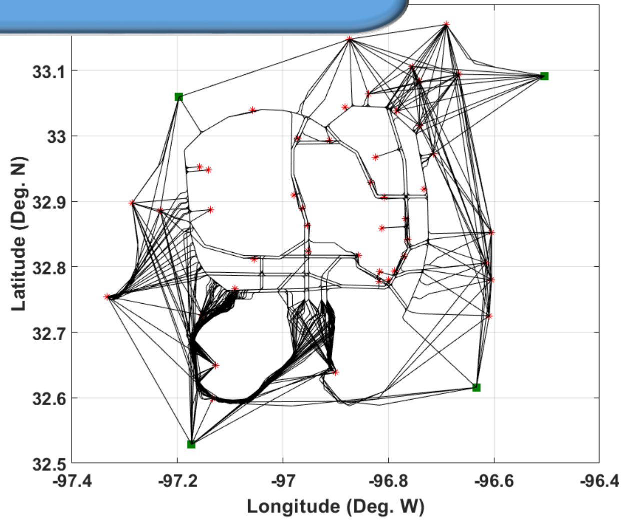
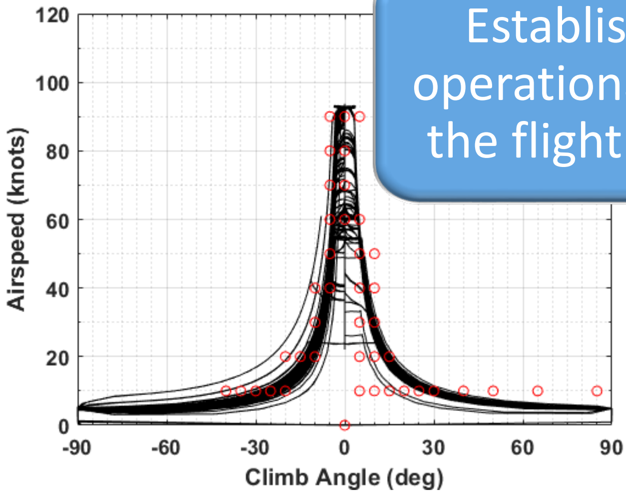


Identify routes, trajectories, and aircraft flight conditions



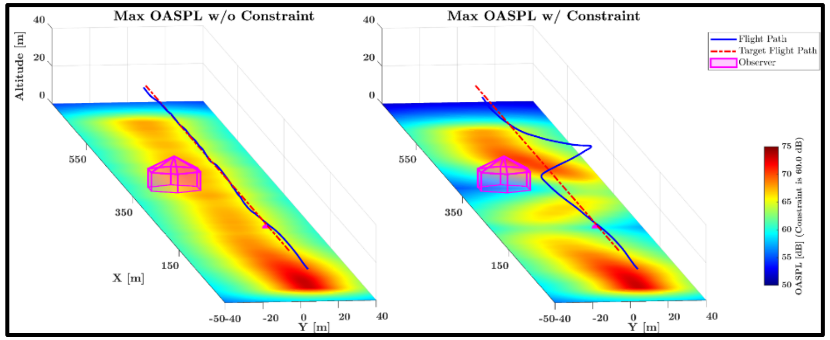
Establish aircraft operational states for the flight conditions



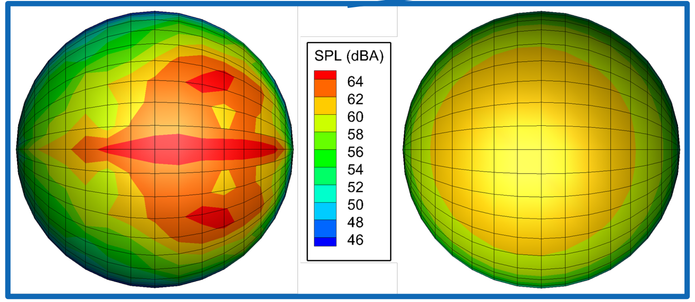
Evaluate source noise and generate noise-power-distance data using AMAT

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

Utilization of Source Noise Predictions



Acoustically Aware Flight Control



Motion Planning

Ackerman, Gregory, Theodorou, Hovakimyan, “A Model Predictive Control Approach for In-Flight Acoustic Constraint Compliance,” 2021 AIAA SciTech Forum, Virtual, AIAA-2021-1958, 2021, 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

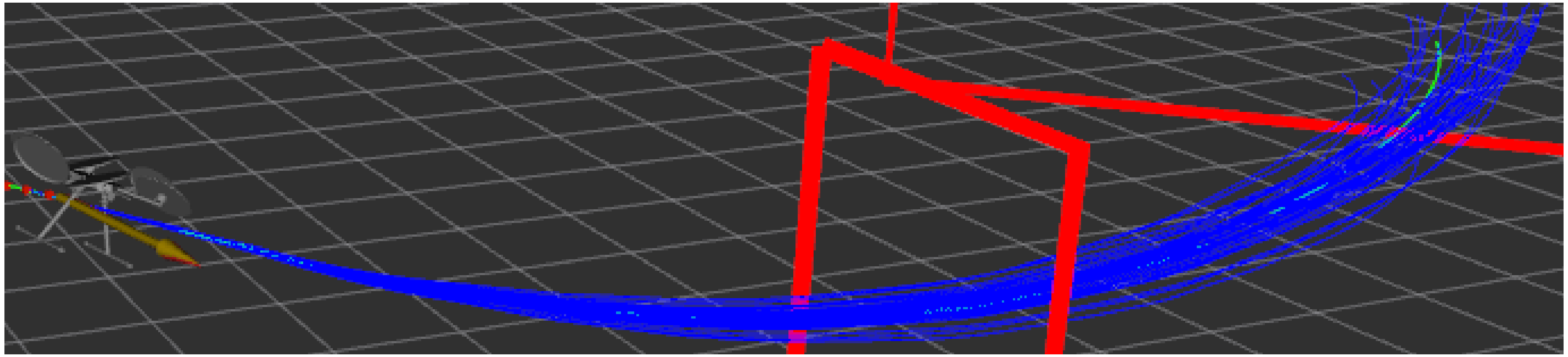
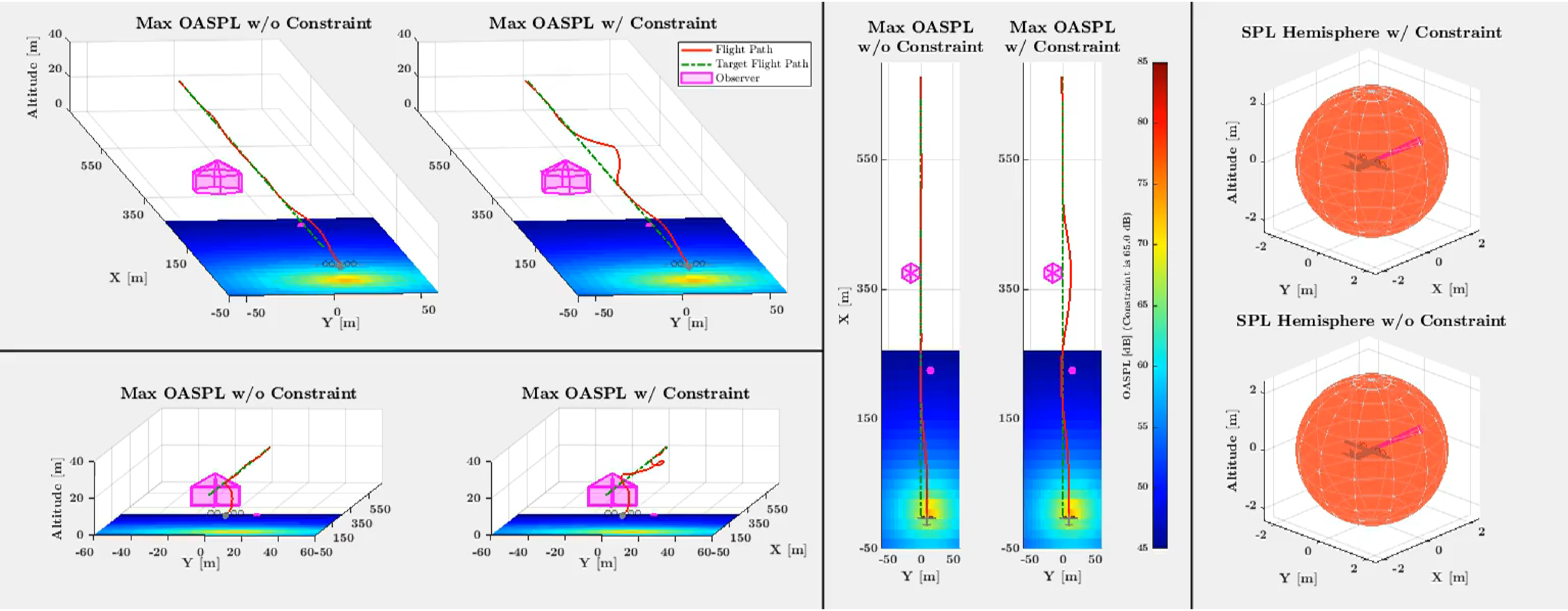


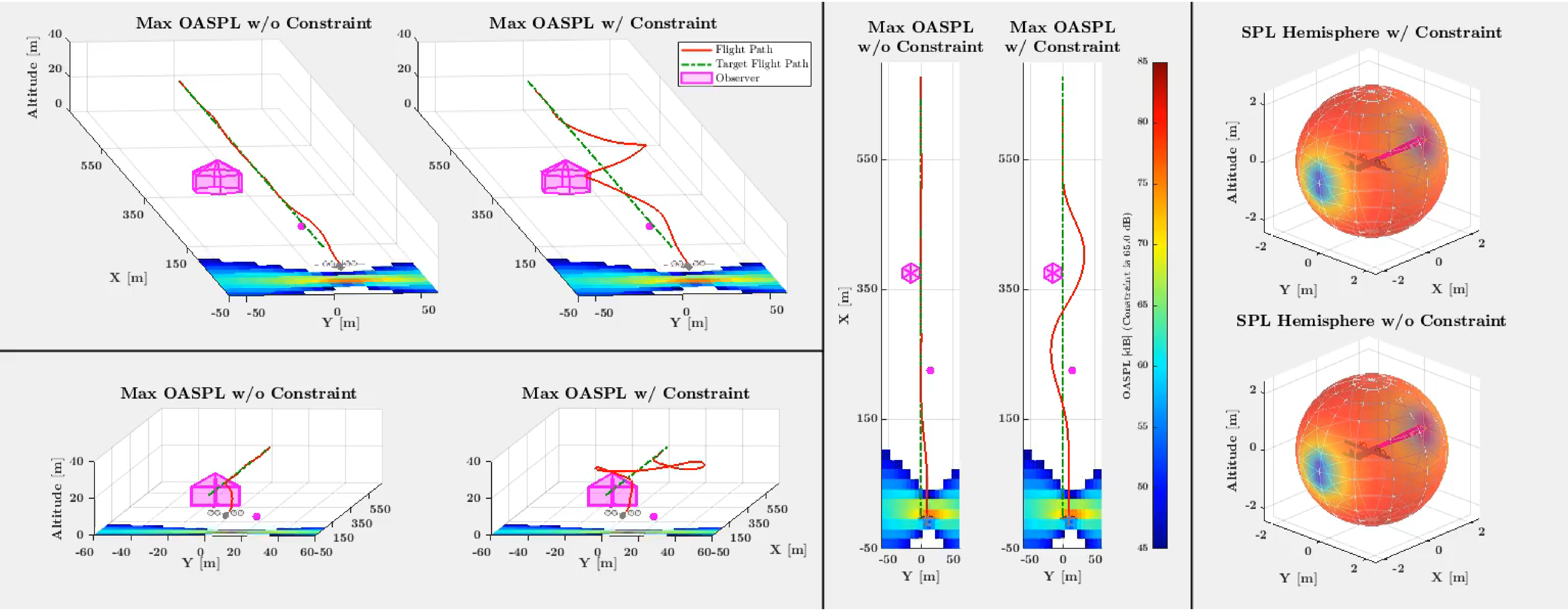
Figure credit: Pravitra, Ackerman, Cao, Hovakimyan, Theodorou, “L1-Adaptive MPPI Architecture for Robust and Agile Control of Multirotors,” IROS, 2020, https://doi.org/10.1109/IROS45743.2020.9341154.

Simulation Results – Video (monopole source)



*Aircraft is animation only, not to scale or representative

Simulation Results – Video (directive source)



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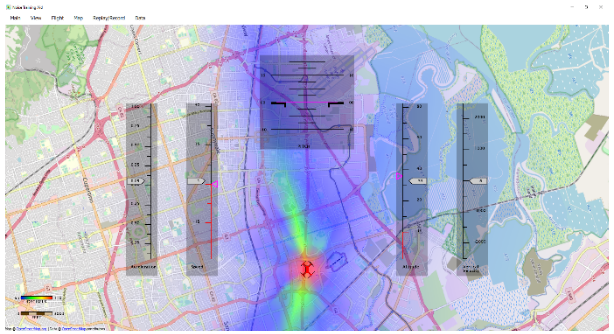
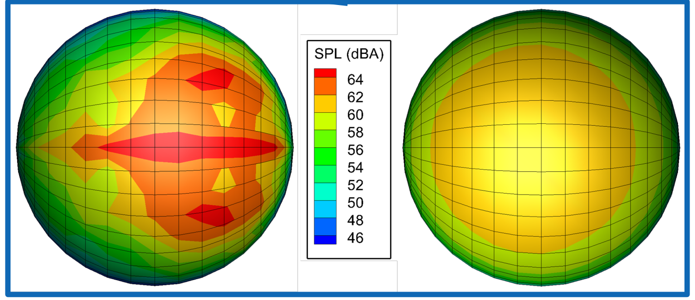
Utilization of Source Noise Predictions

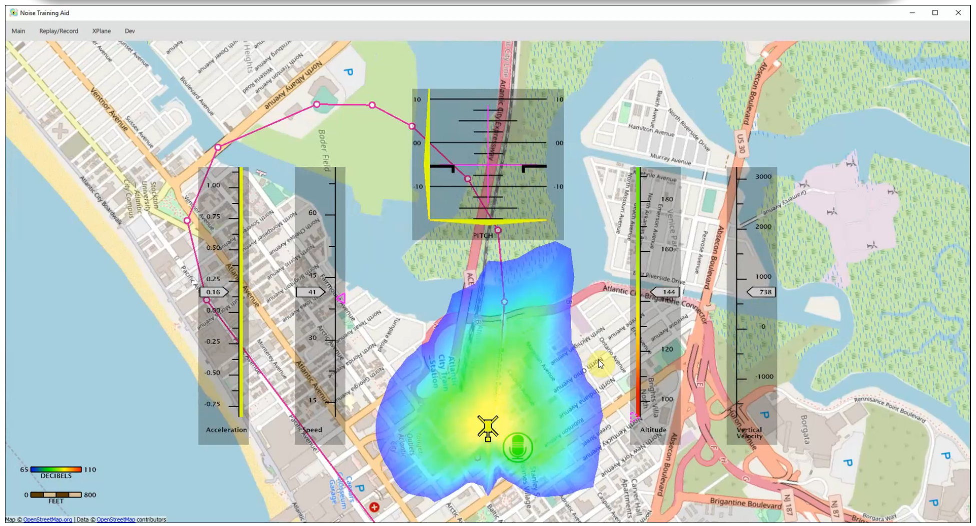


Acoustic Flight Simulator



Generate predicted helicopter ground noise footprint based on:

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



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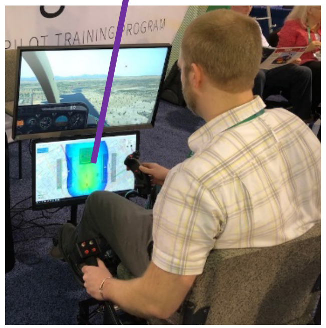
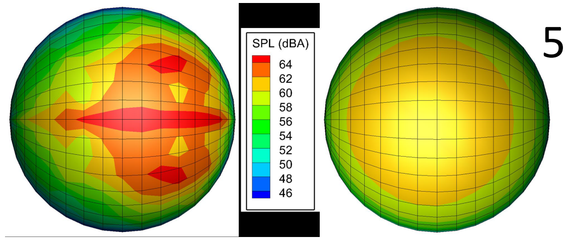


Generate predicted **UAM** ground noise footprint at each timestamp based on:

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



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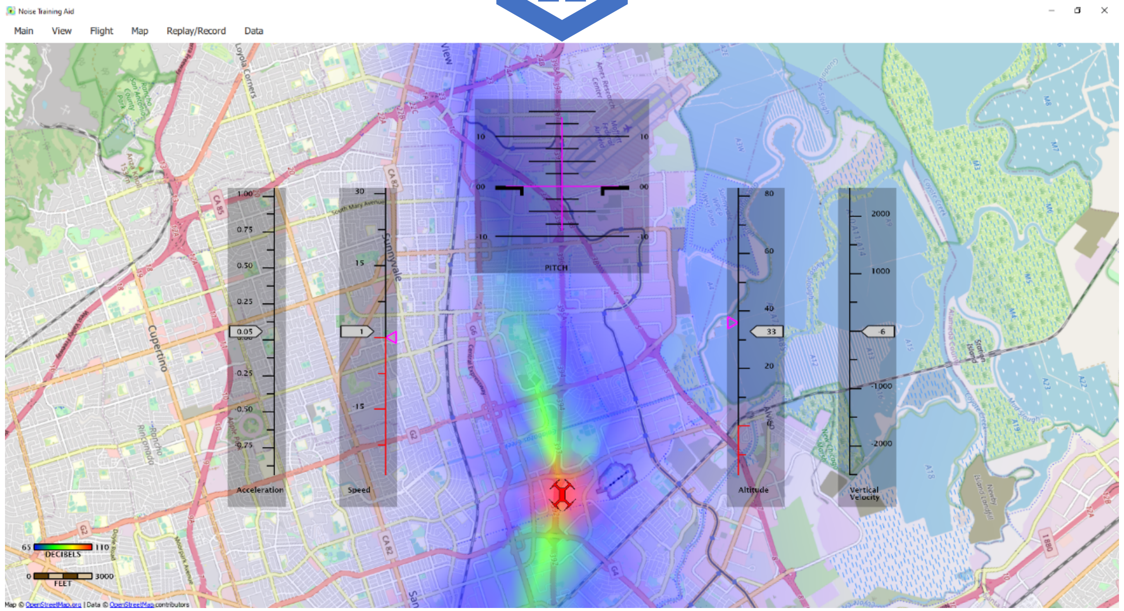

1. Helicopter noise spheres: Greenwood, "Real time helicopter noise modeling for pilot community noise awareness," *Noise-Con 2017,* June 2017.
2. Acoustic flight simulator: Trujillo, Hill, "Acoustic Flight Simulator Architecture, Noise Training Aid Manual, and Its Training Benefits," NASA-TM-2021-0014096, 2021, https://ntrs.nasa.gov/citations/20210014096.
3. Trajectory generation: Ackerman, Gregory, Theodorou, Hovakimyan, "A Model Predictive Control Approach for In-Flight Acoustic Constraint Compliance," AIAA-2021-1958, 2021 AIAA SciTech Forum, Virtual, 2021, https://doi.org/10.2514/6.2021-1958..
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, 2022, https://doi.org/10.2514/6.2022-2839.

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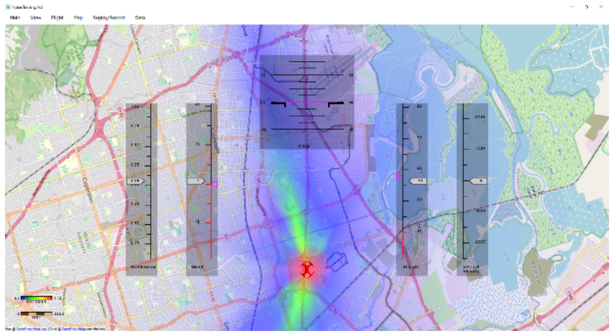

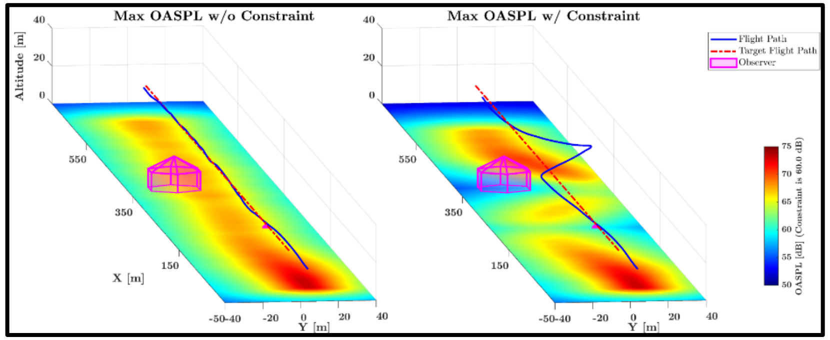

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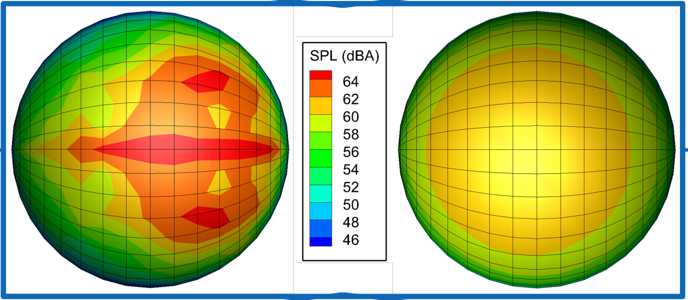
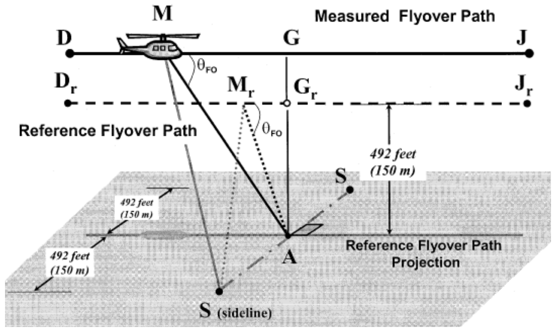
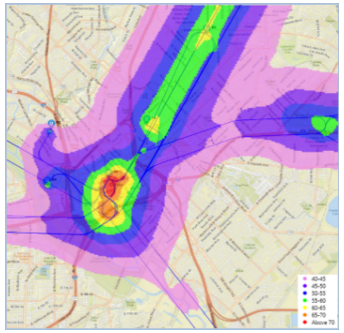


Noise Certification Analyses

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

Community Noise Impact of Urban Air Mobility Vehicle Operations

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DLR Colloquium
Göttingen, Germany
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