Project 77

Measurements to Support Noise Certification for UAS/UAM Vehicles and Identify Noise Reduction Opportunities

Penn State

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Cost Share Partner: Beta Technologies (UAM OEM)

Objective:

To develop repeatable noise measurement methods for UAS and UAM vehicles and to use these methods to collect noise data on a variety of UAS and UAM configurations across different operating modes, speeds, and altitudes.

Project Benefits:

- Inform noise certification standards
- Research database of UAS and UAM noise
- Reduce negative acoustic impacts of UAS and UAM through design changes and operation

Research Approach:

- Simulate UAS and UAM noise measurements
- Develop noise source separation for distributed propulsion vehicles
- Investigate instrumentation requirements for acoustics, weather, and vehicle state
- Collect noise data on UAS and UAM components and vehicles
- Explore acoustical effects of design changes, operating procedures, and flight control laws

Major Accomplishments (to date):

- Simulation of UAS noise to understand rotor interference effects and far-field distance
- Measurements exploring the repeatability and variability of multirotor UAS noise
- Development and acoustic testing of highly reconfigurable multirotor research UAS vehicles
- Flyover and ground test acoustic measurements of Beta Technologies ALIA-250 UAM aircraft
- Development of UAS synchrophasing system

Future Work / Schedule:

- Apply Project 49 noise prediction system to investigate variability of UAS and UAM noise
- Expand measurements of UAS configurations
- Validate multirotor noise source separation
- Explore effects of flight control system on noise

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Motivation

- **Existing methods of characterizing aircraft noise assume "stationarity"**

- **UAS and UAM noise is likely to be highly variable**
  - Smaller vehicles are more susceptible to disturbances
  - RPM control often used to stabilize or maneuver vehicle
  - "Nearly-coherent" addition of tonal noise
  - May be highly over-actuated, e.g., no "unique" trim

- **Need new techniques to *reliably* characterize noise radiation**
  - Noise certification
  - Input data for environmental impact analyses
  - Semiempirical modeling and design of low noise operations
  - Inform flight control and design changes to reduce noise

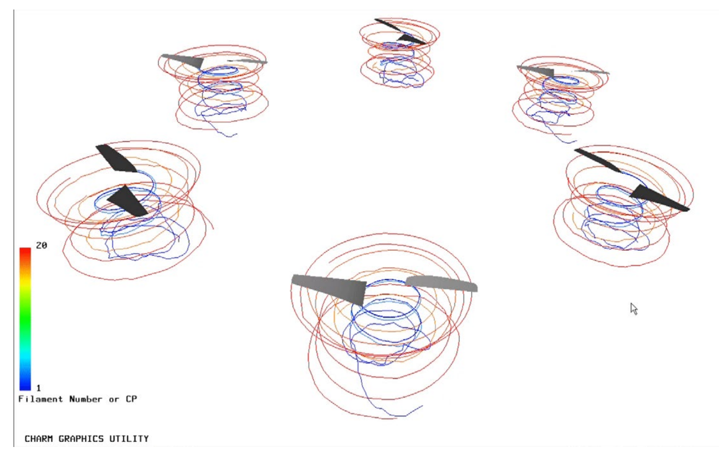

Boeing Cargo Air Vehicle

Beta Ava XC

Approach

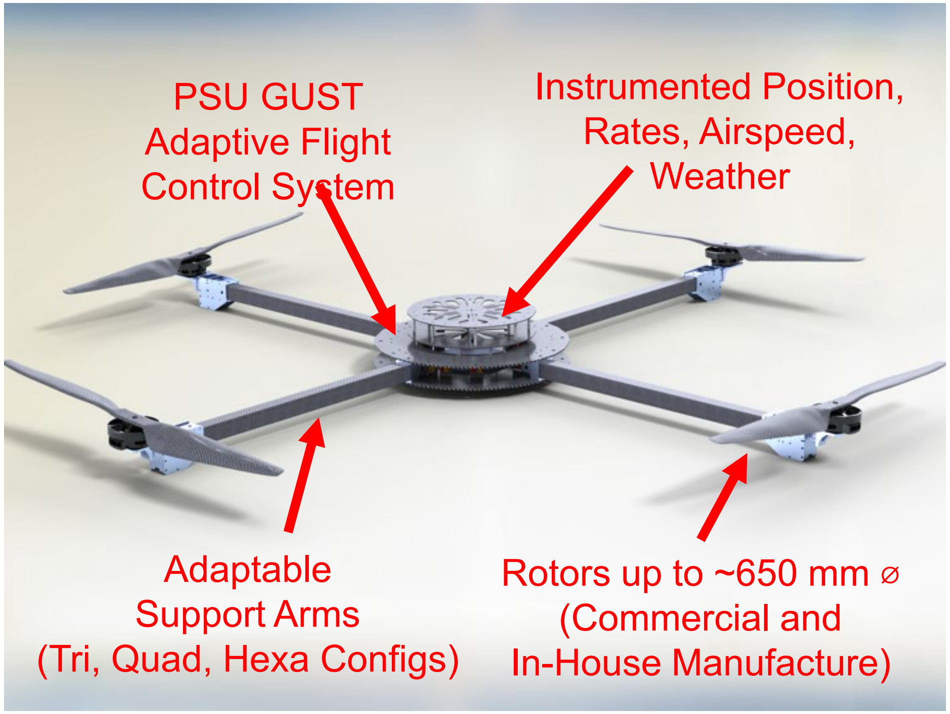
- Leverage noise prediction tools (e.g., Project 49) to conduct simulated acoustic experiments
- Develop flight procedures and processing methods to characterize and reduce variability and uncertainty
- Collect acoustic data on a variety of UAS and UAM aircraft configurations
- Explore the effects of design changes, operating procedures, and flight control laws on noise

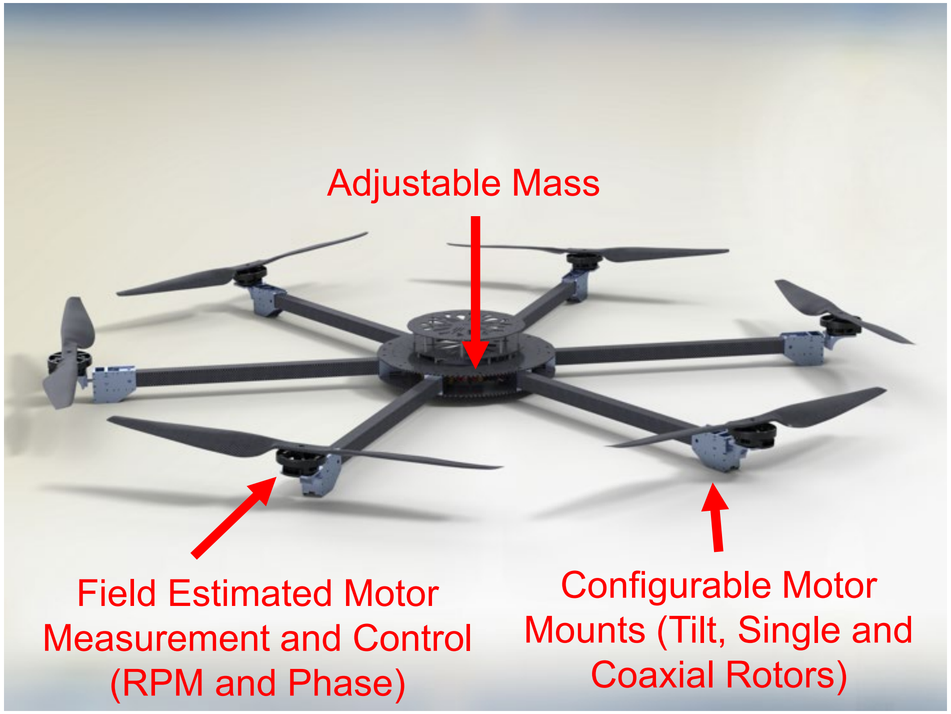
Large reconfigurable UAS in flight



Aerodynamic prediction using CDI's CHARM free vortex wake

Reconfigurable UAS Aircraft

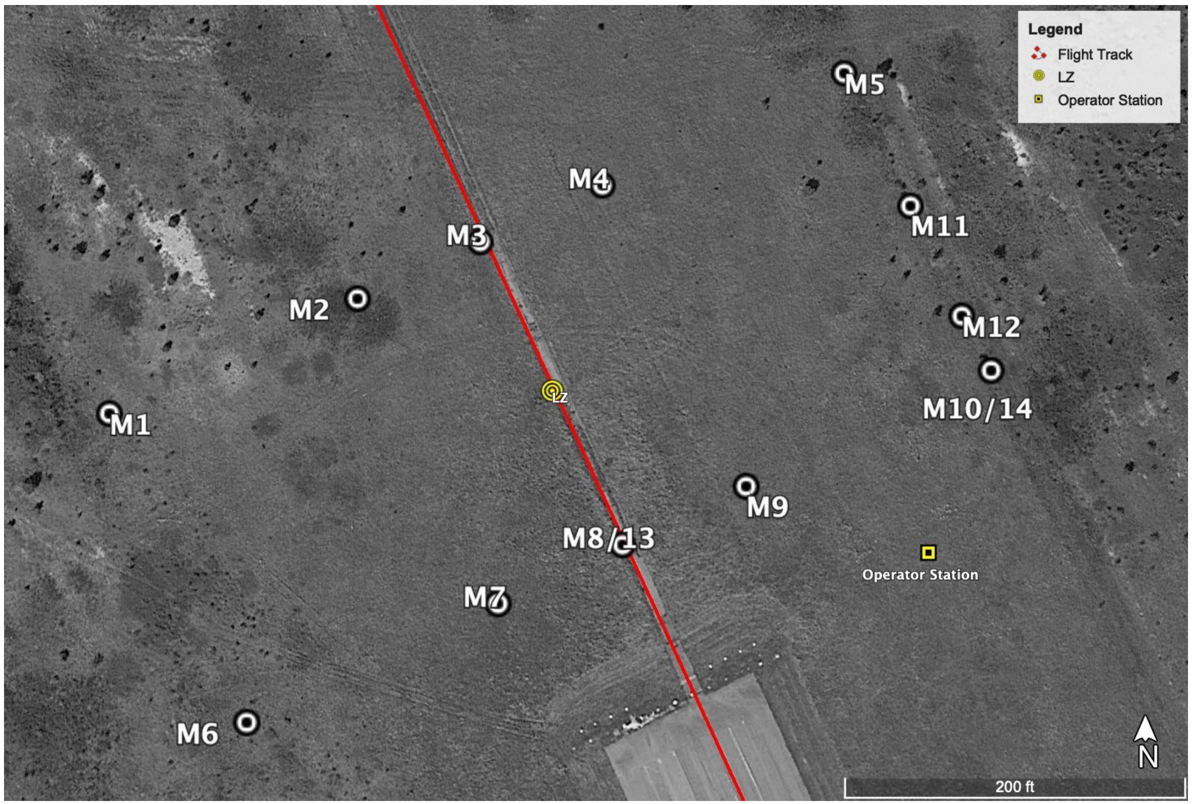




- Large reconfigurable UAS (1.5m tip-to-tip)
- Large payload capacity (over 50 kg max gross weight with waiver)
- Space, weight, and power for research instrumentation sensors
  - Ultrasonic airspeed measurement
  - Motor encoders
  - Real Time Kinematic Different GPS
- Additional provisions for rotor tilt and aerodynamic surfaces

UAS Noise Measurements

Ground Instrumentation



Instrumentation

- Acoustics
  - Up to 36 microphones
  - 131 kHz @ 24 bit
  - GPS time synchronization
- Survey-grade GPS position (~6" accuracy)
- 4' met stations
- Soon: ultrasonic anemometers

Beta Technologies ALIA-250

Several rounds of measurements with Beta Technologies to characterize ALIA-250 UAM:

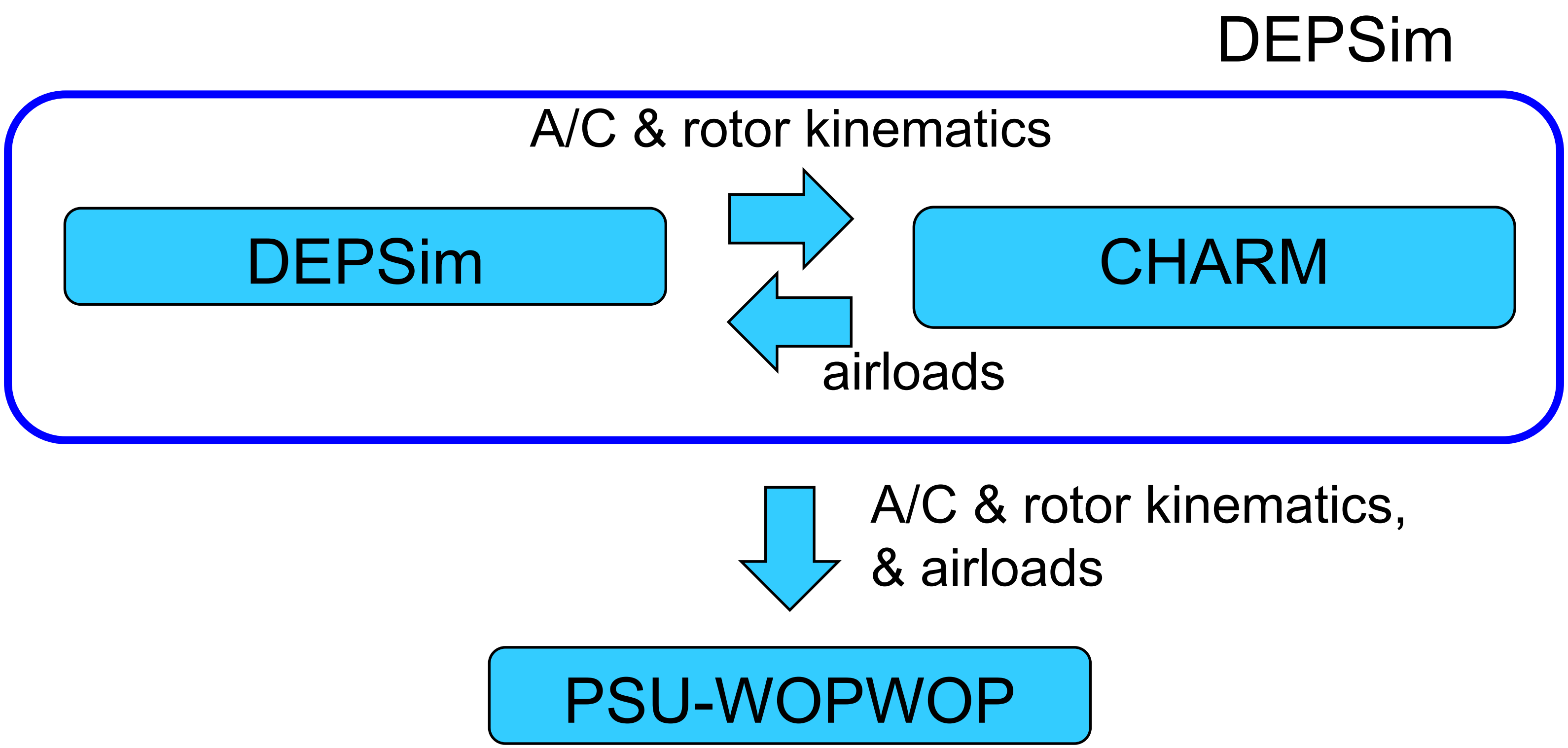
- Flyover
- Full scale isolated rotor
- Hover*
- Subscale*

Planned

Noise Prediction System

Components:

- DEPSim: flight simulation code for DEP aircraft
- CHARM: aeromechanics modeling code by CDI
- PSU-WOPWOP: acoustic propagation solver



DEPSim: Distributed Electric Propulsion Simulator
CHARM: Comprehensive Hierarchical Aeromechanics Rotorcraft Model

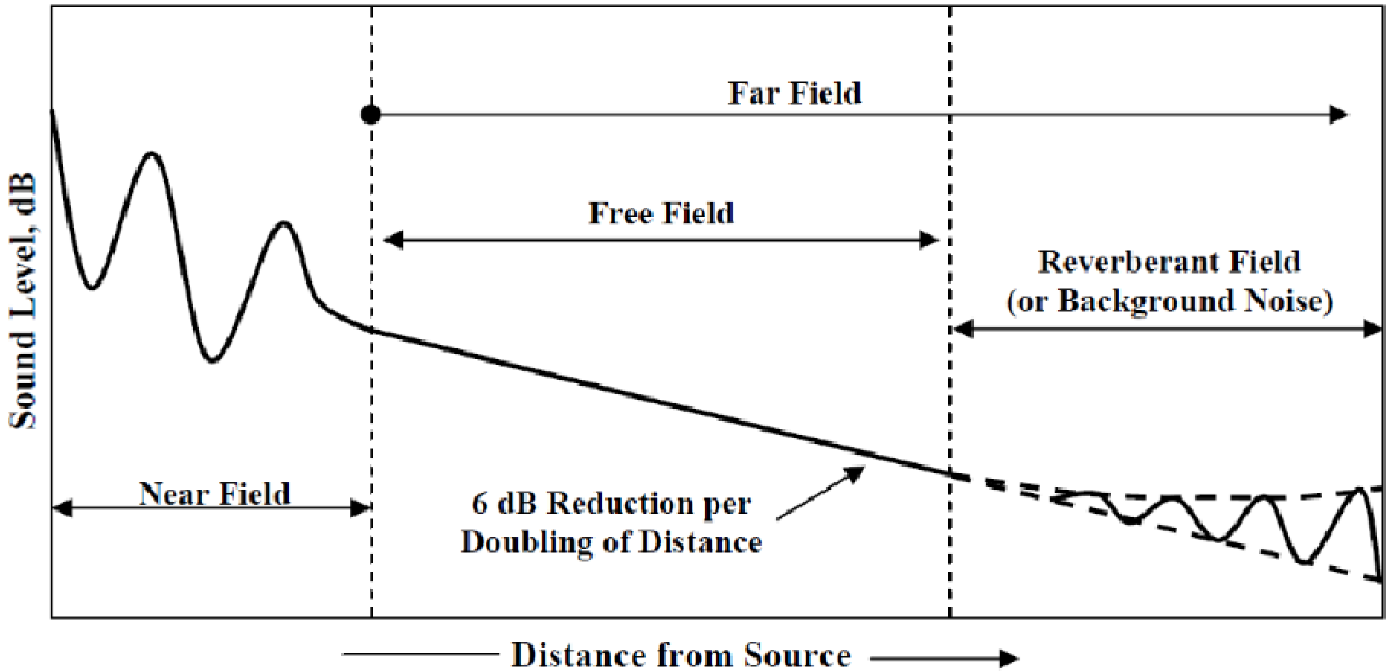
Recent Highlights

- Computational and experimental investigations of the extent of the acoustic far field for multirotor aircraft

- Experimental investigation and characterization of the variability of UAS and UAM noise

- Development and validation of a synchrophasing controller for UAS noise reduction

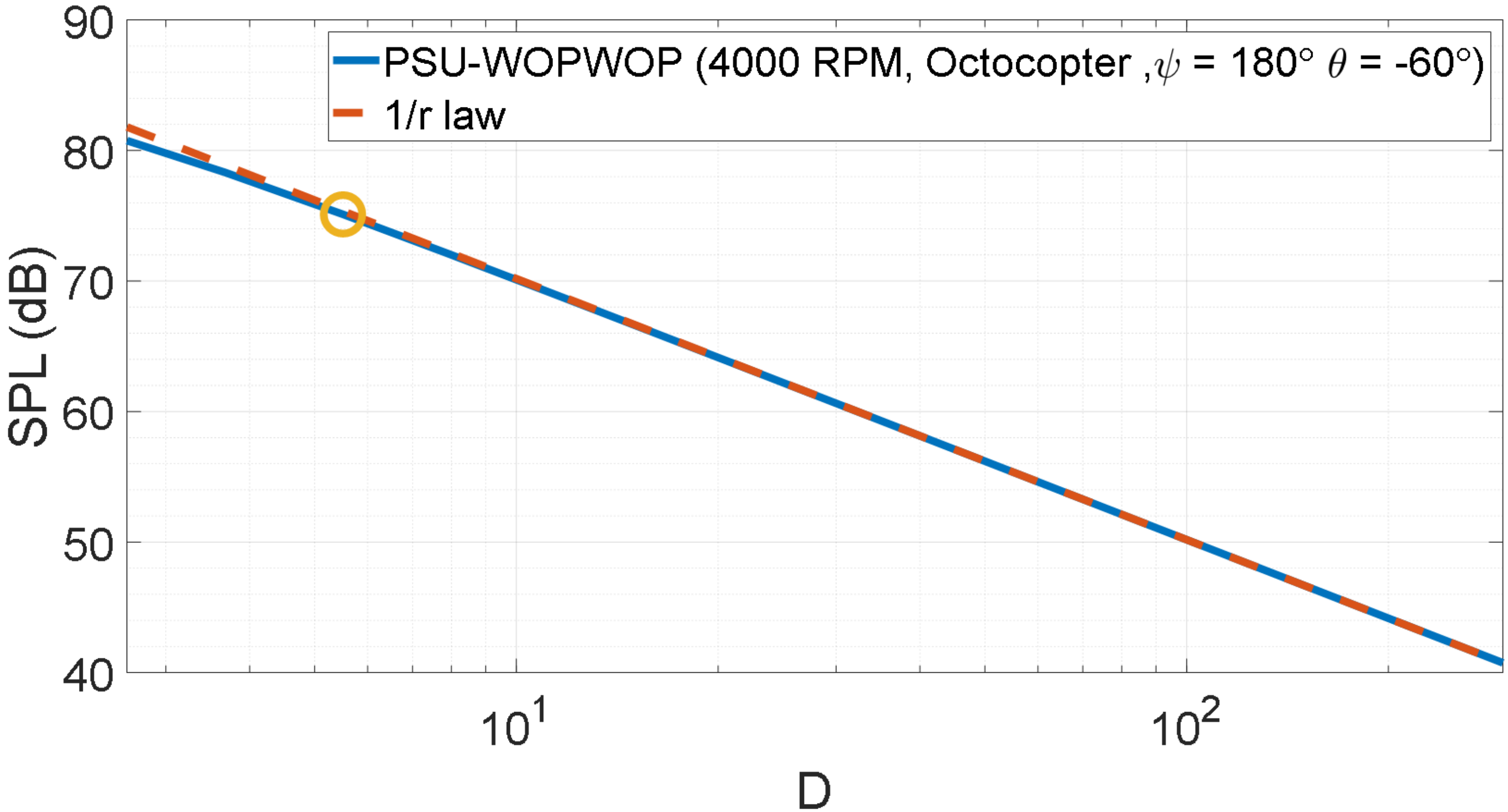
Far-Field Noise Measurement



Ray, Elden F. "Industrial Noise Series, Part IV, Modeling Sound Propagation." June 16 (2010): 2010.

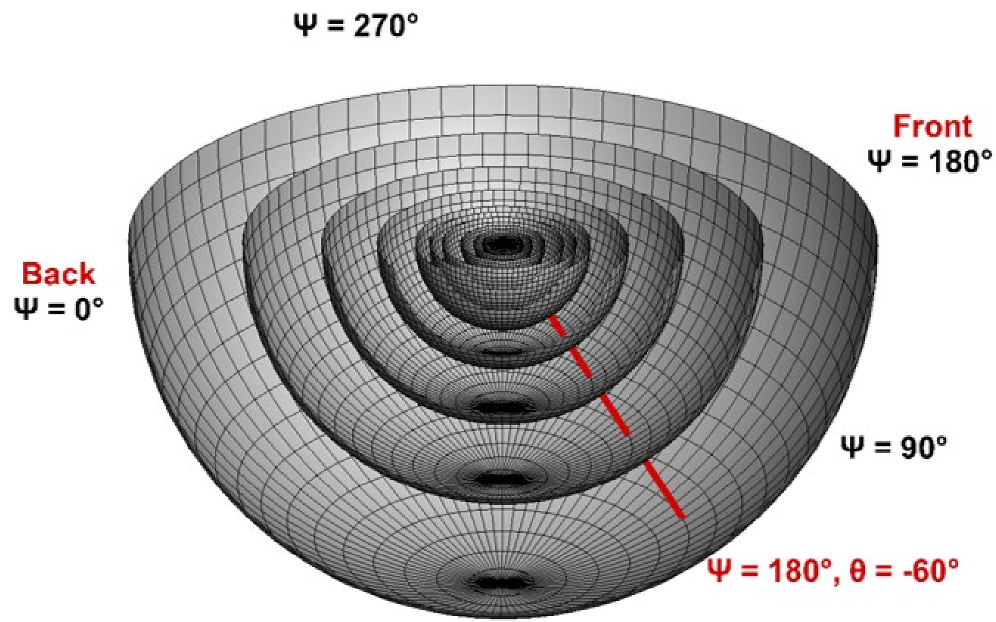
- Near field acoustics are complex
- Far field noise measurements are easily generalized
- Far-field measurement criteria for conventional aircraft established based on prior experience
- Far field of multirotor aircraft is not well understood

Far-Field Distance Determination



- Sound Pressure Levels (SPL) are computed using PSU-WOPWOP for logarithmically-spaced distances along selected direction
- SPL at farthest observer is scaled back to closer observers using the $1/r$ law
- Set far-field where predicted and scaled SPL differ less than prescribed tolerance

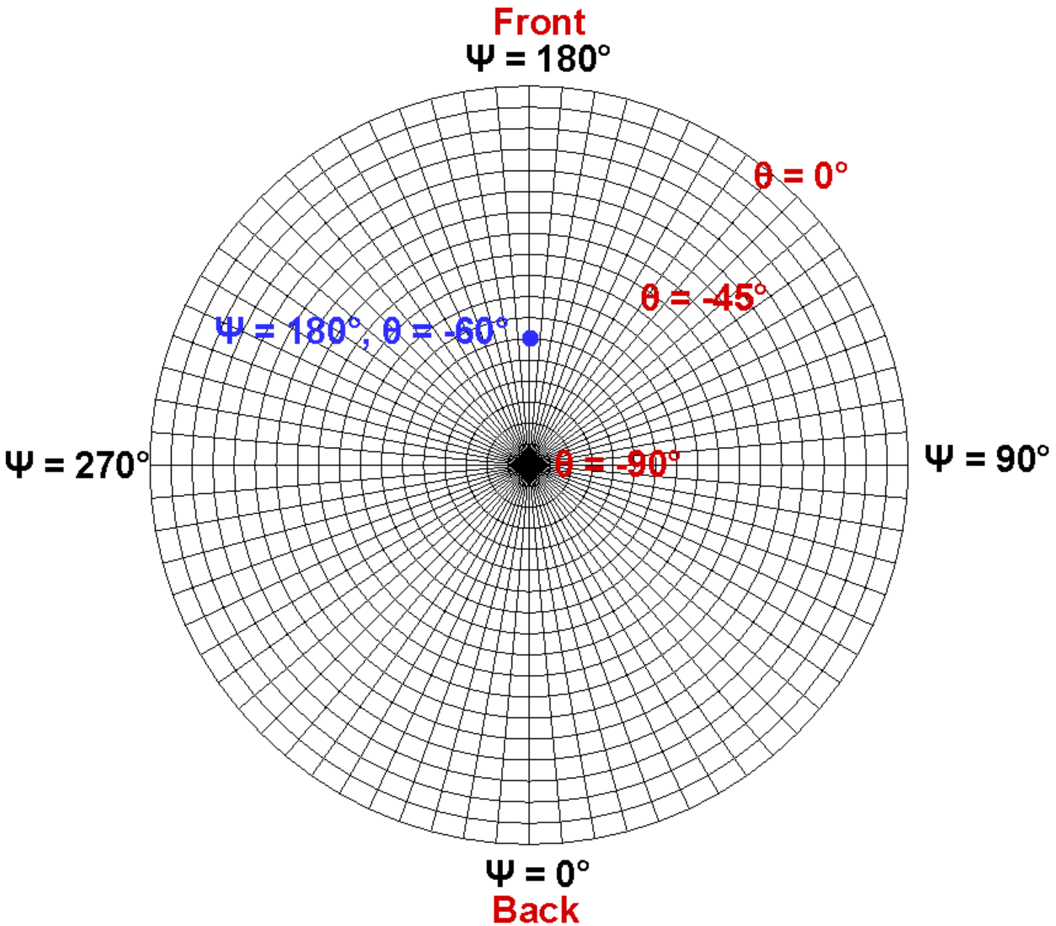
Far-Field Distance Directivity



Nested Noise Hemispheres
5° resolution in azimuth and elevation

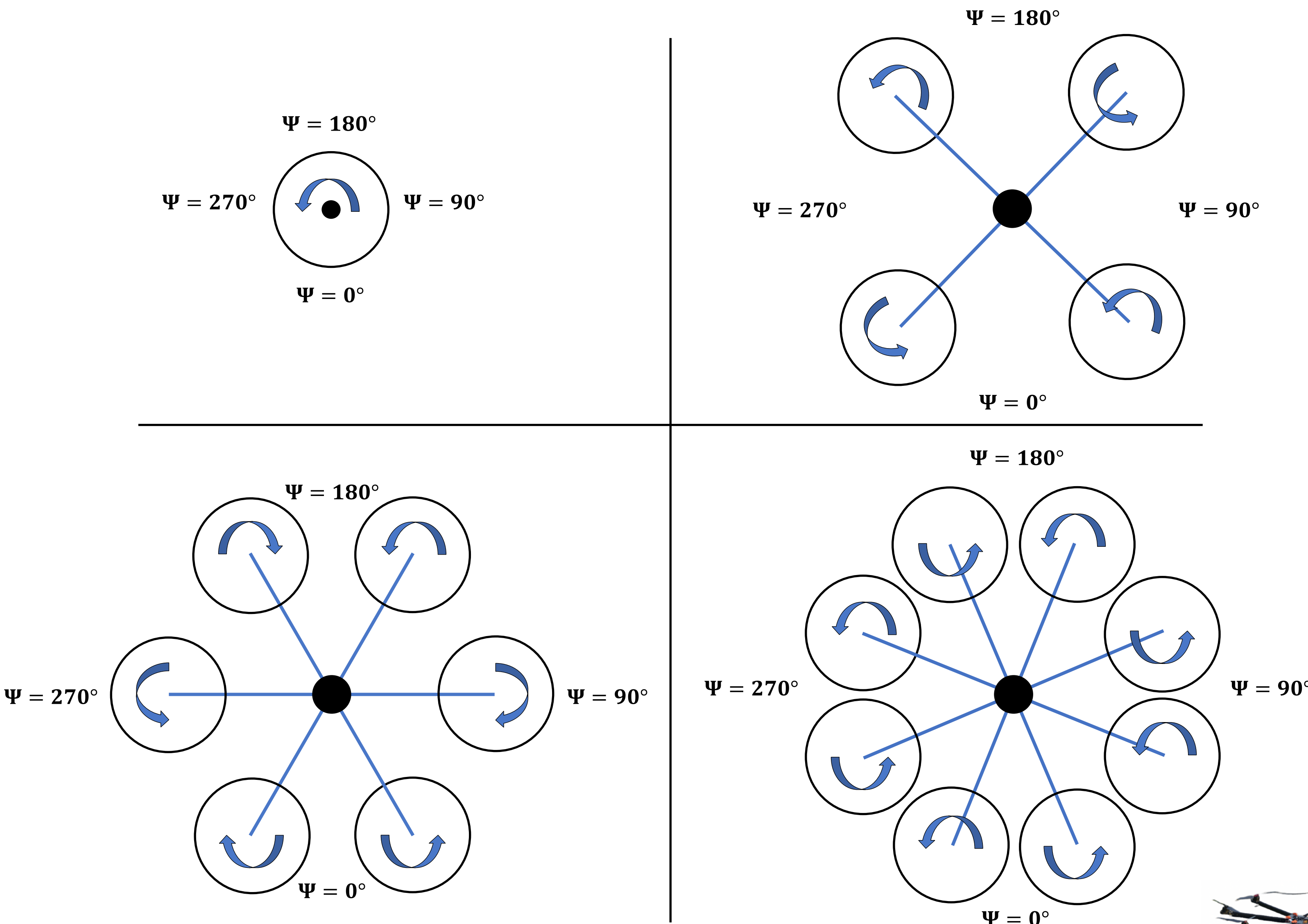
- Acoustic characteristics of rotors vary with direction
- SPL predicted on hemisphere to assess noise directivity
- Nested set of hemispheres used for far-field distance determination
- Procedure provides far-field distance directivity

Hemisphere Projections



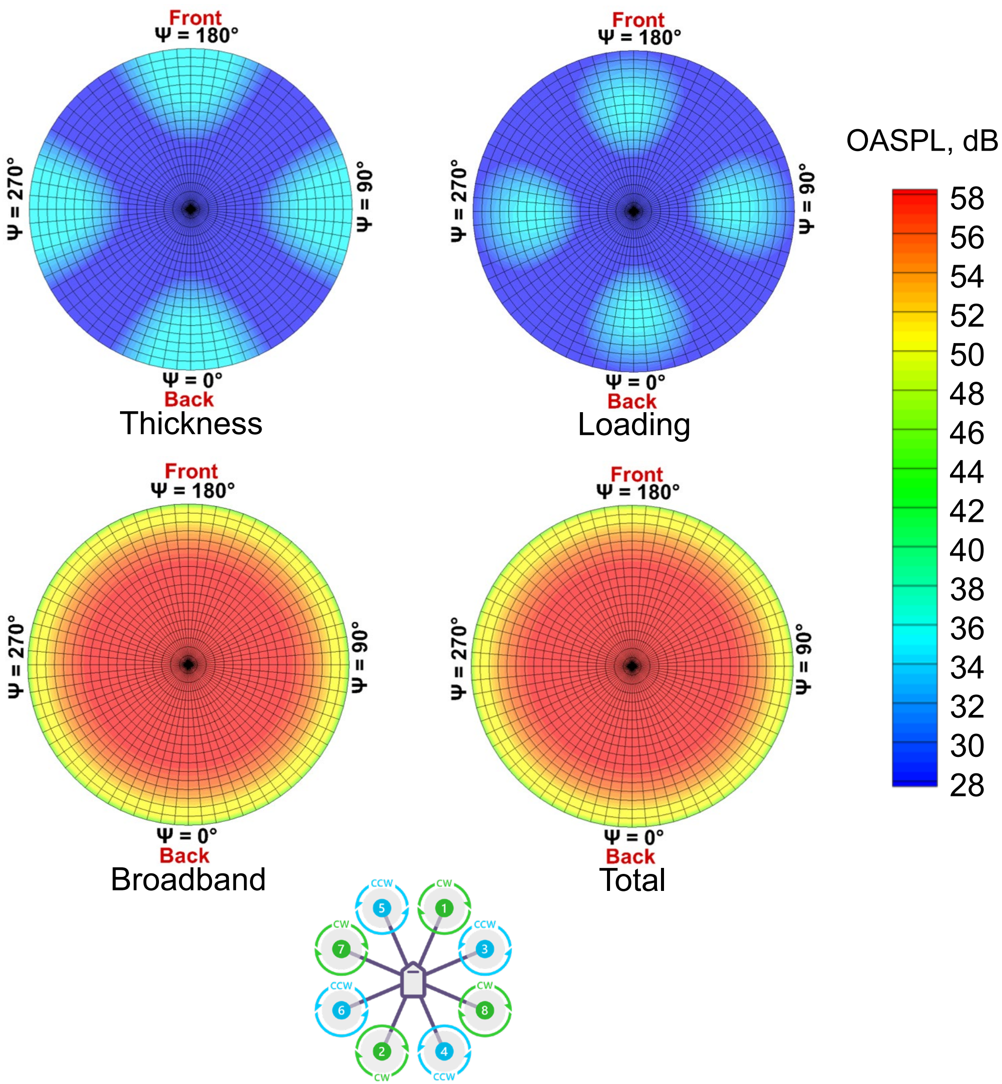
- A stereographic projection is used to plot both SPL and far-field distance hemispheres
- Elevation angles are plotted radially with equal spacing
- Azimuth angles are plotted azimuthally with equal angles

Effects of Varied Numbers of Rotors



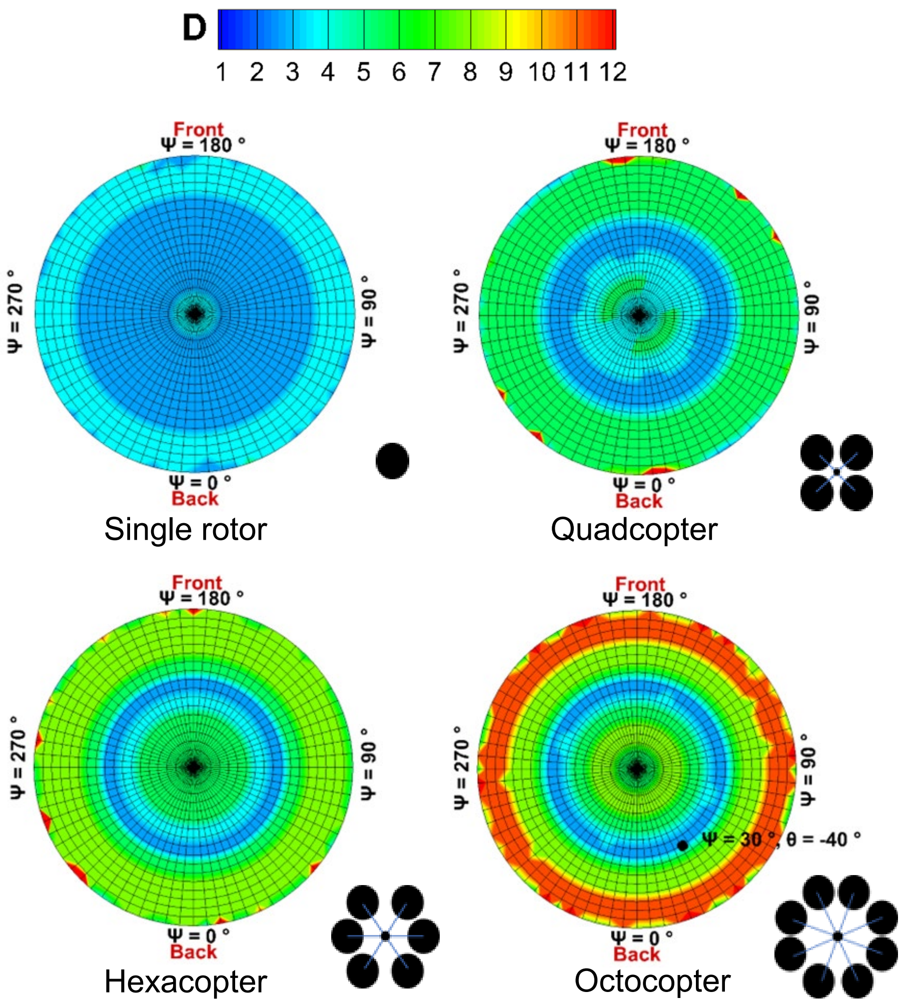
Tarot X8 baseline

Tarot X8 Noise Predictions



- Tarot X8 octocopter noise prediction using VSP2WOPWOP
- No aerodynamic interactions modeled
- Trimmed to hover
- Tonal noise shows interference pattern
- Broadband noise is dominant

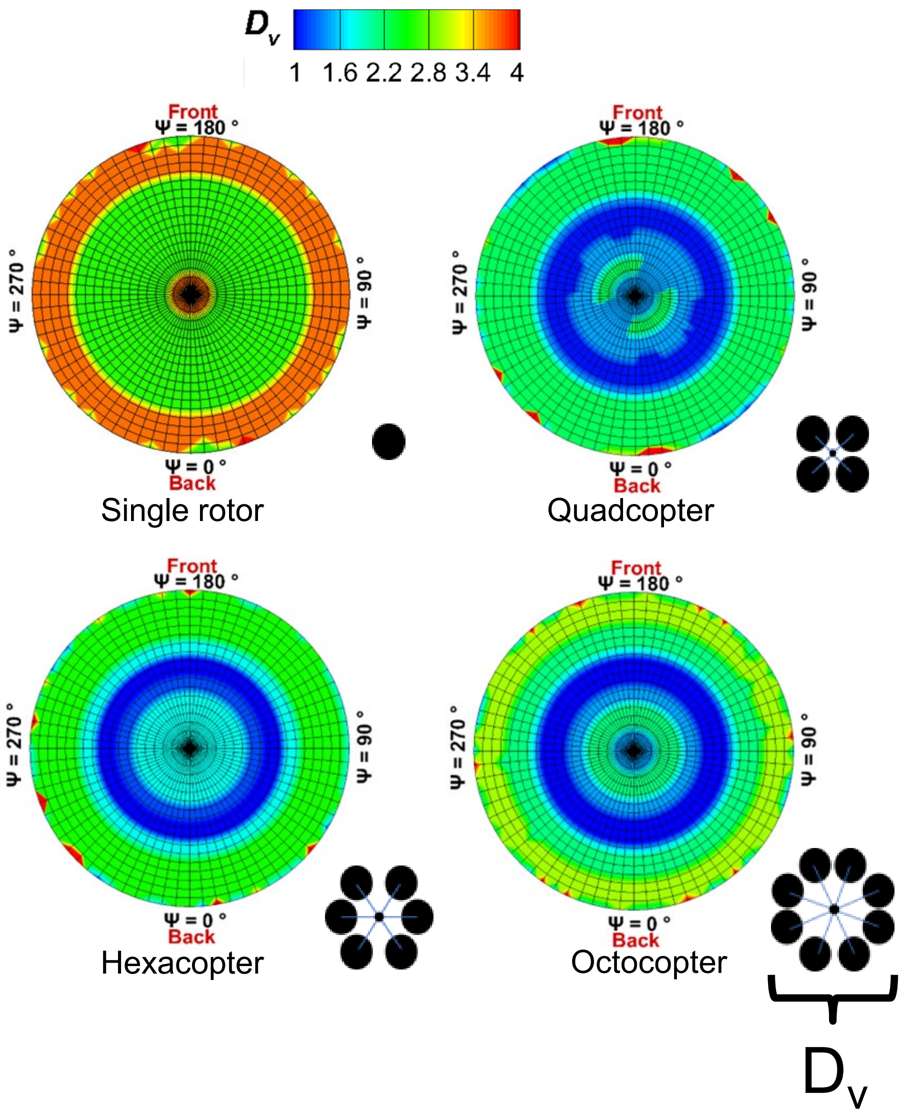
Far-Field Distance vs. # of Rotors



- Far-field distance normalized by rotor diameter (D)
- Average distance increases with # of rotors

Number of Rotors	Average Far-Field Distance (D)
1	3.0
4	4.2
6	5.7
8	6.9

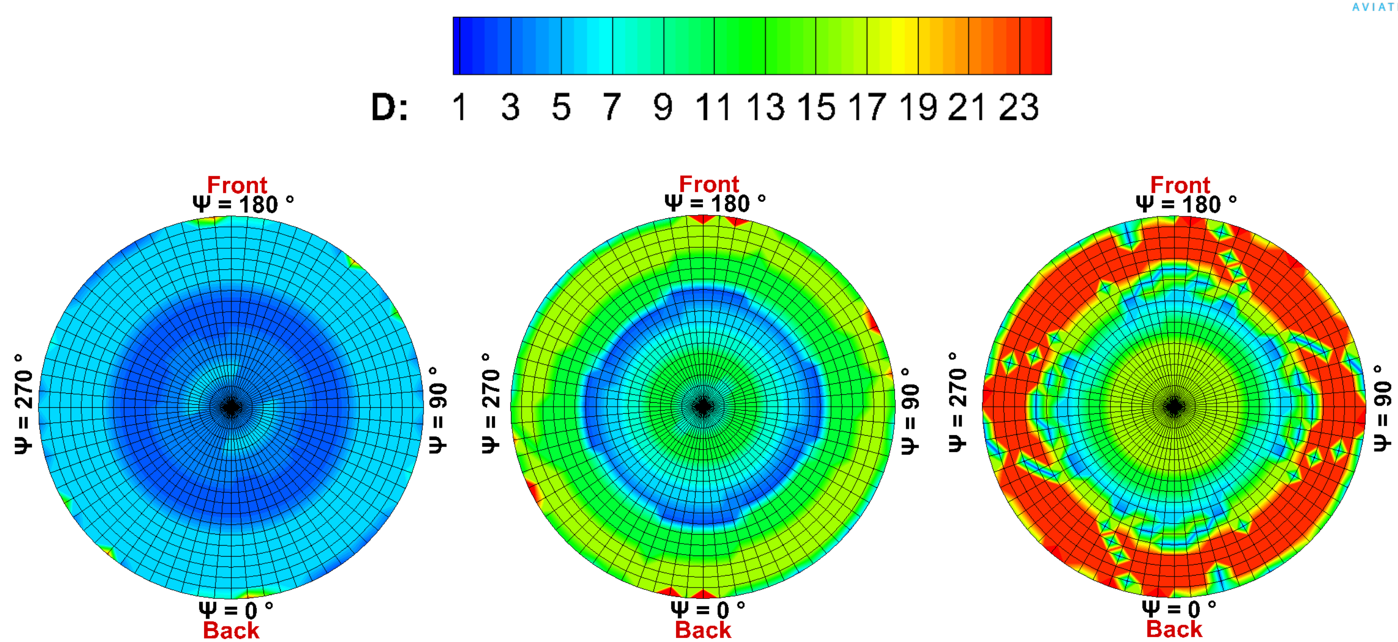
Far-Field Distance vs. # of Rotors



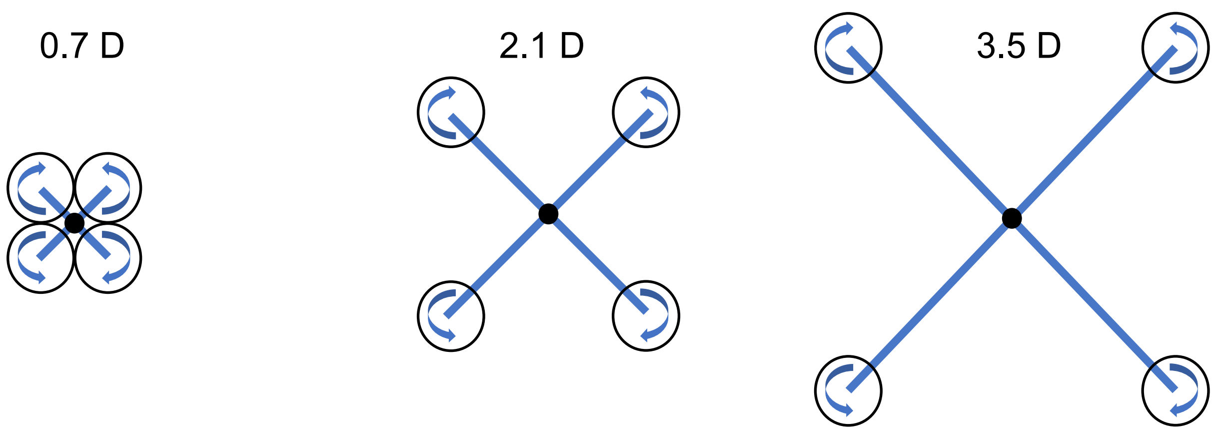
- Far-field distance normalized by vehicle diameter (D_v)
- Average distance scales with vehicle diameter

Number of Rotors	Average Far-Field Distance (D_v)
1	3.0
4	1.7
6	1.8
8	1.8

Far-Field Distance with Arm Length

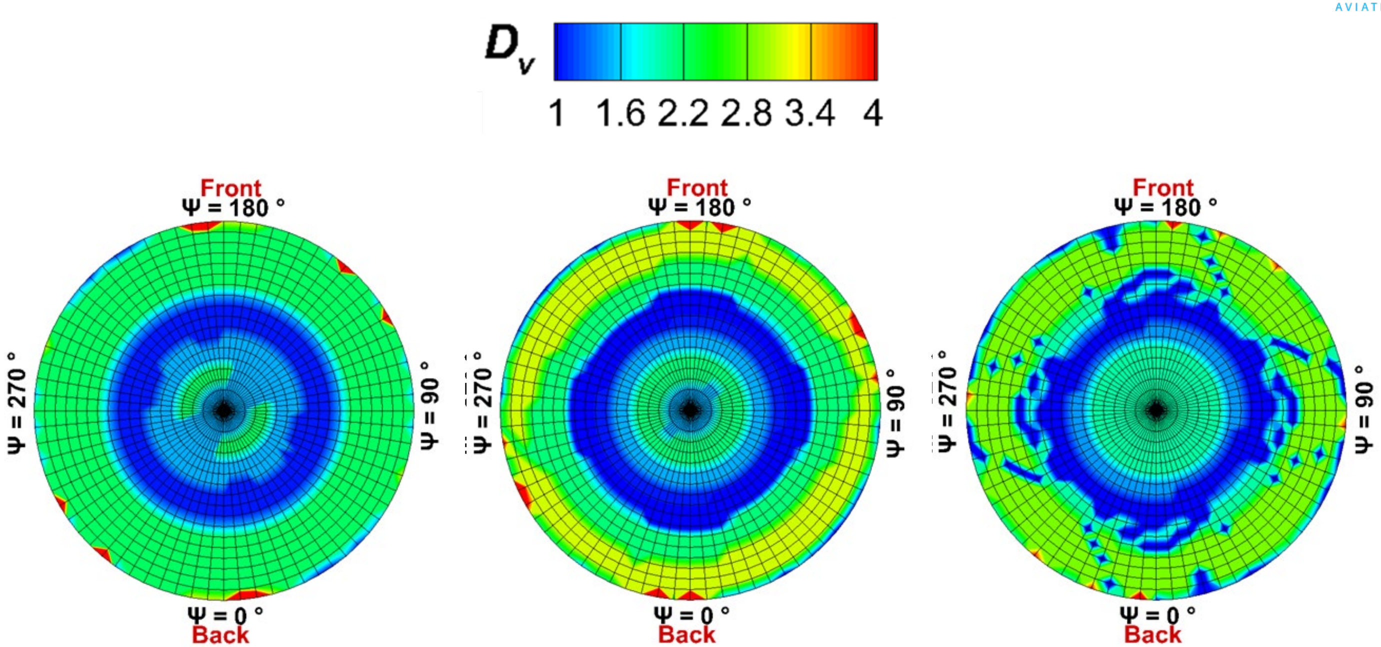


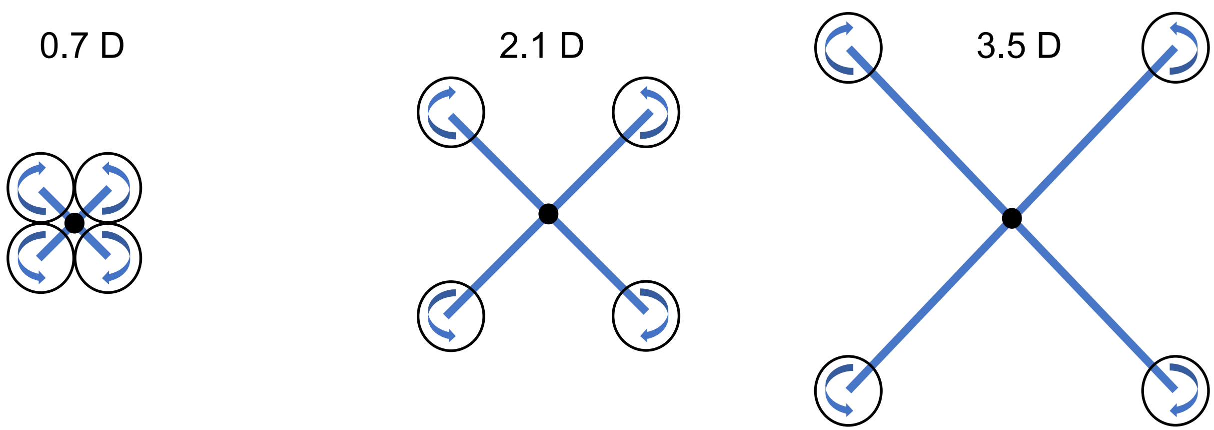
Arm Length	0.7 D	2.1 D	3.5 D



Average Far-Field Distance	**4.2 D**	**10.0 D**	**15.9D**

Far-Field Distance with Arm Length



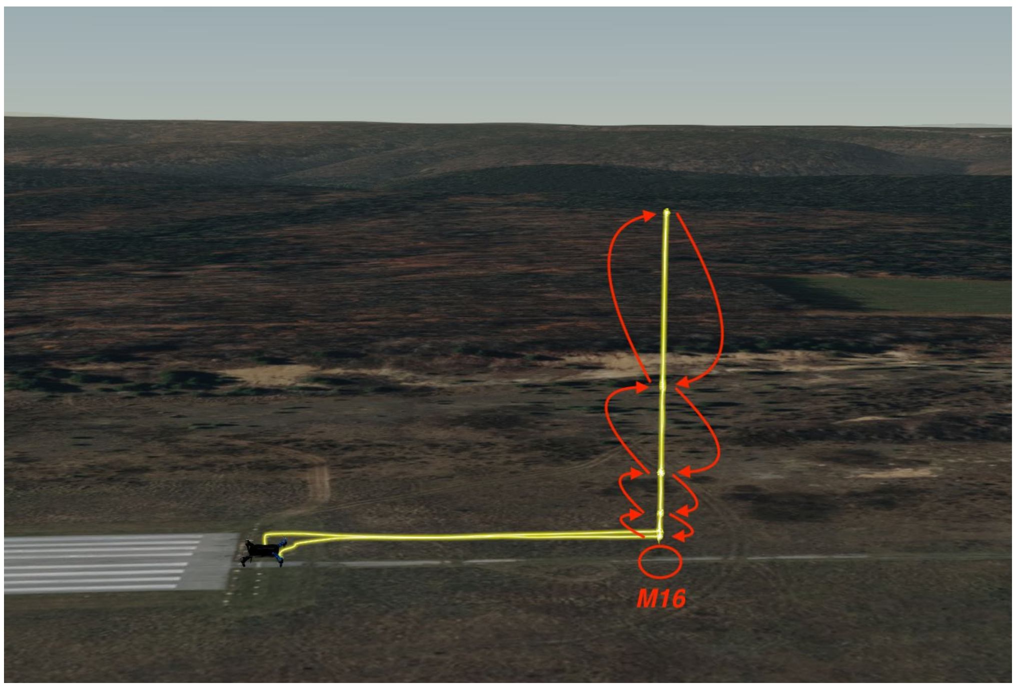


Arm Length	0.7 D	2.1 D	3.5 D
Average Far-Field Distance	**1.7 D_v**	**1.9 D_v**	**2.0 D_v**

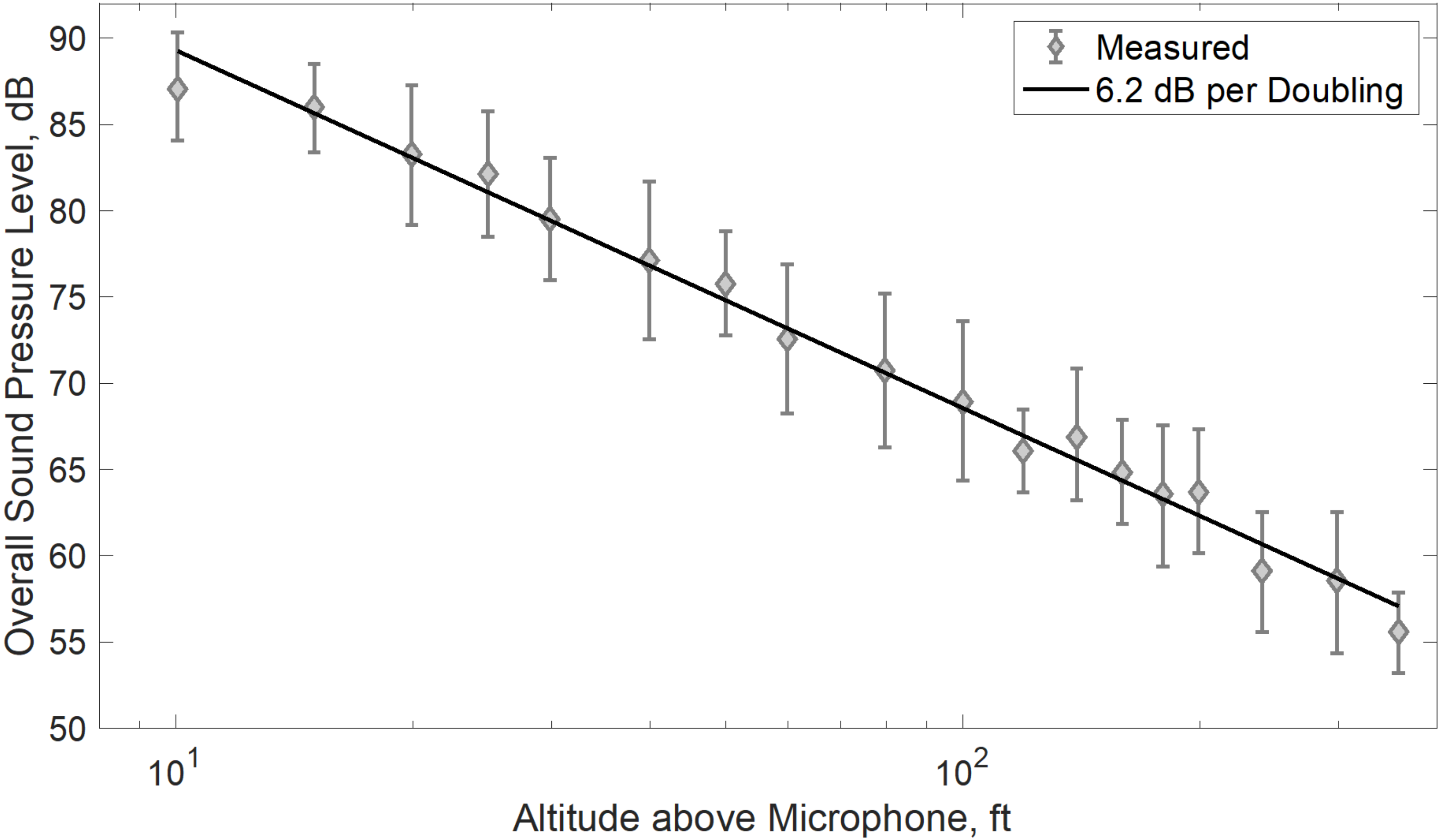
Experimental Determination

Test Procedure

- Inverted ground-plane microphone M16 added to investigate noise versus altitude with constant horizontal position (within ~5”)
- Vertical climb/descents with hover holds at multiple logarithmically-spaced altitudes



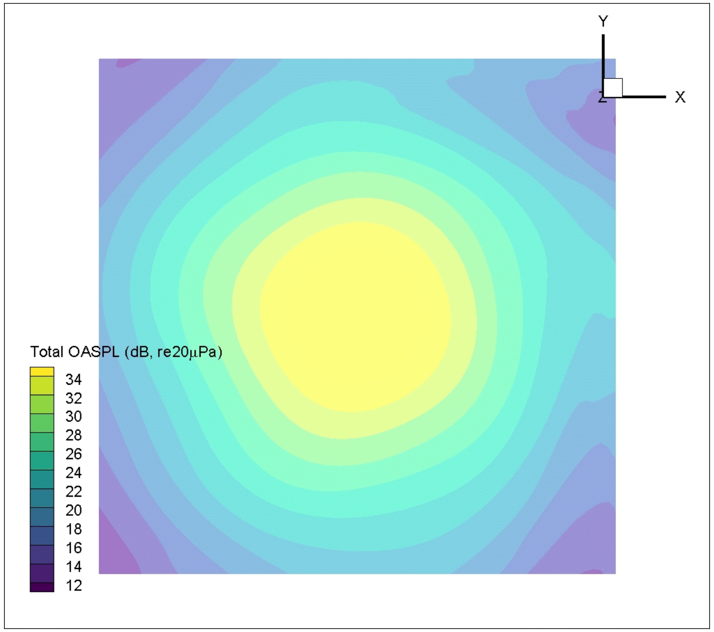
Hover Noise with Altitude



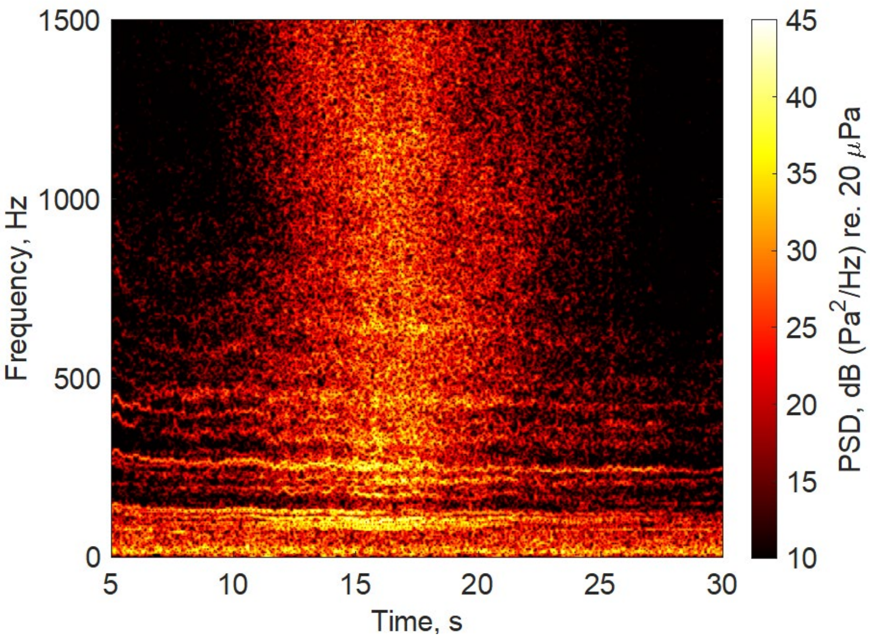
Measured OASPL decays with spherical spreading within measured variability

Variability

- Multirotor aircraft noise is likely highly variable
  - Acoustic interference / beating
  - Smaller aircraft more susceptible to disturbances
  - Fixed-pitch / variable RPM rotors used for control
- Can we quantify this variation and how does it effect the characterization of aircraft noise?



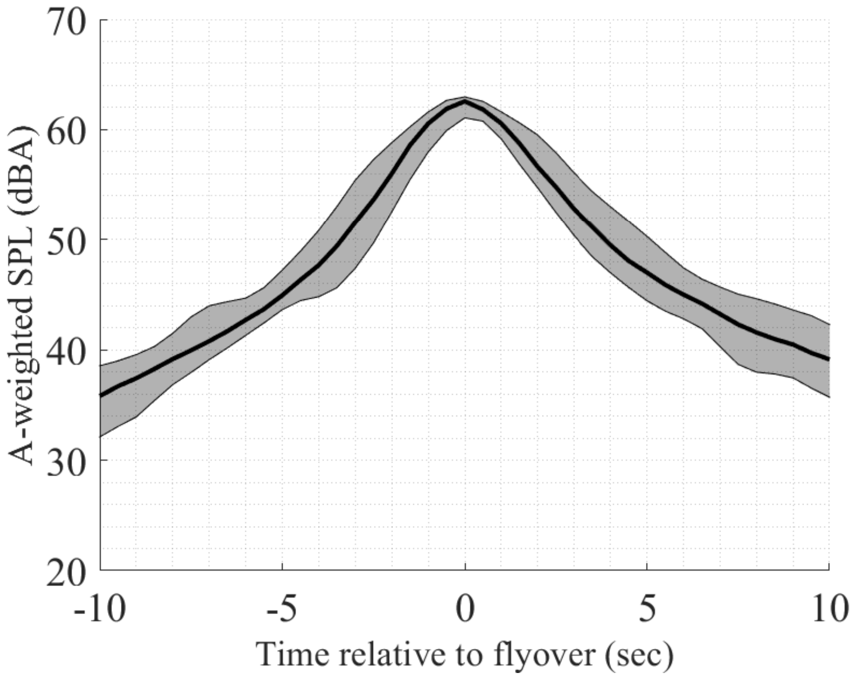
Predicted Tarot X8 noise carpet OASPL, dB



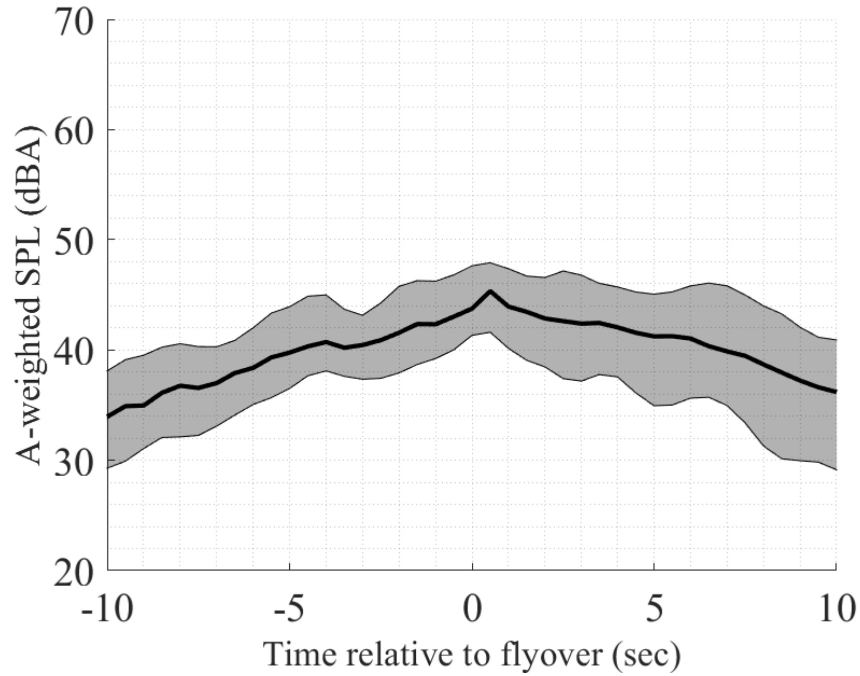
Measured Tarot X8 flyover spectrogram, PSD

Flyover SPL Time Histories

Tarot X8, 20 mph @ 50' AGL
18 repeated runs



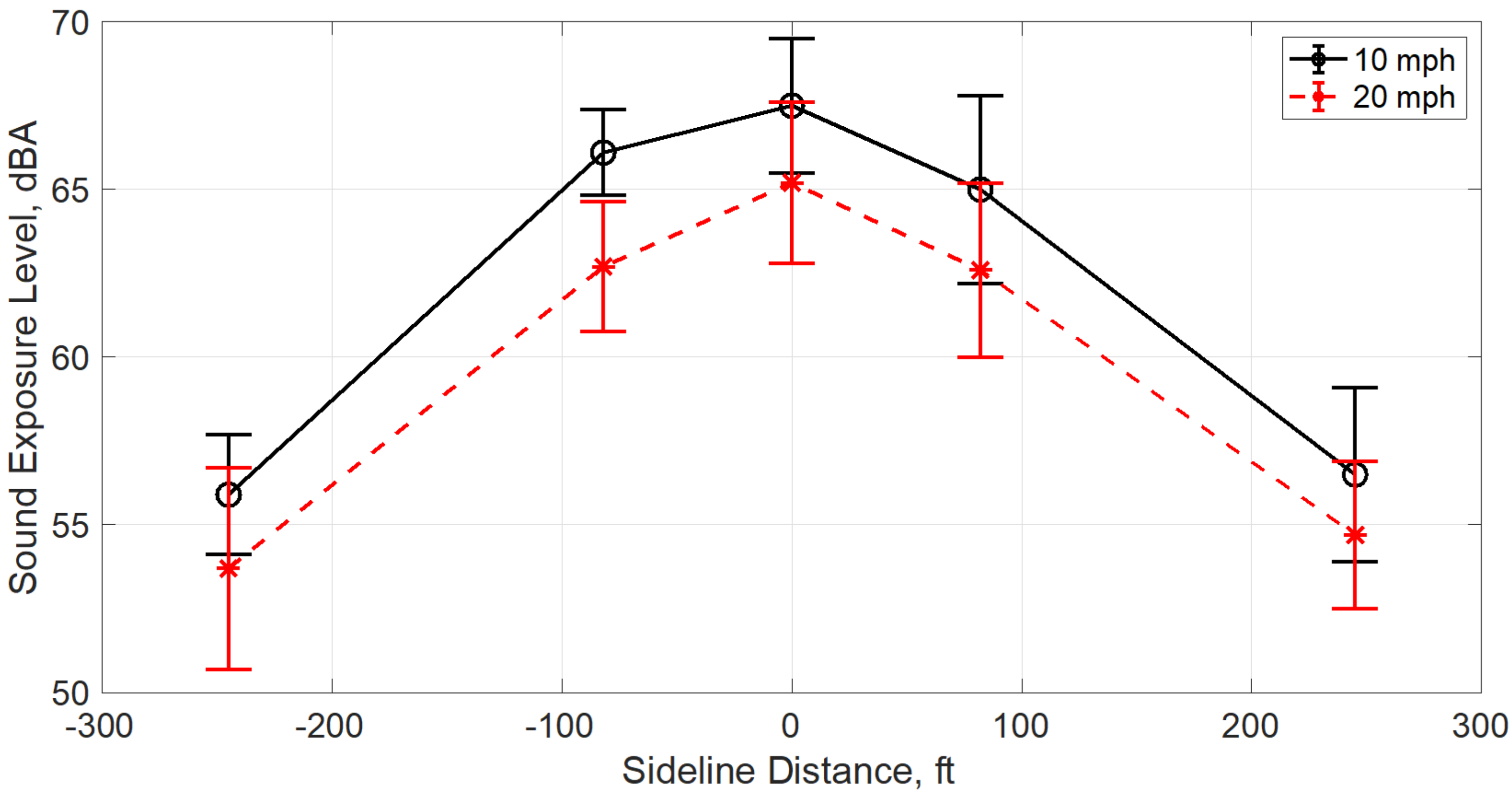
Centerline



Sideline

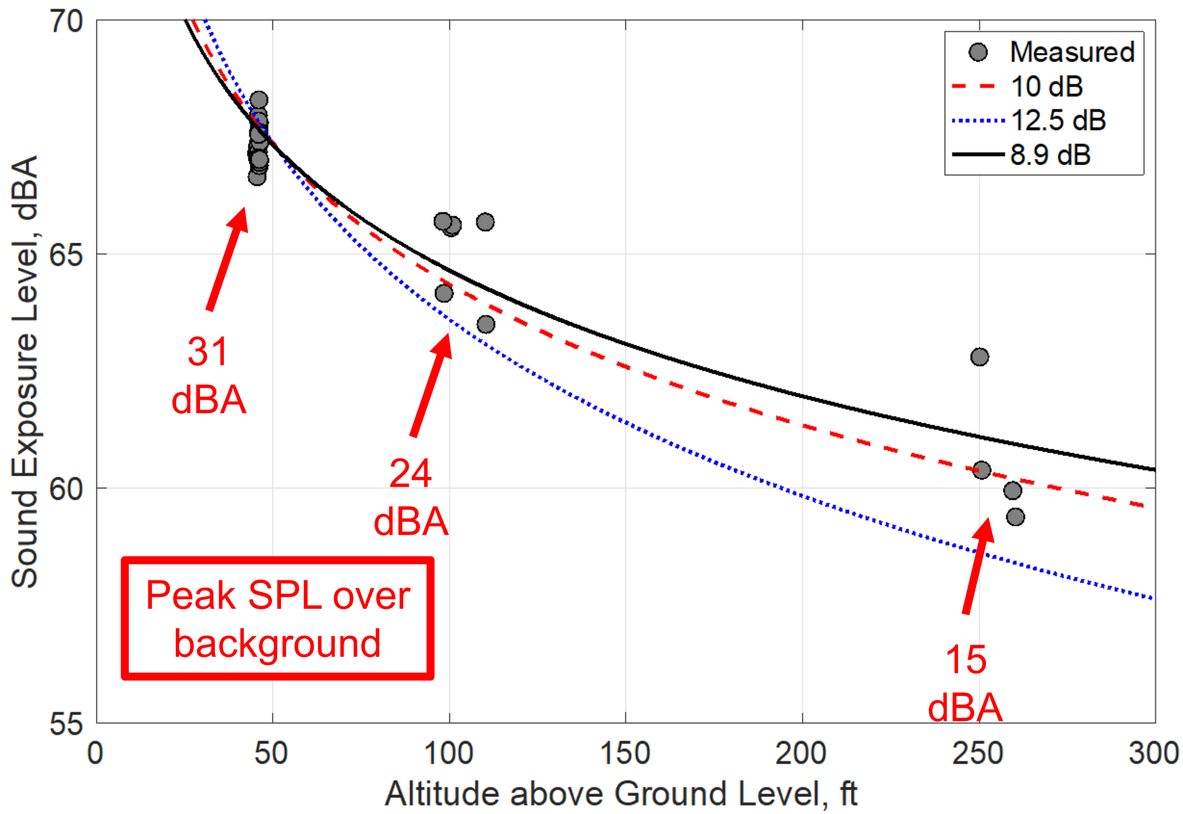
- 3-10 dBA variation in A-weighted SPL across all runs
- Variability tends to increase with distance to microphone

Sideline Sound Exposure Levels



- 3-6 dBA variation in A-weighted SEL across all runs
- SEL increases with decreasing flight speed

Centerline SEL Variation with Altitude

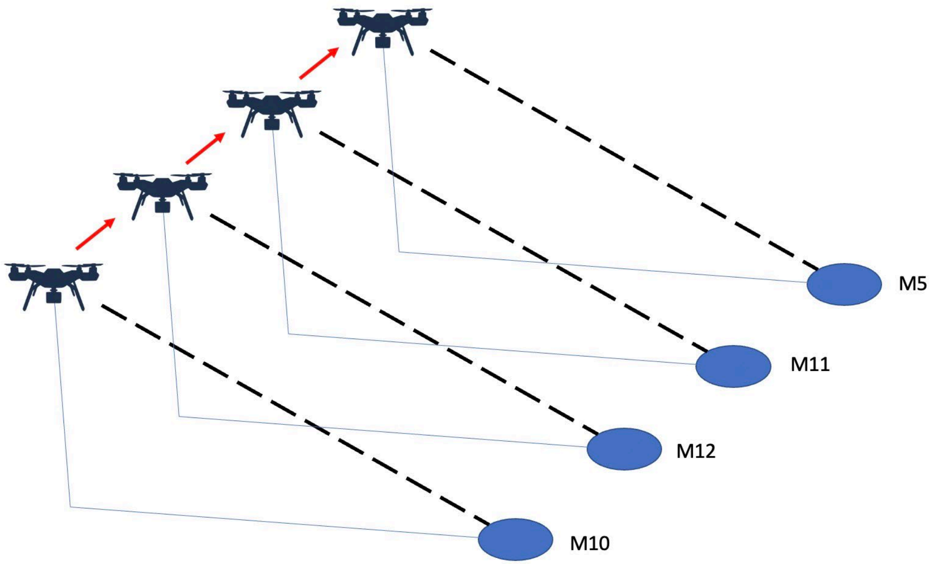


- SEL plotted for all 10 mph flyover conditions
- Curves fit to

$$L_{AE} = \bar{L}_{AE\,50} + C \log_{10} \frac{H}{50}$$

- $C = 12.5$ per J36.205
- $C = 10.0$ omnidirectional
- $C = 8.9$ best fit

Temporal Variation



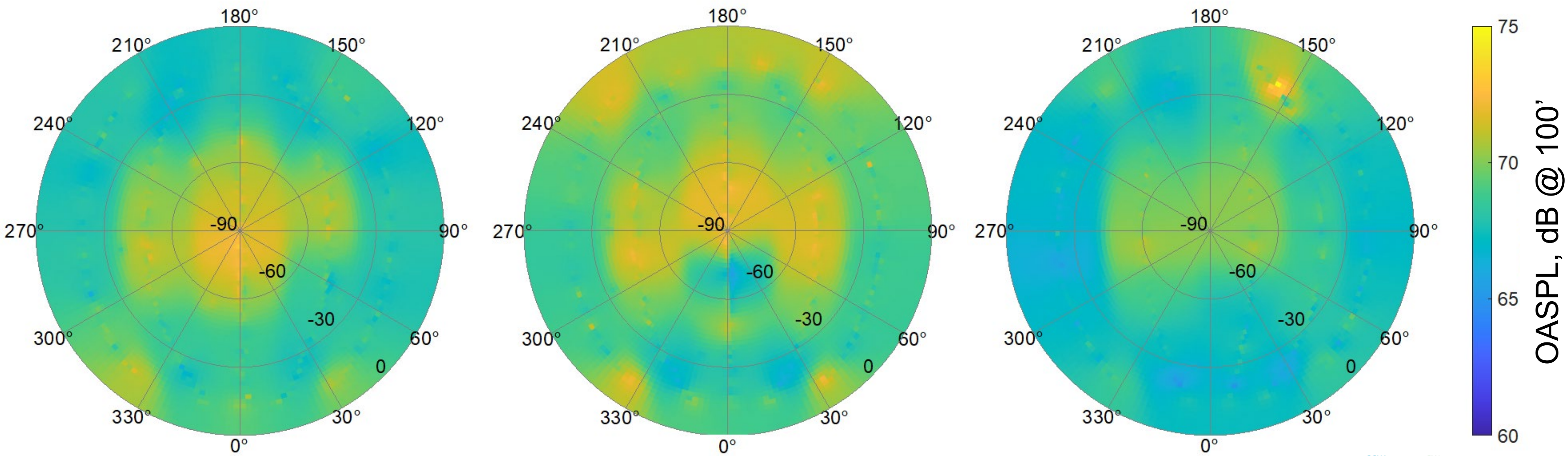
	Run	M10	M12	M11	M5	Mean	Range
Nominal FPH	19	39.3	39.1	37.8	39.9	39.0	2.1
	20	37.6	38.2	37.9	38.3	38.0	0.7
	21	38.7	38.1	35.8	38.1	37.7	2.8
	22	38.3	38.4	36.6	39.4	38.2	2.8
	23	39.0	37.4	37.0	39.2	38.1	2.2
	24	38.1	38.0	36.9	39.7	38.2	2.8
	25	39.6	38.9	38.2	39.8	39.1	1.6
	9	38.0	40.4	36.8	37.6	38.2	3.6
	12	38.3	40.7	38.2	40.2	39.3	2.4
Opposite FPH	19	39.2	38.0	36.5	38.4	38.0	2.7
	20	38.7	38.1	37.6	39.0	38.4	1.4
	21	38.8	38.5	37.7	39.6	38.6	1.8
	22	38.5	38.7	39.1	40.6	39.2	2.2
	23	39.4	38.5	38.2	39.9	39.0	1.7
	24	40.8	38.9	38.3	39.2	39.3	2.5
	25	41.2	41.3	39.7	40.9	40.8	1.6
	9	41.3	39.7	39.0	41.8	40.4	2.7
	12	42.8	42.3	41.3	41.1	41.9	1.7
	Mean	39.3	39.1	37.9	39.6		
	Range	5.3	5.0	5.5	4.2		

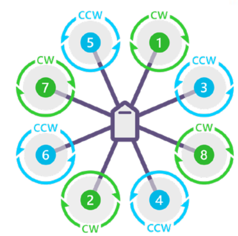
- Comparison of SPL for multiple microphones during the same flyover versus same microphone for multiple flyovers (short versus long timescale)

- Intra-run variation = 2.2 dBA
- Inter-run variation = 5.0 dBA

Tarot X8 OASPL Noise Spheres

All for the *same* flight condition
10 mph @ 100’ AGL





Greatest variations seem to occur near-in-plane

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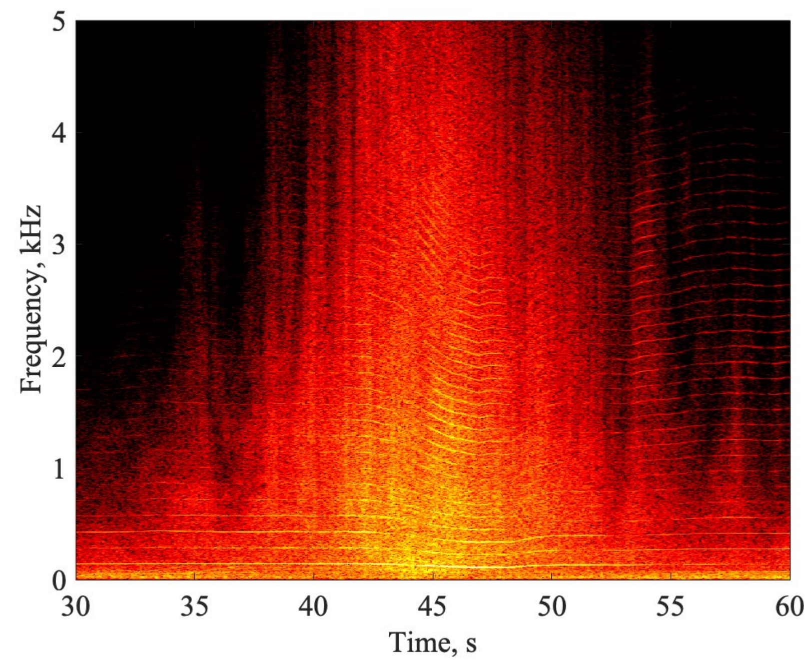
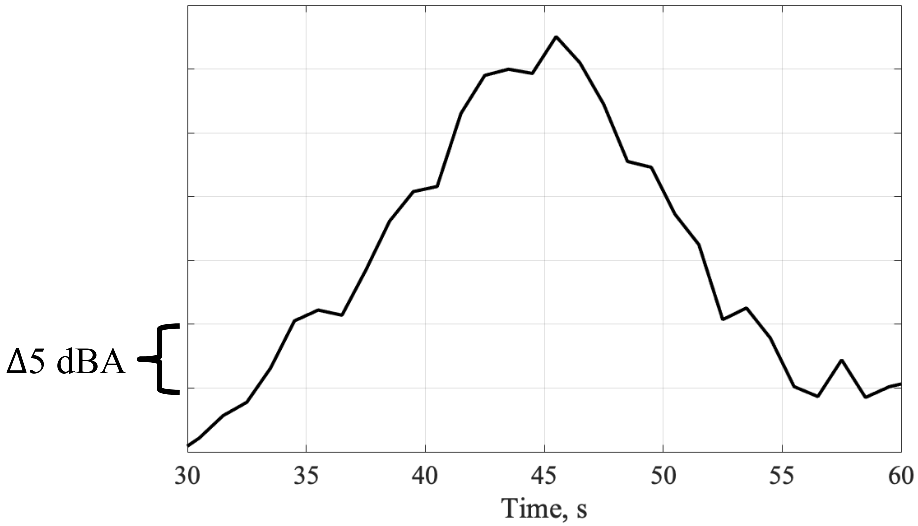
PSU/Beta Noise Measurements

- Lift+Cruise eVTOL Aircraft
- Fixed wing operation
  - 11 position linear array
  - 11 ground plane microphones
  - 3 elevated microphones collocated with ground plane mics
  - Flyovers
    - 85, 95, 110 KIAS
    - 300’, 500’, 1500’ AGL
    - Six repeats for most points
  - Takeoff and Landing
    - To / from runway target
    - Takeoff at BROC
    - Landing at approach speed
    - Two repeats each
- Proptruck Test Rig
  - Stationary and rolling
  - 500-1400 RPM
  - 0-20 KIAS
- Will capture VTOL and subscale measurements on following trip

Initial Observations

- Fixed pitch propeller introduces some variability
- Variability may have been reduced by flying fixed power setting
- But, wingborne flight envelope is narrower than CTOL aircraft
- Detailed data processing is underway

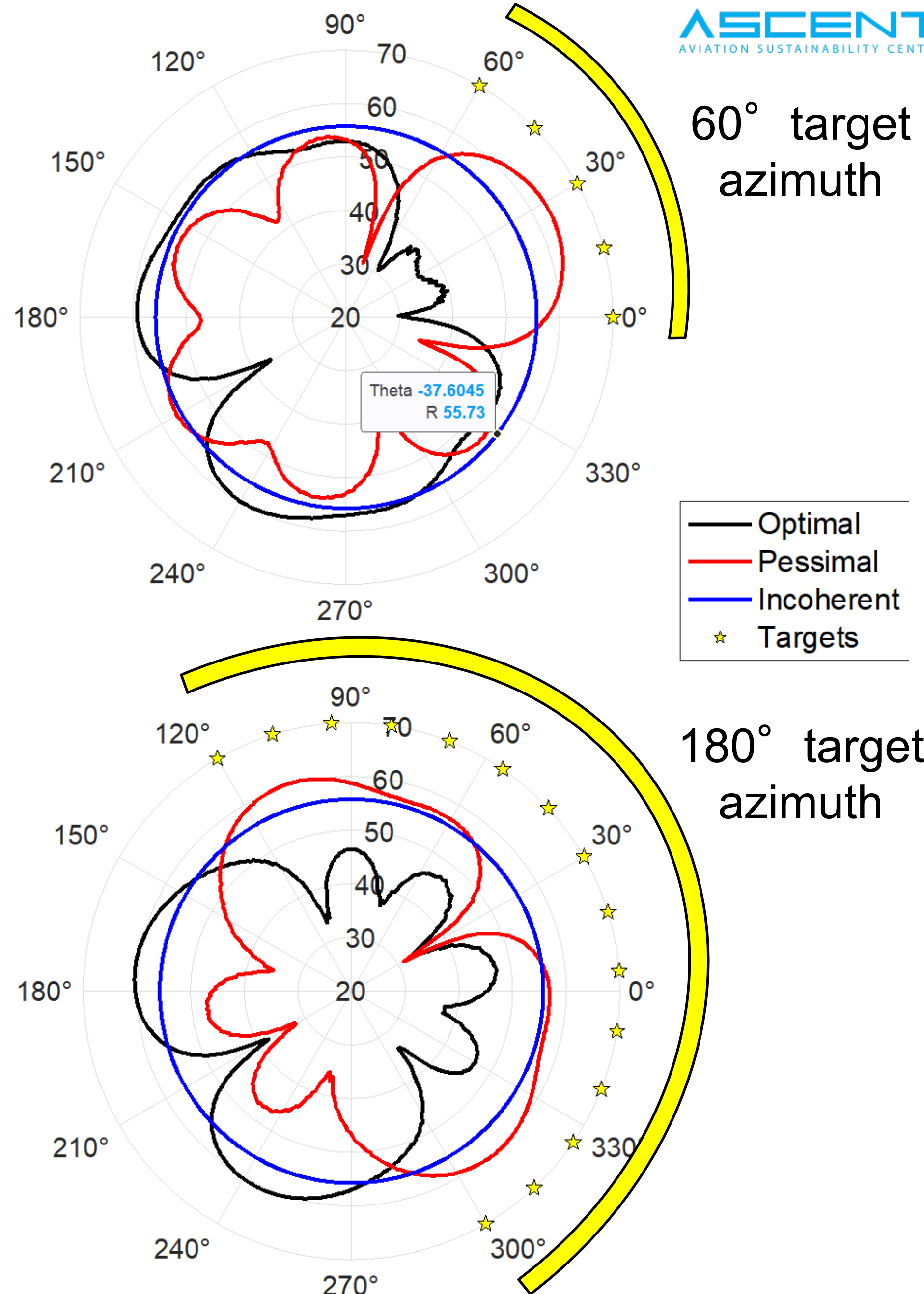




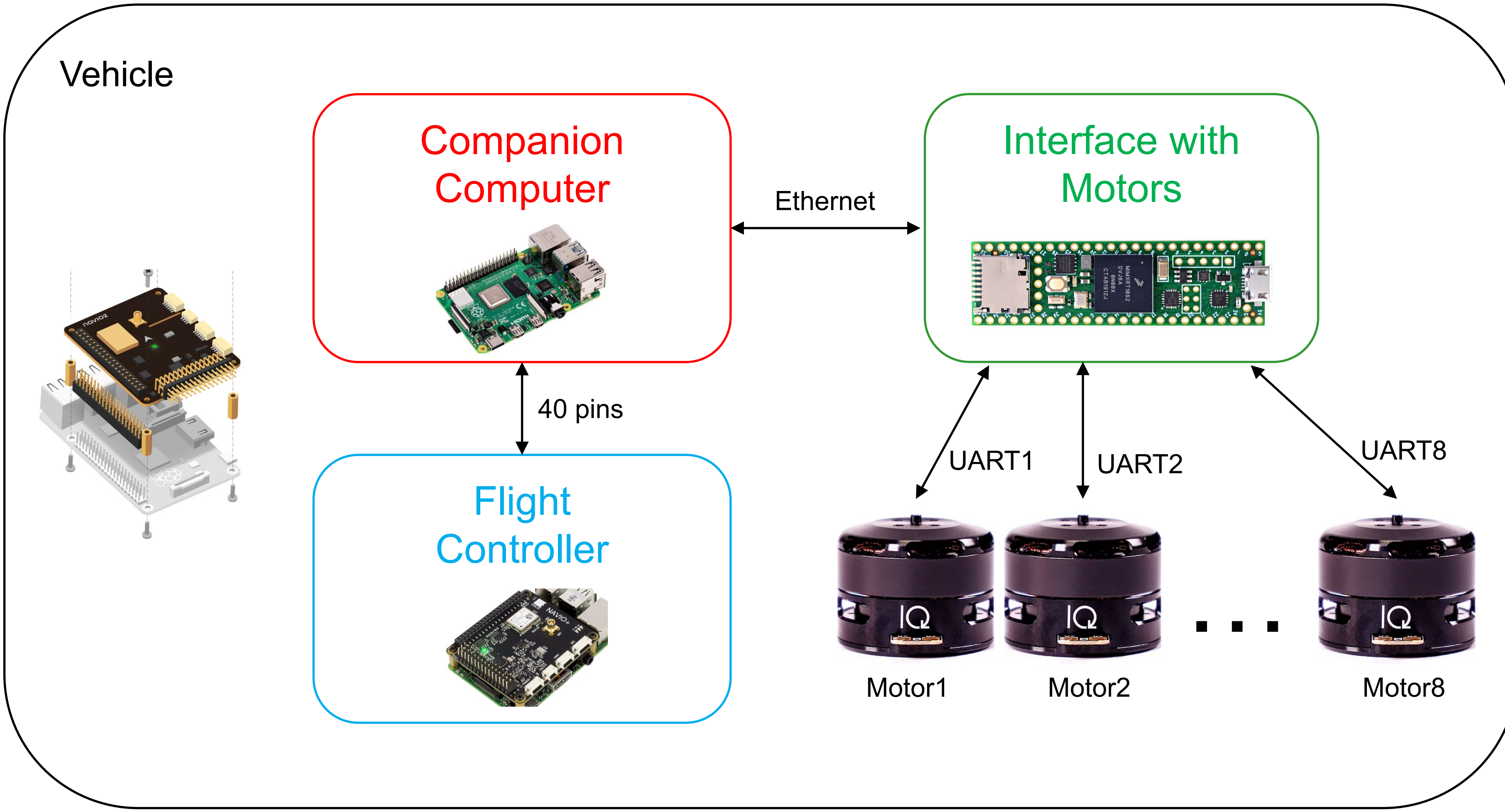
CTOL: Conventional Take Off and Landing

Multirotor Noise Reduction by Synchrophasing

- Simulation for the small hexacopter configuration
- Uses simplified compact thickness noise model
- Rotor phase relationships are adjusted to minimize noise at target observers using a genetic algorithm
- Also compared to maximized noise (pessimal) and incoherent addition
- Sufficient authority to control low frequency tonal noise over a wide area



Synchrophasing Architecture



Synchrophasing Demo

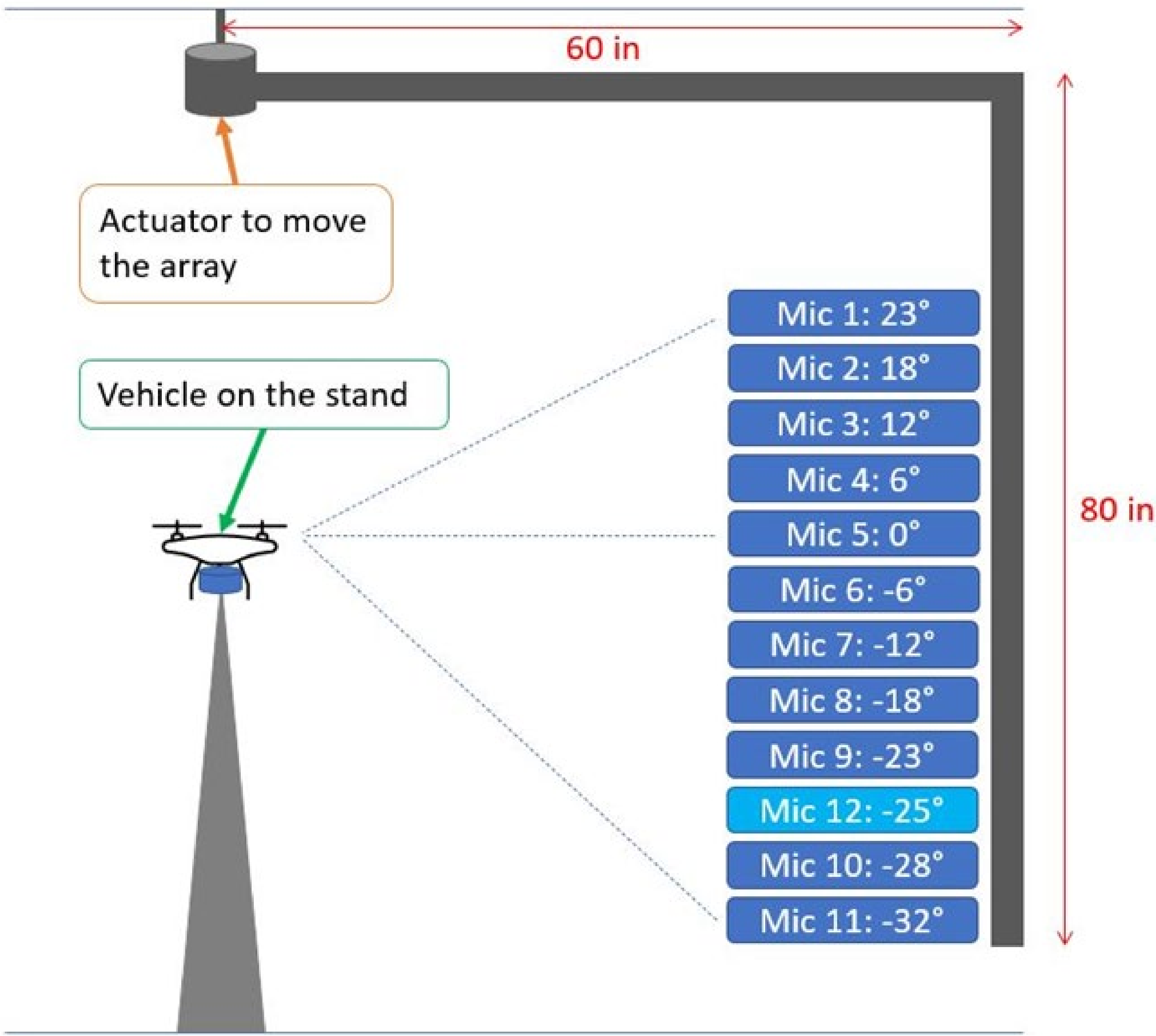
Strobe light triggered by laser tachometer on one motor.

Noise Measurements

Small-size hexacopter UAS installed in anechoic chamber:

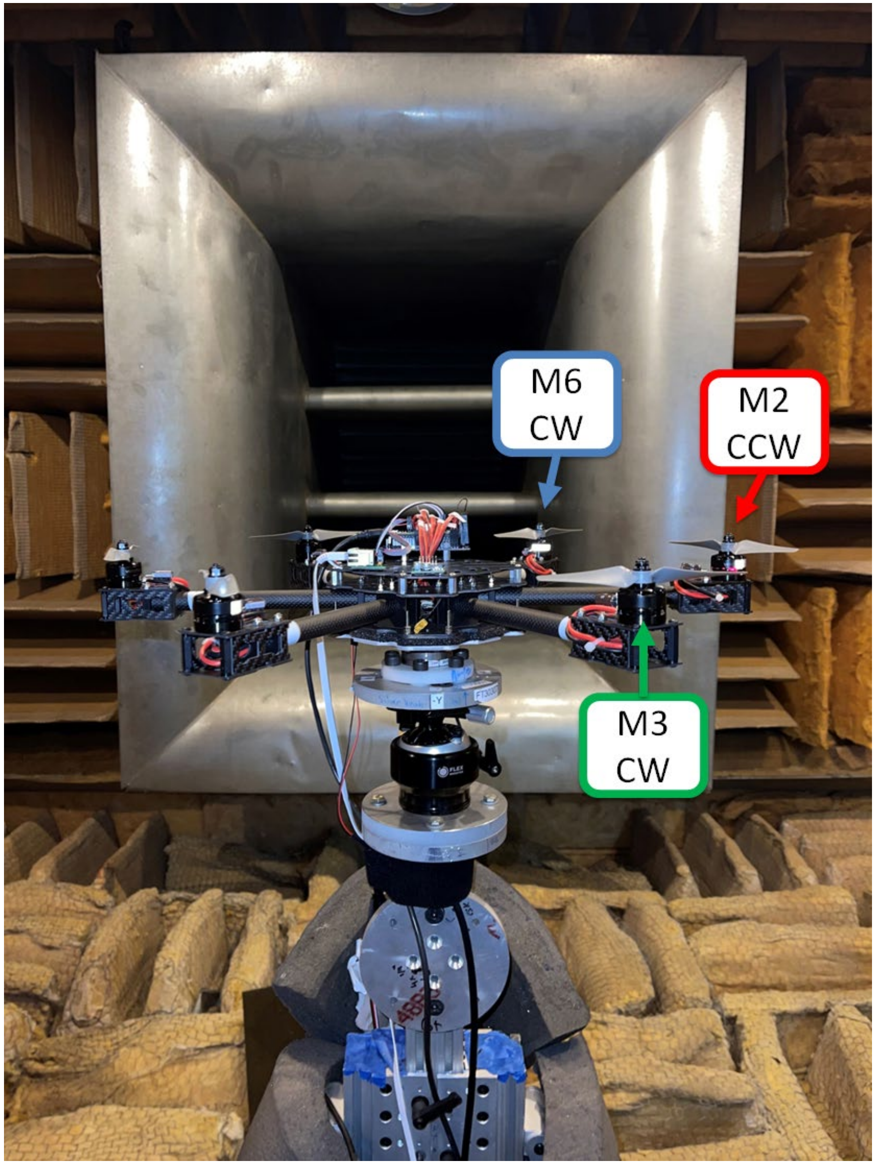
- Characterize individual rotor noise
- Explore potential of synchrophasing to control multirotor aircraft noise

Acoustic Array Layout



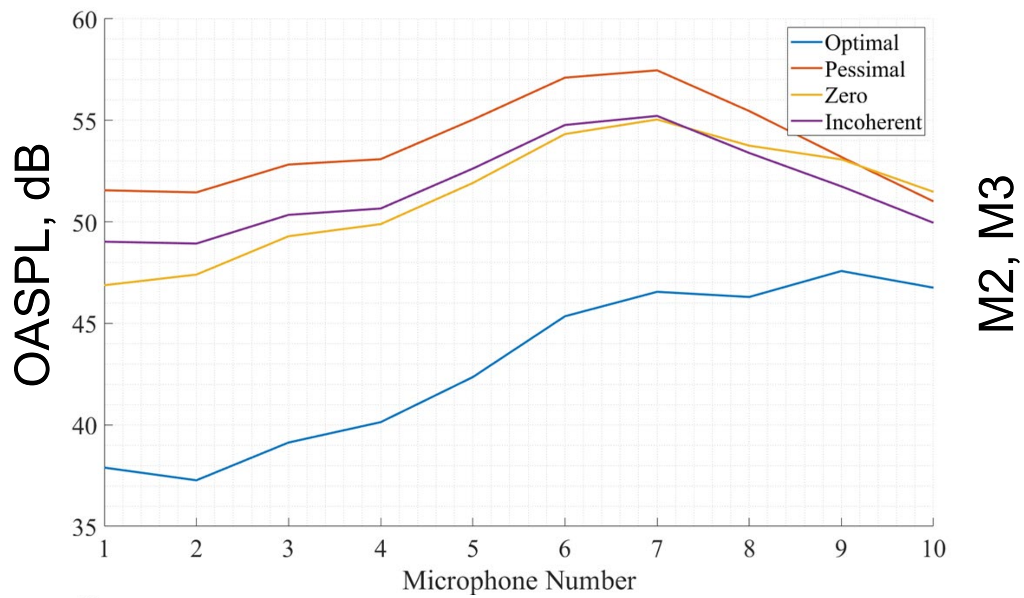
Simplified Setup

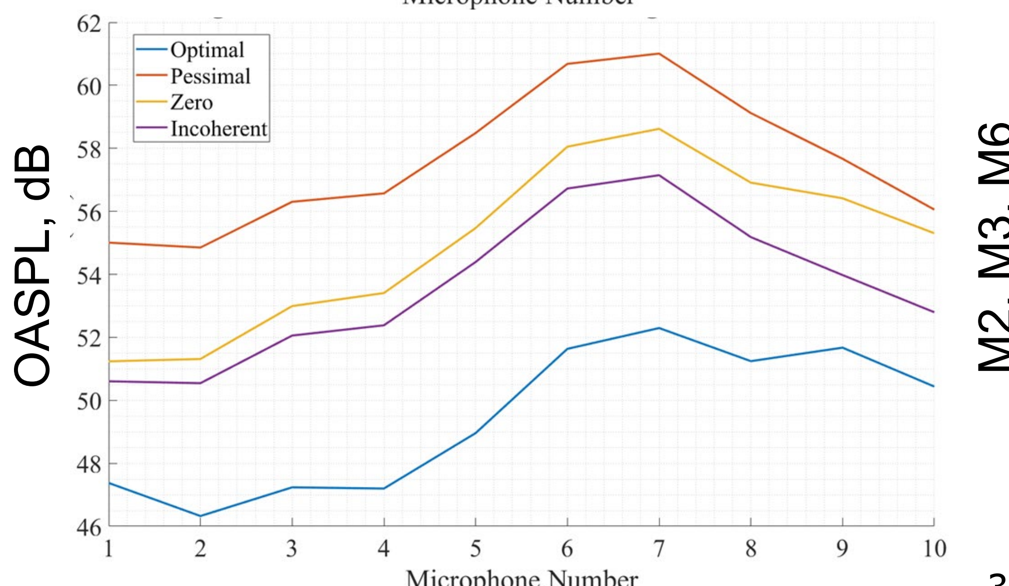
- Initial focus on two and three rotor cases
- Can sweep though various phase combinations
- Evaluate effect of aerodynamic interactions between rotors
- Assess effectiveness of synchrophasing



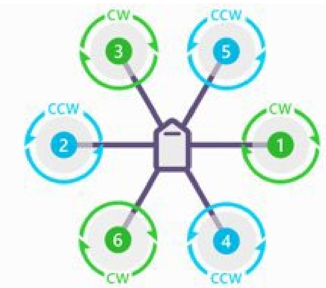
Initial Results

- Best and worst phase combinations determined for both two and three rotors
- Incoherent and zero relative phase conditions also tested
- Optimal configuration reduces noise across all elevation angles
- 3-12 dB reductions in OASPL relative to incoherent

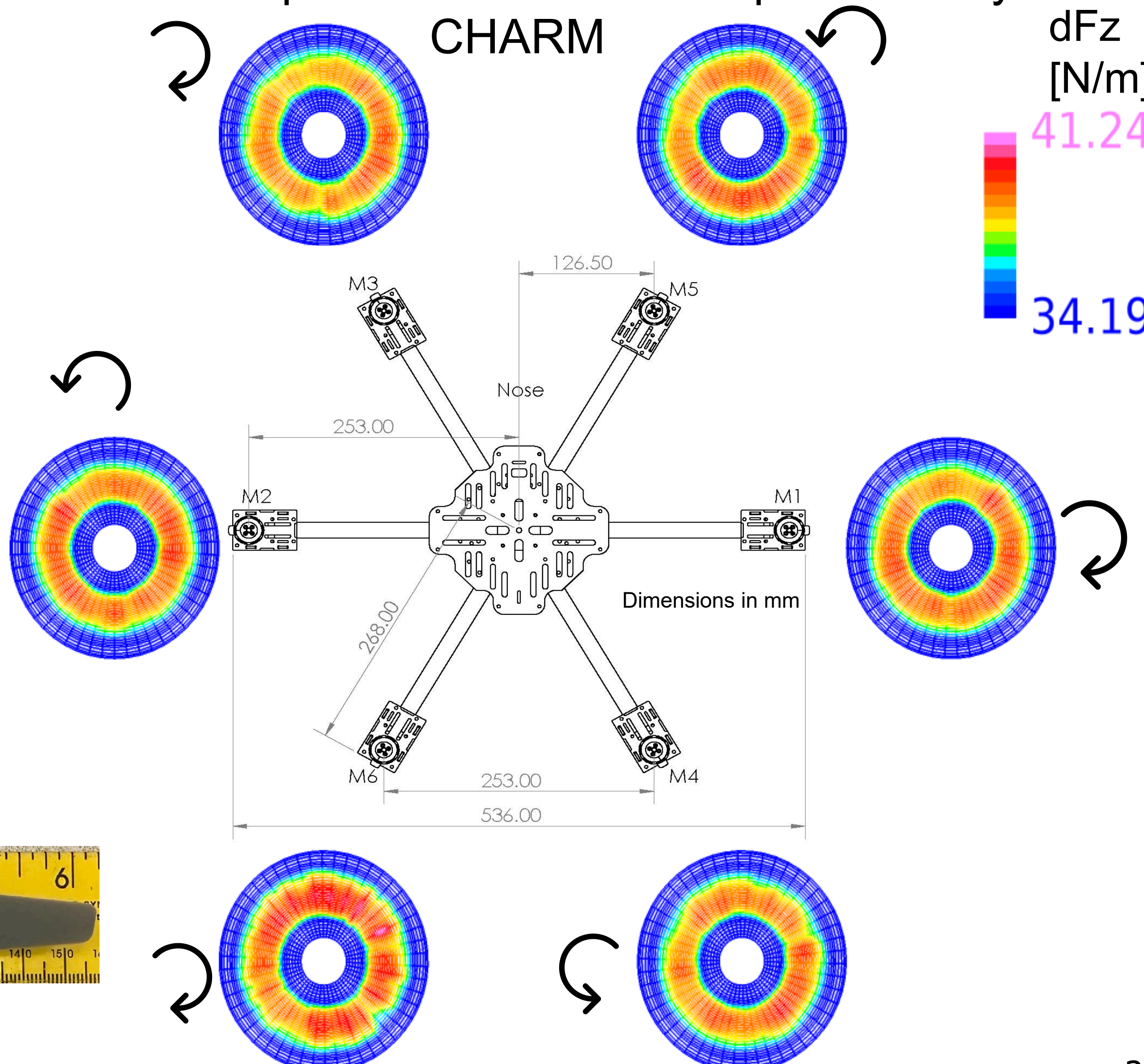




Synchrophasing Simulation

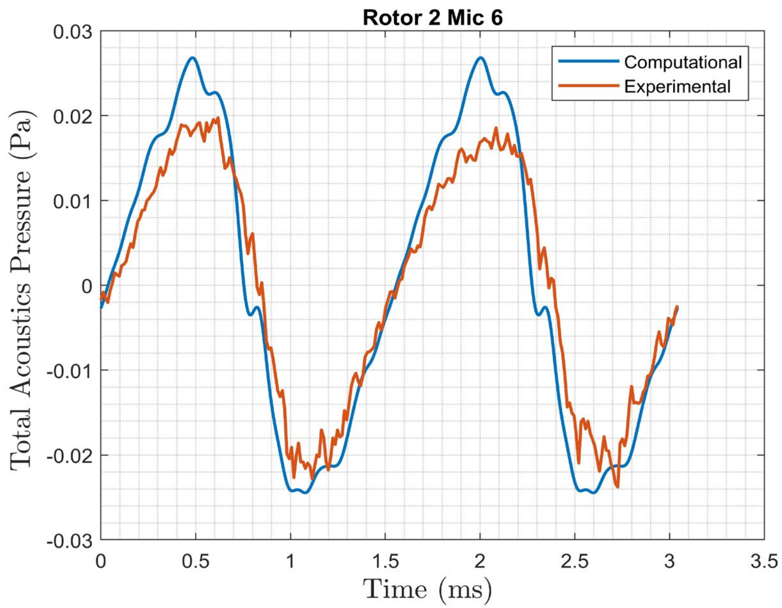


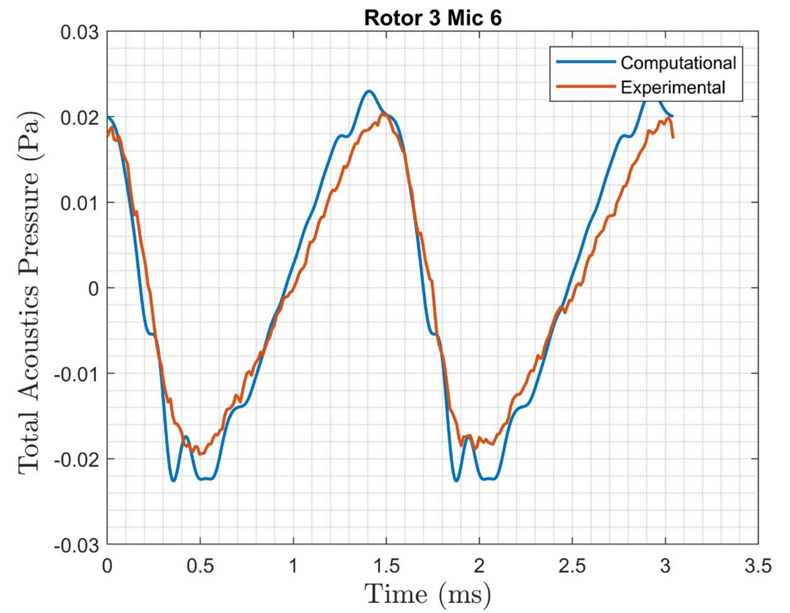
Vertical component of blade loads predicted by CHARM

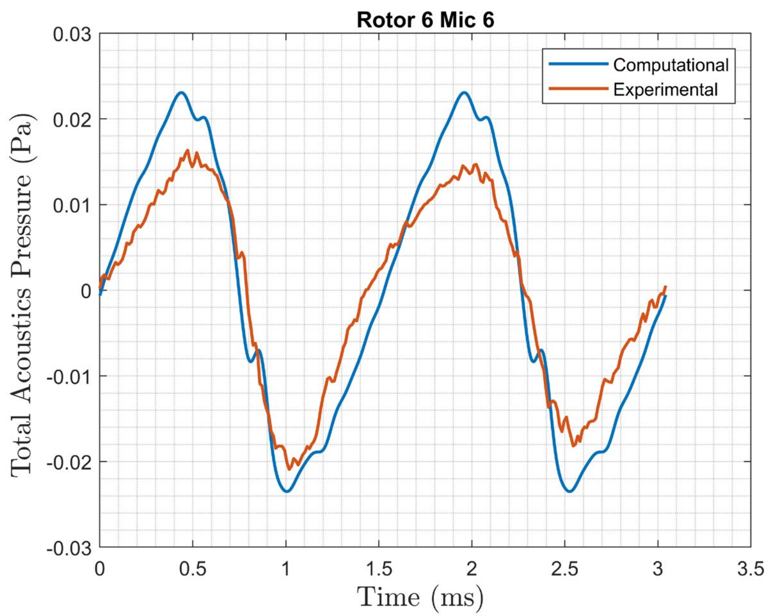


Rotor Speed	2000 rad/s
Tip Speed	0.38 Ma
C_T (Per Rotor)	0.0115
Rotor Radius	0.0635m (2.5in)

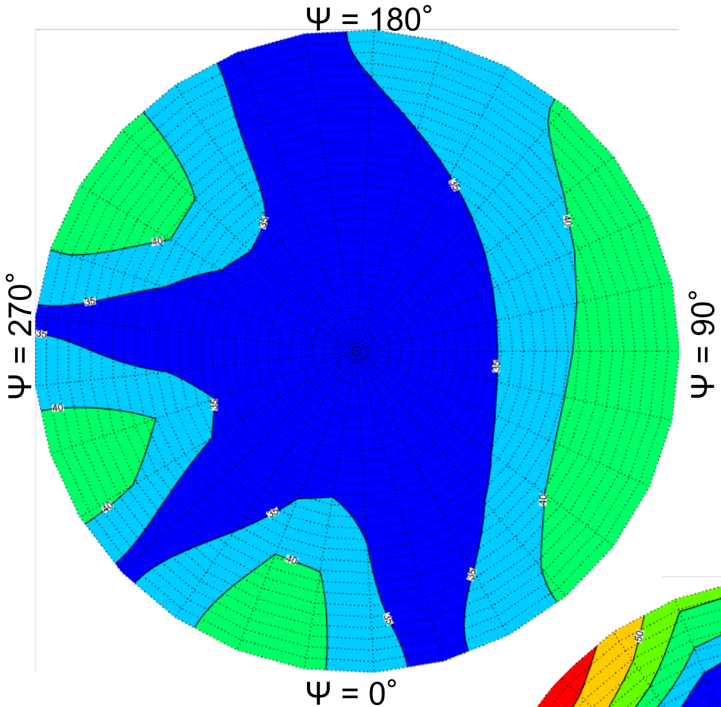
Predicted vs. Measured Pressure Time Series



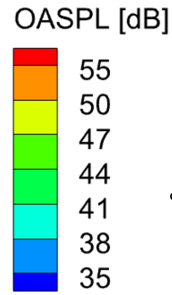


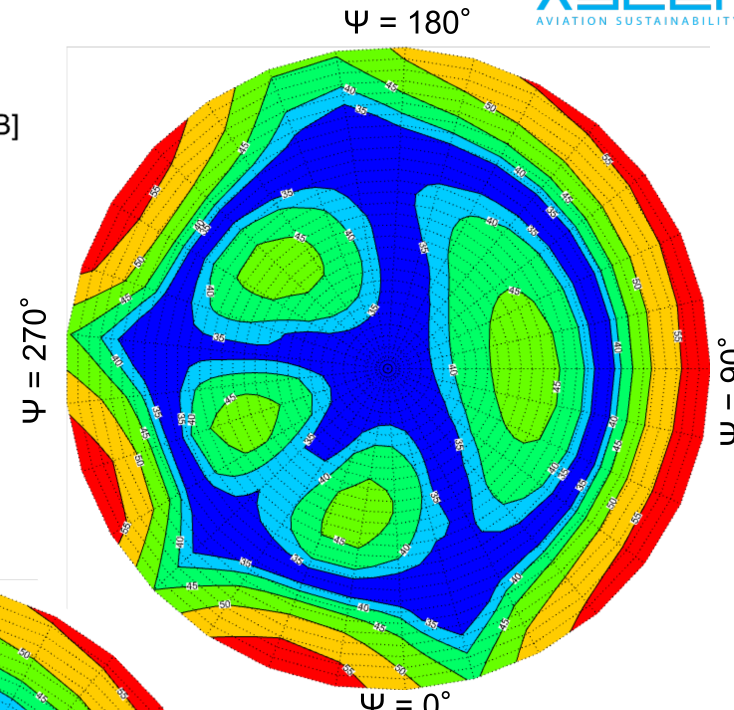


Two Rotor Prediction @ Optimal (Mic 6 : Ψ = 270°, ϕ = 0°)



Thickness





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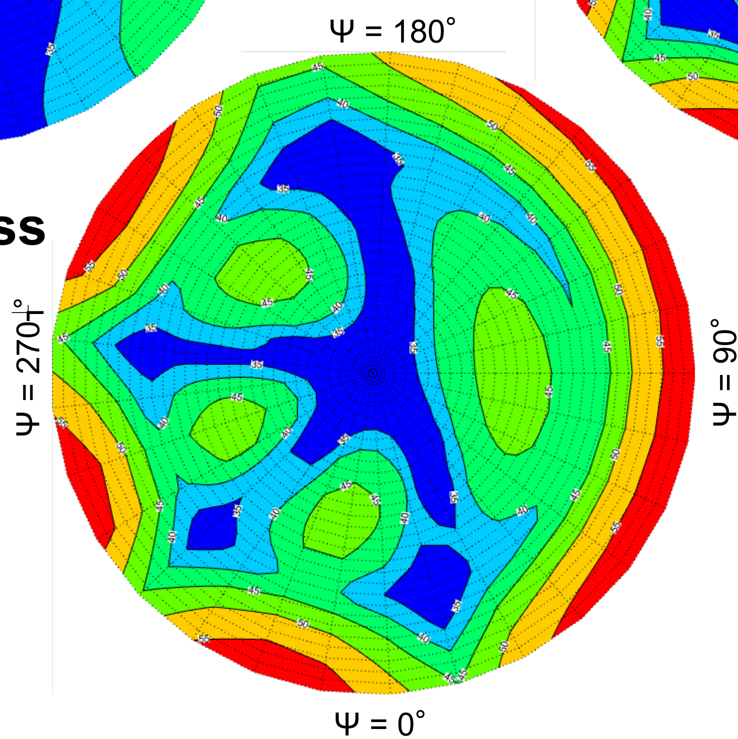
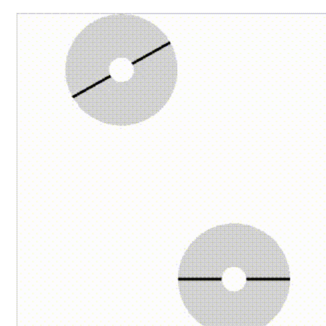
Total

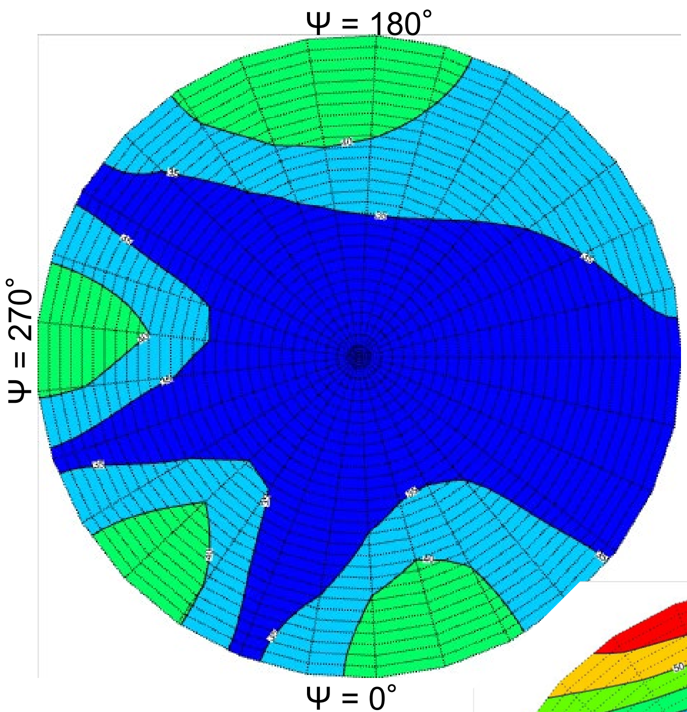


Units in dB
(re: 20 μPa)

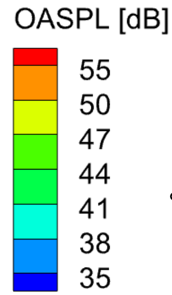


Radius: *R* = 5 m
Flight Condition: Hover

Two Rotor Prediction @ Pessimal (Mic 6 : Ψ = 270° , ϕ = 0°)



Thickness



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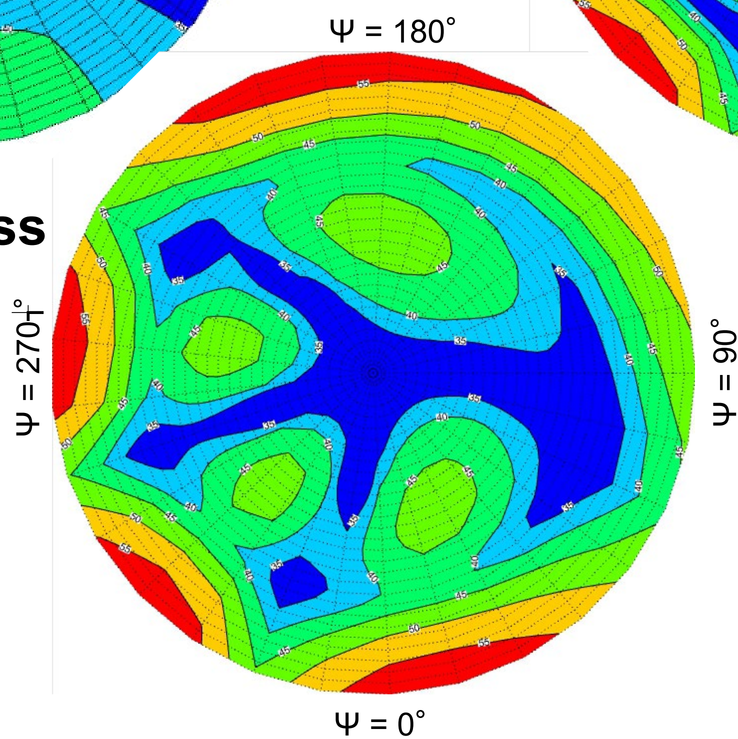

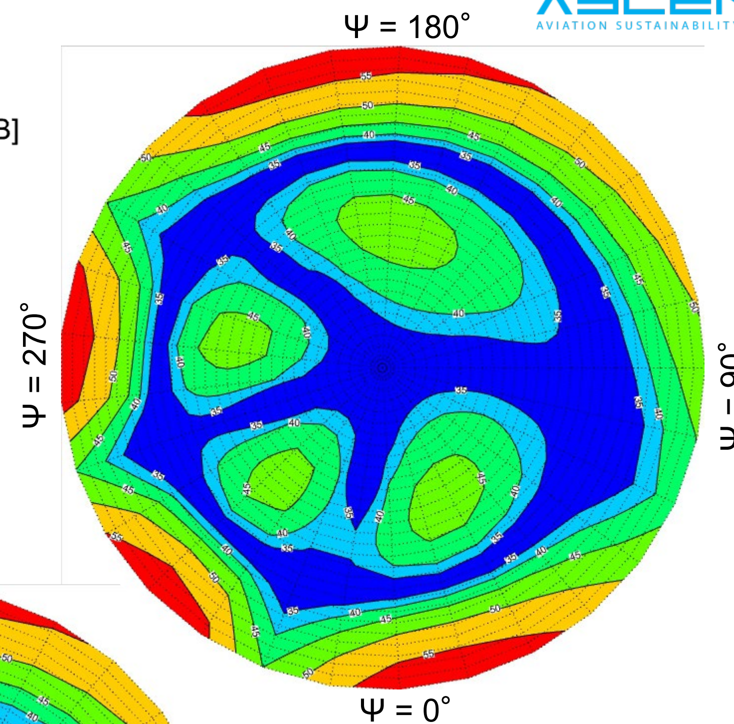

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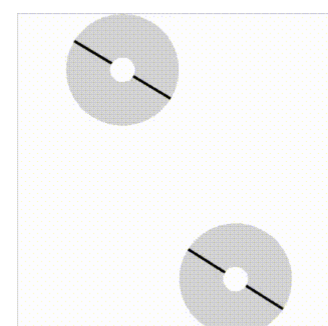

Units in dB
(re: 20 μPa)

Radius: *R* = 5 m
Flight Condition: Hover

Project 77
Measurements to Support Noise Certification for UAS/UAM Vehicles and Identify Noise Reduction Opportunities

Penn State

PI: Eric Greenwood

PM: Hua (Bill) He

Cost Share Partner: Beta Technologies (UAM OEM)

Objective:
To develop repeatable noise measurement methods for UAS and UAM vehicles and to use these methods to collect noise data on a variety of UAS and UAM configurations across different operating modes, speeds, and altitudes.

Project Benefits:
- Inform noise certification standards
- Research database of UAS and UAM noise
- Reduce negative acoustic impacts of UAS and UAM through design changes and operation

Research Approach:
- Simulate UAS and UAM noise measurements
- Develop noise source separation for distributed propulsion vehicles
- Investigate instrumentation requirements for acoustics, weather, and vehicle state
- Collect noise data on UAS and UAM components and vehicles
- Explore acoustical effects of design changes, operating procedures, and flight control laws

Major Accomplishments (to date):
- Simulation of UAS noise to understand rotor interference effects and far-field distance
- Measurements exploring the repeatability and variability of multirotor UAS noise
- Development and acoustic testing of highly reconfigurable multirotor research UAS vehicles
- Flyover and ground test acoustic measurements of Beta Technologies ALIA-250 UAM aircraft
- Development of UAS synchrophasing system

Future Work / Schedule:
- Apply Project 49 noise prediction system to investigate variability of UAS and UAM noise
- Expand measurements of UAS configurations
- Validate multirotor noise source separation
- Explore effects of flight control system on noise

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- Advisory Panel: Rick G. Riley (FAA), Christopher M. Hobbs (FAA), Rudramuni K. Majjigi (FAA), David A. Senzig (FAA), D. Caleb Sargent (Sikorsky), Royce Snider (Bell), Parthiv Shah (ATA), David R. Read (Volpe), Juliet A. Page (BRRC), Kyle A. Pascioni (NASA), Jacques Virasak (Maglev Aero)

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Thank You!