National Aeronautics and Space Administration

CELEBRATING 100 YEARS

NASA Langley Research Center 1917-2017

Overview of Unmanned Aircraft System (UAS) Noise Research at NASA Langley Research Center

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Aircraft Noise and Emissions Reduction Symposium

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ACKNOWLEDGMENTS

- The presentation represents work from several dedicated researchers and staff:
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OUTLINE

I. Introduction/Motivation
   A. Scaling
   B. Facilities
I. Source Modeling and Prediction
II. Ground Testing
III. Flight Testing
IV. Auralization and Psychoacoustic Studies
V. Concluding Remarks

INTRODUCTION / MOTIVATION

- UAS in the National Airspace
  - Companies can file for exemption from obtaining COAs
  - Of first 500 exemptions, 71% are rotary-wing in nature*
    - More than 90% of these are multi-copters*
- Impacts on civilian populations (in large numbers) unknown
  - Vehicle sightings sometimes referred to as "annoying"
  - Vehicle acoustics require consideration

Image: *Kesselman, S., *Snapshot of the First 500 Commercial UAS Exemptions*, Association for Unmanned Vehicle Systems International (AUVSI), 2015.

INTRODUCTION / MOTIVATION

Work funded by NASA's DELIVER Project

- *3-year project ending 9/2017*
- *Feasibility assessment of design tools*

Emerging Vertical Lift Vehicle Concept Space

Vehicle Data & Missions

Conceptual Design (NDARC):

- Enables design and sizing of vehicles for specific missions
- Validated only for larger (>2 PAX), convention vehicles

Gaps / Challenges:

- Tools not calibrated to small and alternative configurations
- Limited data available for novel and small vehicles

Data & Models

Autonomy:

- High impact on mission and operational capability

Gaps / Challenges:

- No current ability to include autonomy constraints in conceptual design

Data & Models

Hybrid Electric Propulsion:

- Enabling technology for all vehicles in concept space

Gaps / Challenges:

- Limited hybrid-electric propulsion system models – for large vehicles only
- No data for novel cryogenically cooled power systems

Data & Models

Noise:

- Key for community acceptance

Gaps / Challenges:

- No current ability to account for noise in conceptual design

UAS SCALING CONSIDERATIONS

- Common rotor noise sources
  - Deterministic
  - Broadband
- Effects of reduced scale
  - $M_{\text{tip}} \approx 0.15 - 0.3$
  - $Re_c(0.75R) \approx 10^4 - 10^5$
- Effects of multiple rotors
  - Multiple BPFs
  - Rotor-rotor, rotor-airframe interaction effects
- Tonal vs. Broadband Noise
  - Reduced scale may increase importance of broadband noise

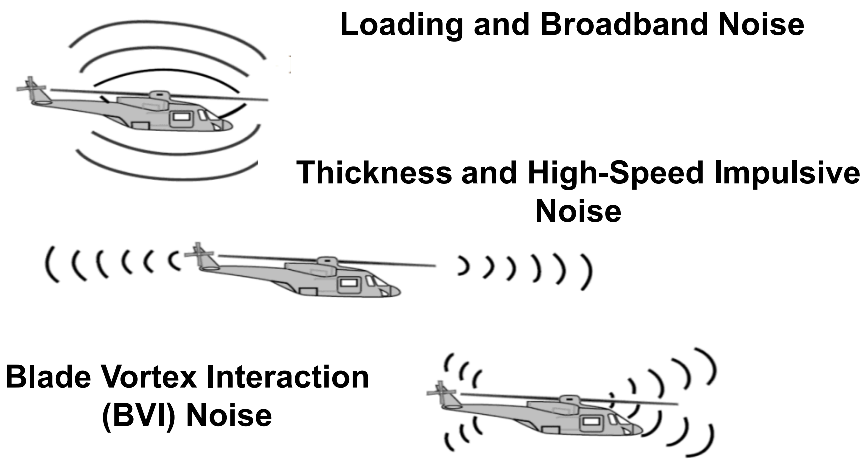


Image: Brentner, K. and Farassat, F., "Modeling aerodynamically generated sound of helicopter rotors," *Progress in Aerospace Sciences*, Vol. 39, Apr 2003.

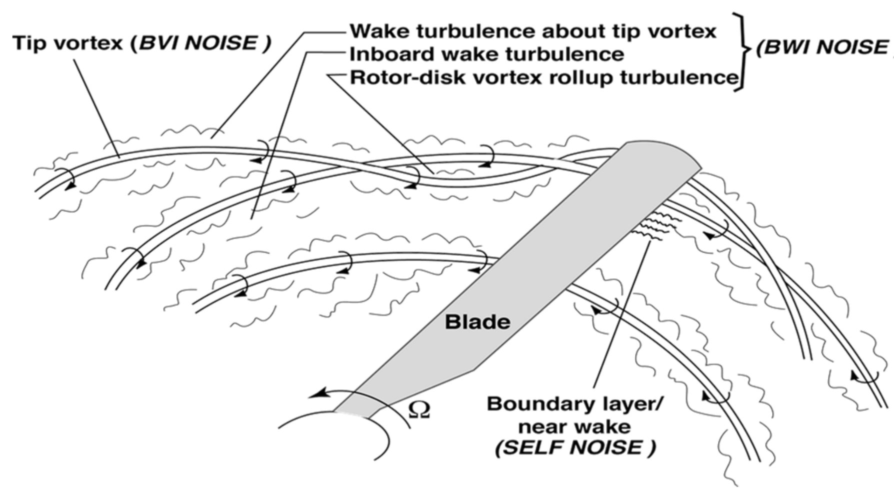
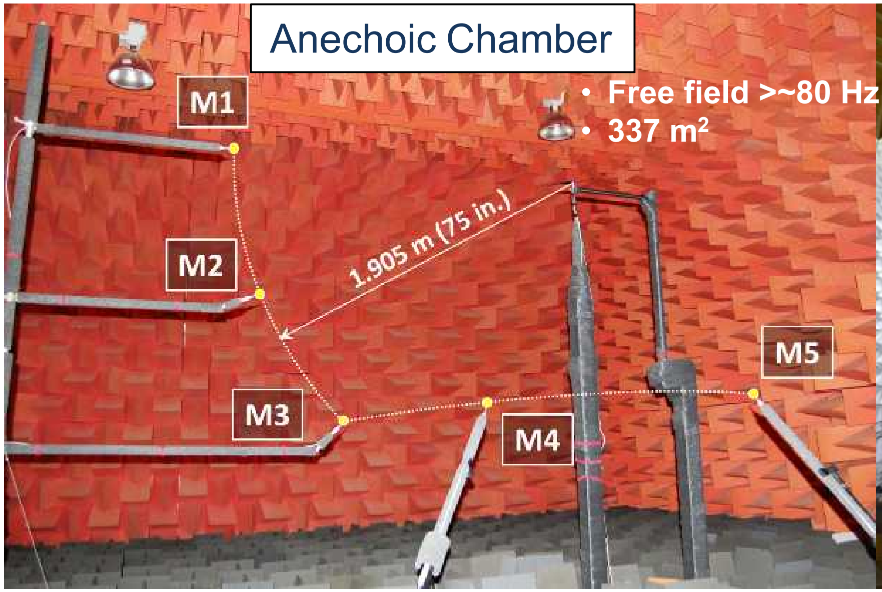
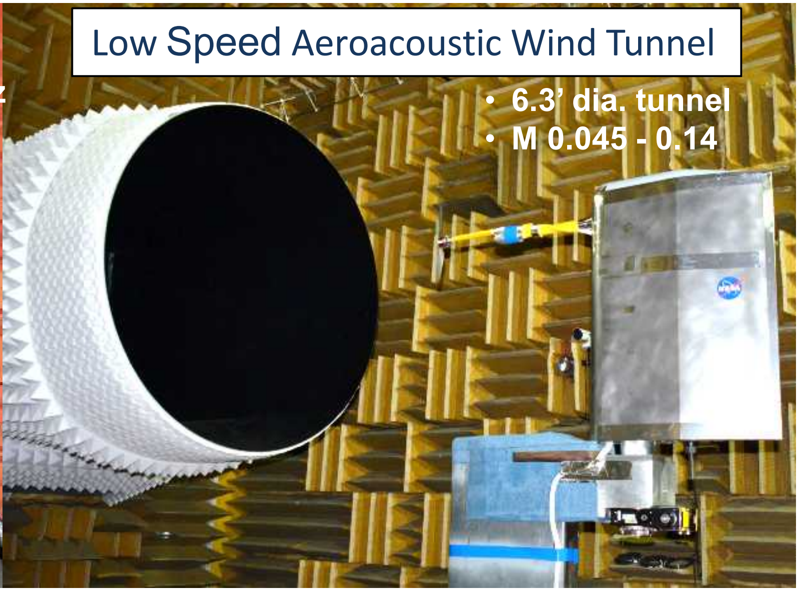
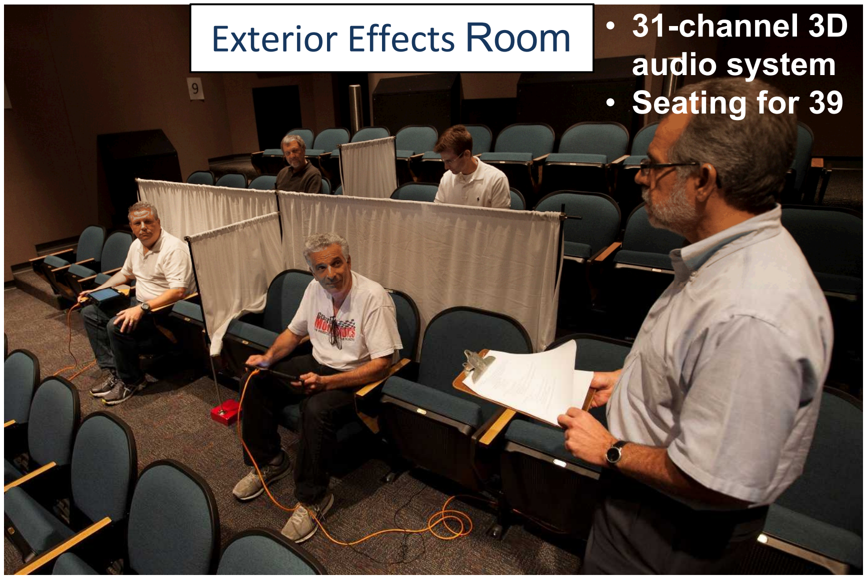


Image: Burley, C. L. and Brooks, T. F., "Rotor Broadband Noise Prediction with Comparison to Model Data," *Journal of the American Helicopter Society*, Vol. 49, (1), 2004.

FACILITIES


Anechoic Chamber
• Free field >~80 Hz
• 337 m²
M1
M2
M3
M4
M5
1.905 m (75 in.)


Low Speed Aeroacoustic Wind Tunnel
• 6.3' dia. tunnel
• M 0.045 - 0.14

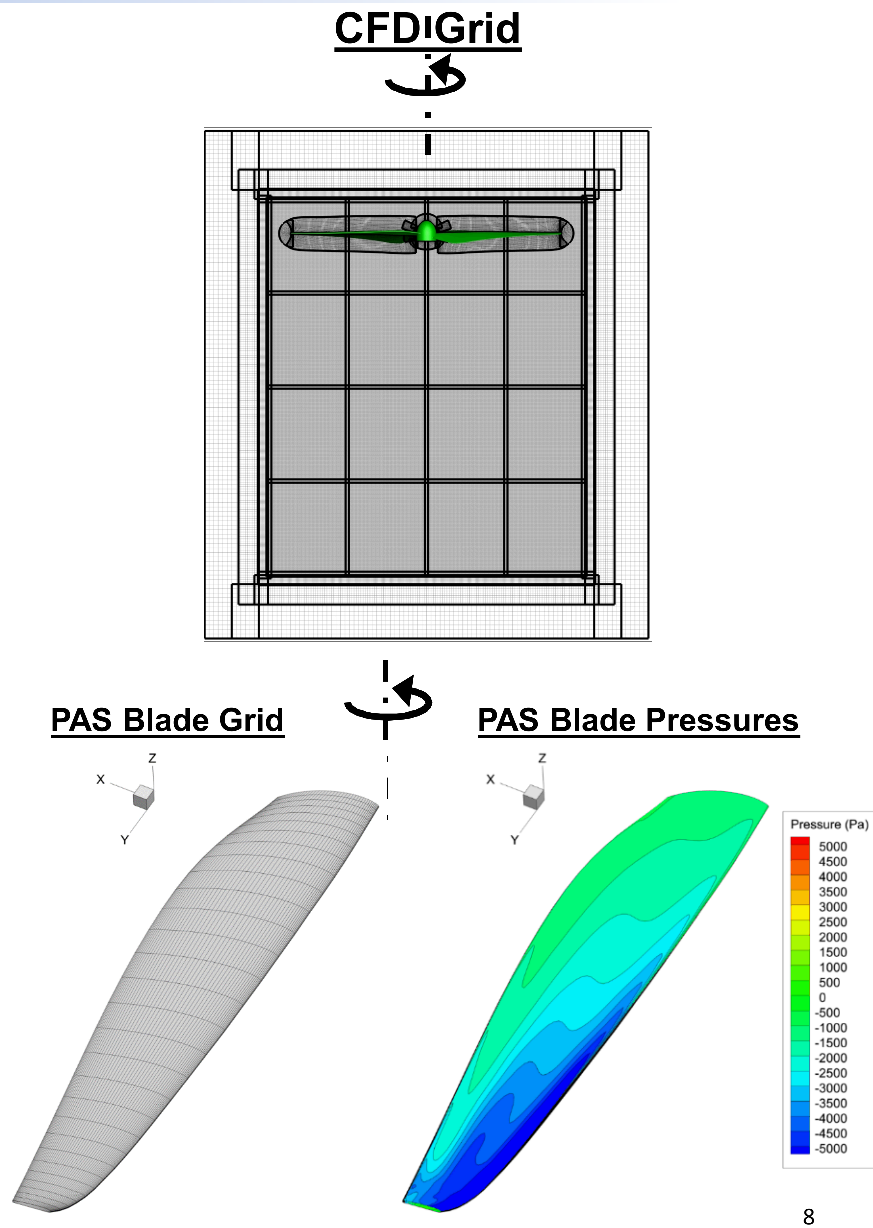

Exterior Effects Room
• 31-channel 3D audio system
• Seating for 39


Langley's UAS Operations Office
• Coordinates pilots, vehicles, support personnel
• Supports multiple flight locations

SOURCE MODELING AND PREDICTION

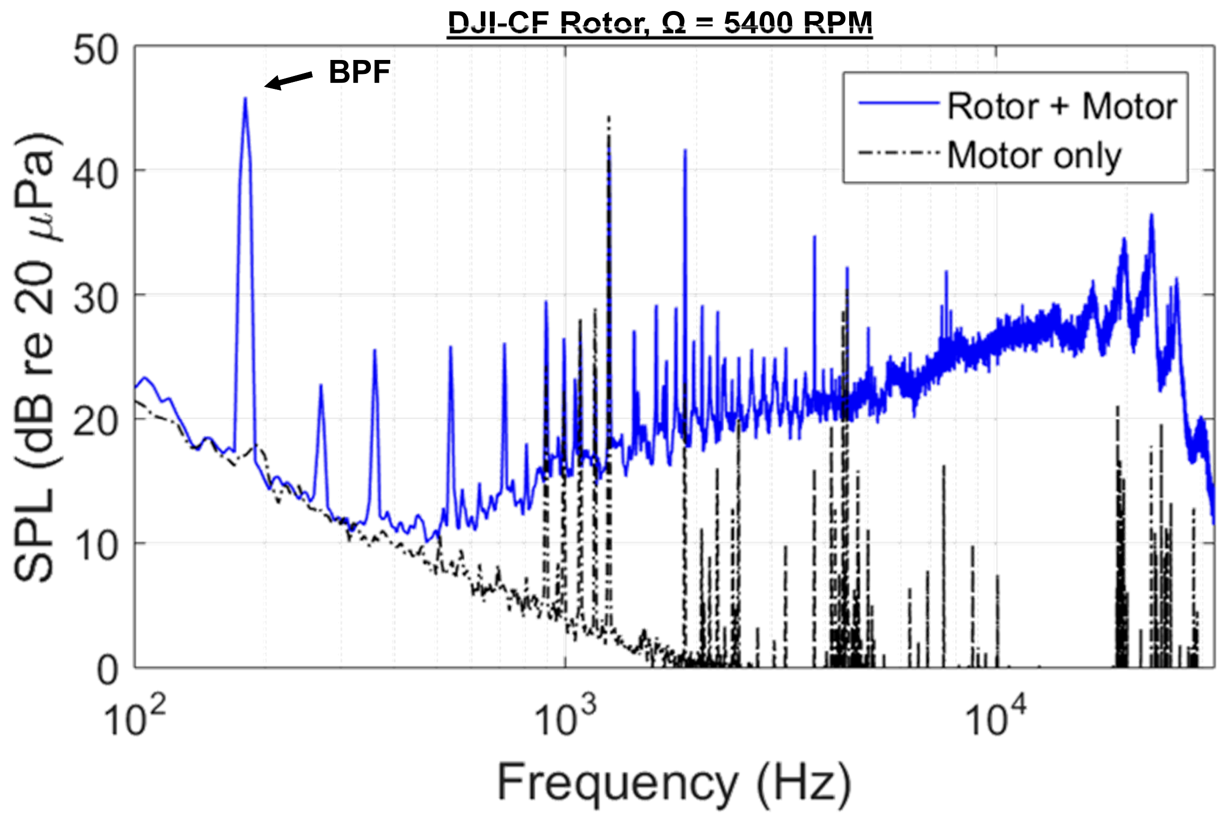
- High-fidelity CFD **(DJI-CF rotor)**
  - OVERFLOW2 uRANS
  - Computes impermeable blade surface loadings
  - Coupled with PSU-WOPWOP (referred to as OF2-PSW)
  - Utilize off-body adaptive mesh refinement (AMR)

- Low-fidelity BEA **(TM-CF rotor)**
  - Propeller Analysis System (PAS) suite of ANOPP
  - Only applicable to cases of isolated rotors/propellers



POC: Nik Zawodny, Doug Boyd

SOURCE MODELING AND PREDICTION

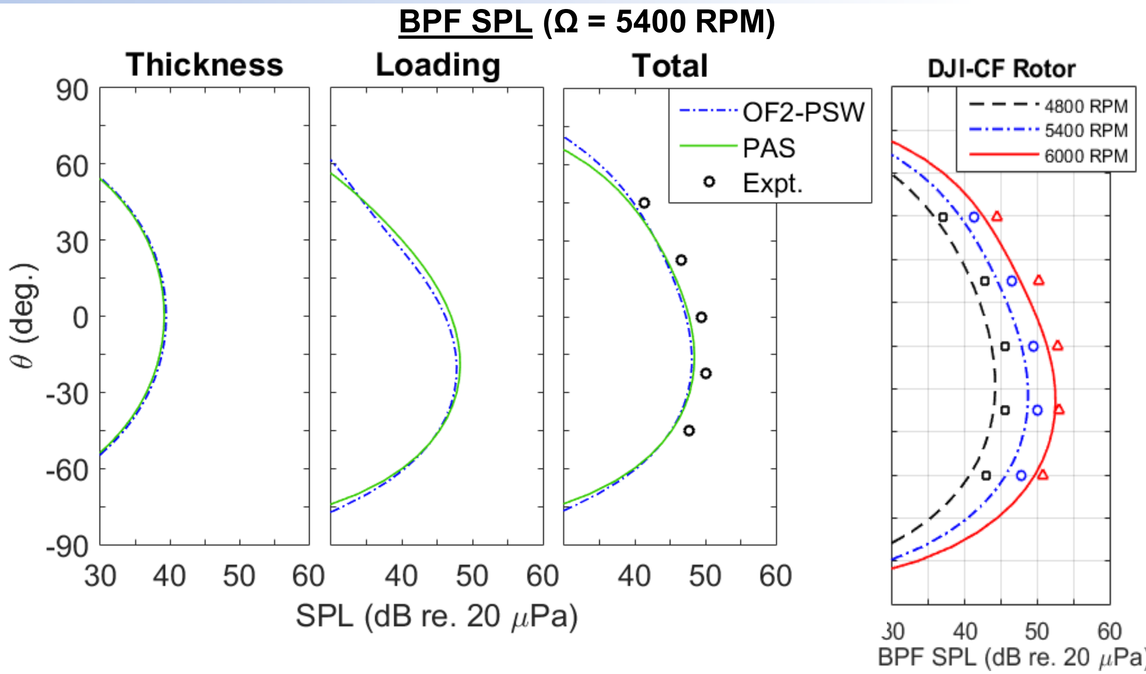


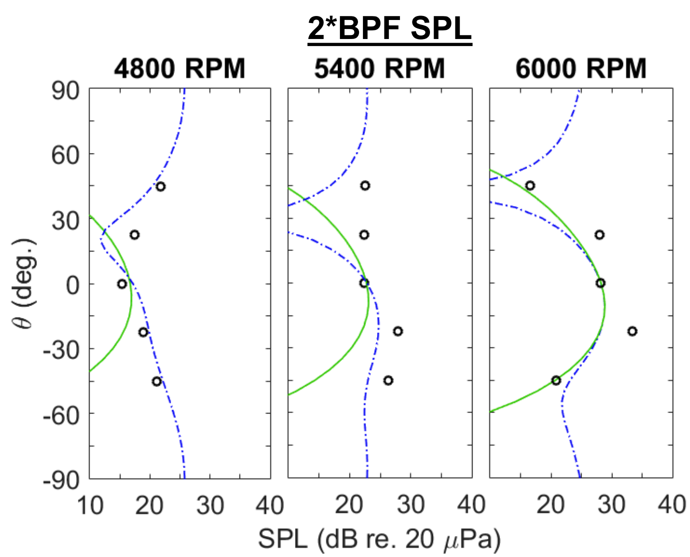
- Acoustic Spectra
  - Data at $\theta = -45°$
  - Low freqs.: Rotor BPF and first several harmonics
  - Mid- and high-freqs.: Mixture of motor and broadband noise
  - Certain motor tone levels similar b/w loaded vs. unloaded cases

POC: Nik Zawodny

SOURCE MODELING AND PREDICTION

- Method Comparisons (OF2-PSW vs PAS-SPN)
  - DJI-CF rotor
  - Excellent BPF directivity agreement
- BPF Predictions using PAS
  - 3 mid-range rotation rates per rotor
  - Good comparisons with experimental data (within ±2.5 dB)
- Two BPF Predictions
  - Better 2*BPF agreement b/w OF2-PSW and expt.
  - 2*BPF levels considerably lower than BPF levels
  - Negligible higher frequency content predicted by both methods





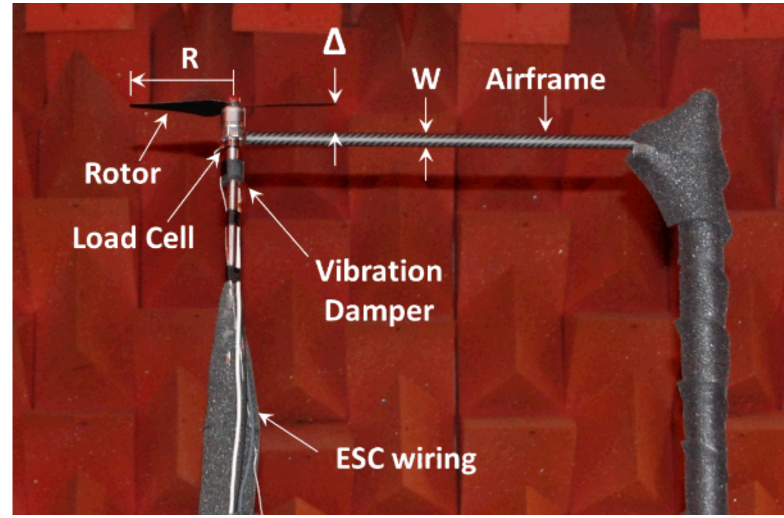
POC: Nik Zawodny

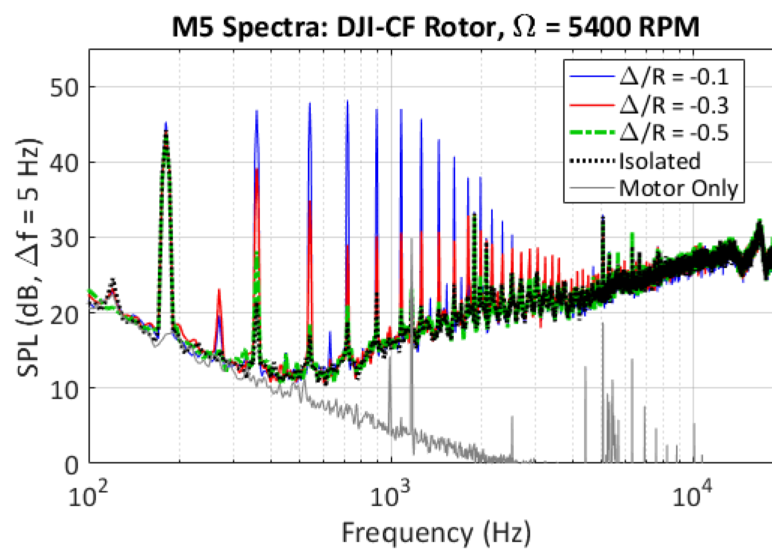
GROUND TESTING

- Determine contributions of rotor and rotor-airframe interactions to radiated noise for simple vehicle configurations

- Rotor and airframe support stands
  - Physically separate from one another
  - Able to vary rotor tip separation distance (Δ)
  - Airframes of constant and variable cross-section considered
  - $^{W}/_{c_{\mathrm{ref}}} \approx 1$

- Results show
  - Harmonically rich for small rotor tip clearances (Δ)
  - Case of $\Delta/R = -0.5$ nearly identical to case of isolated rotor





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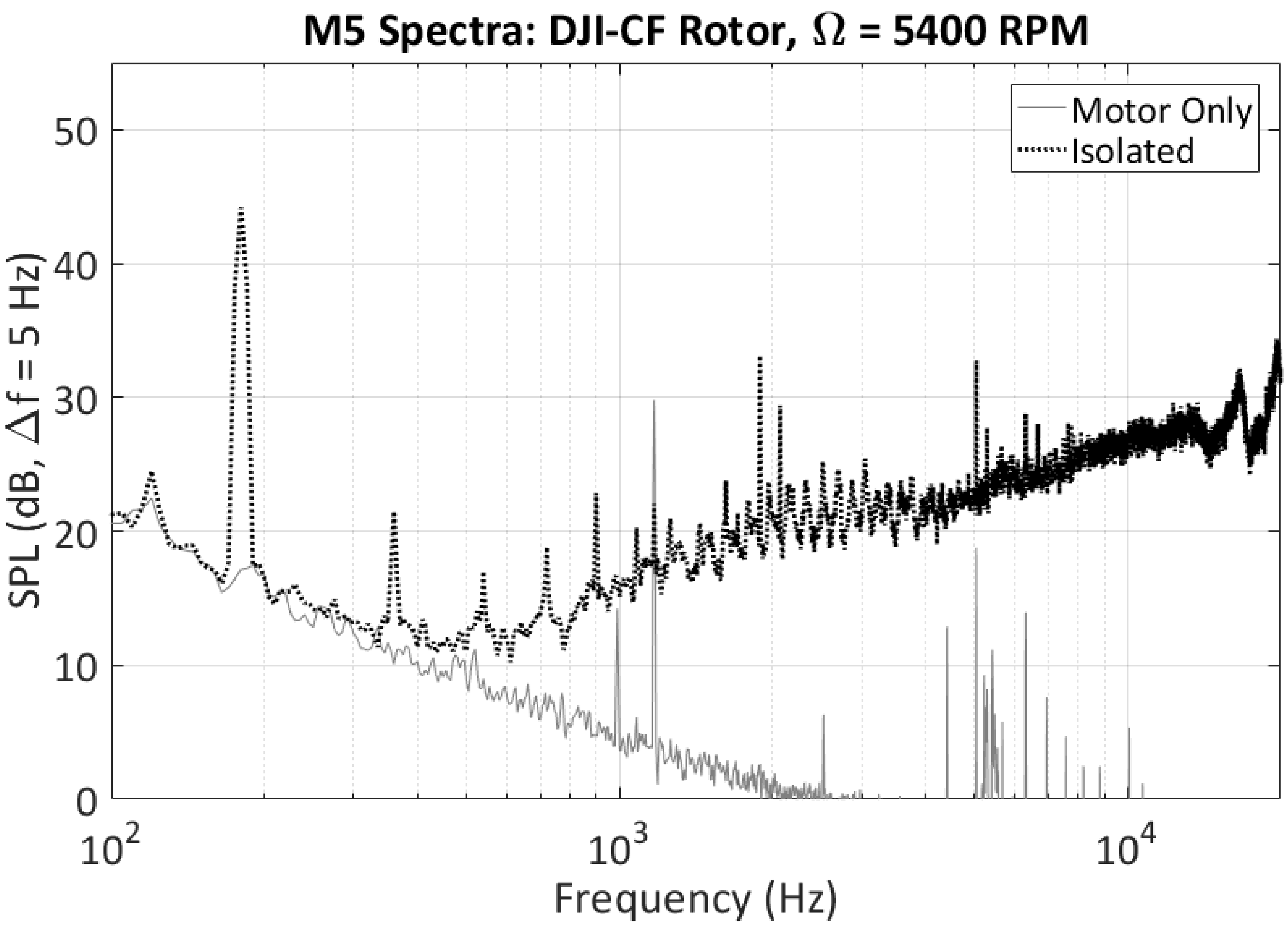
GROUND TESTING



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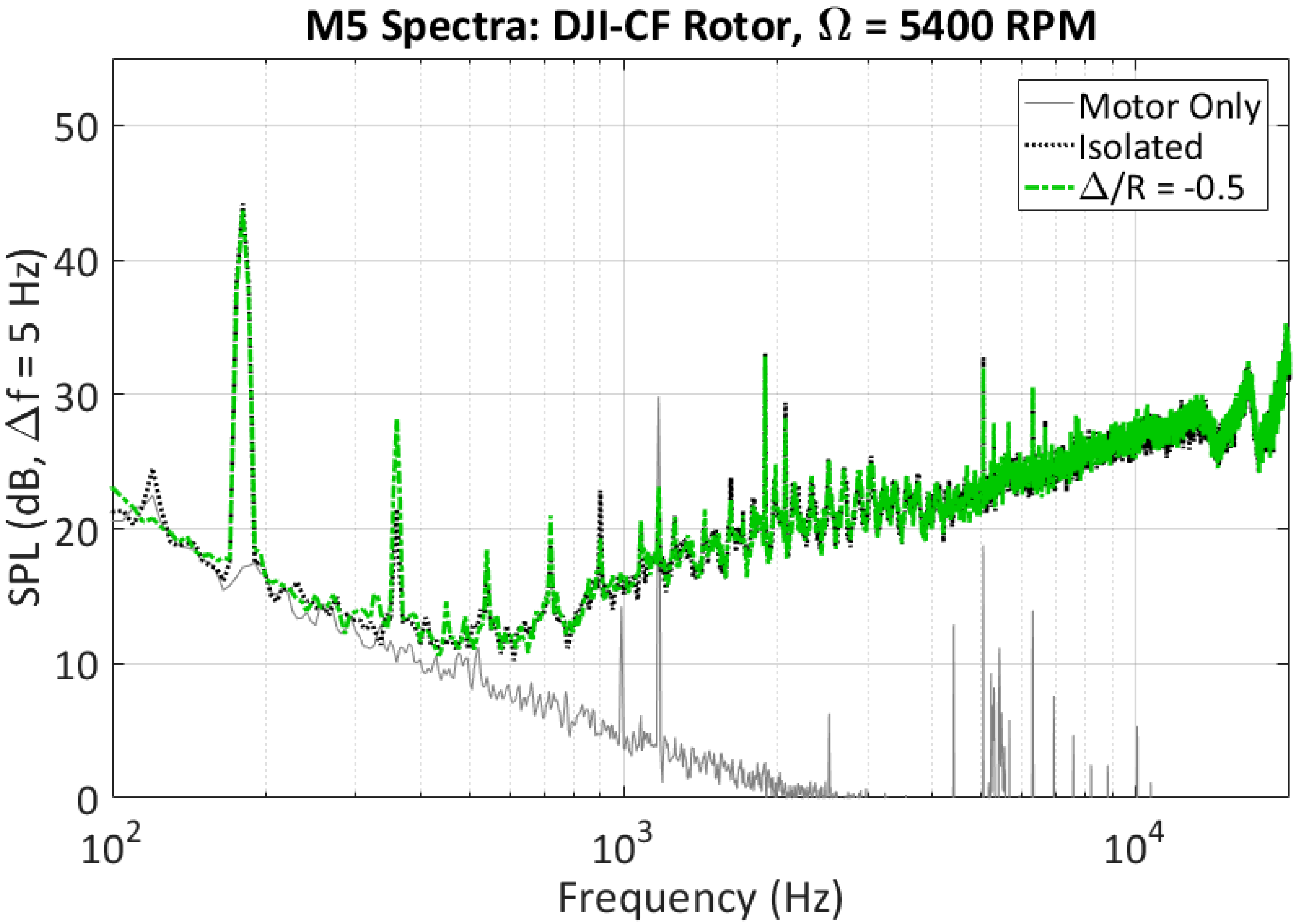
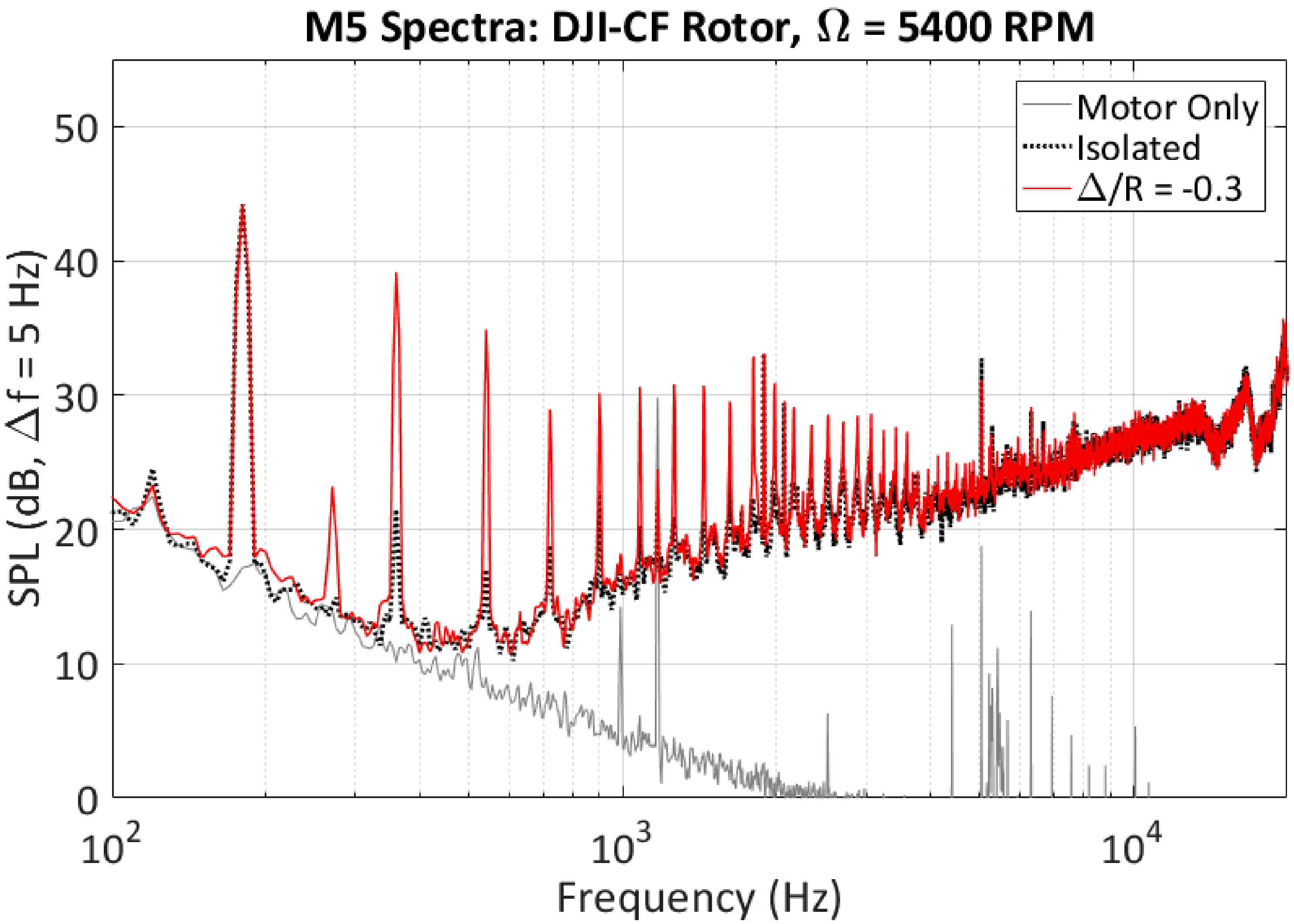
GROUND TESTING



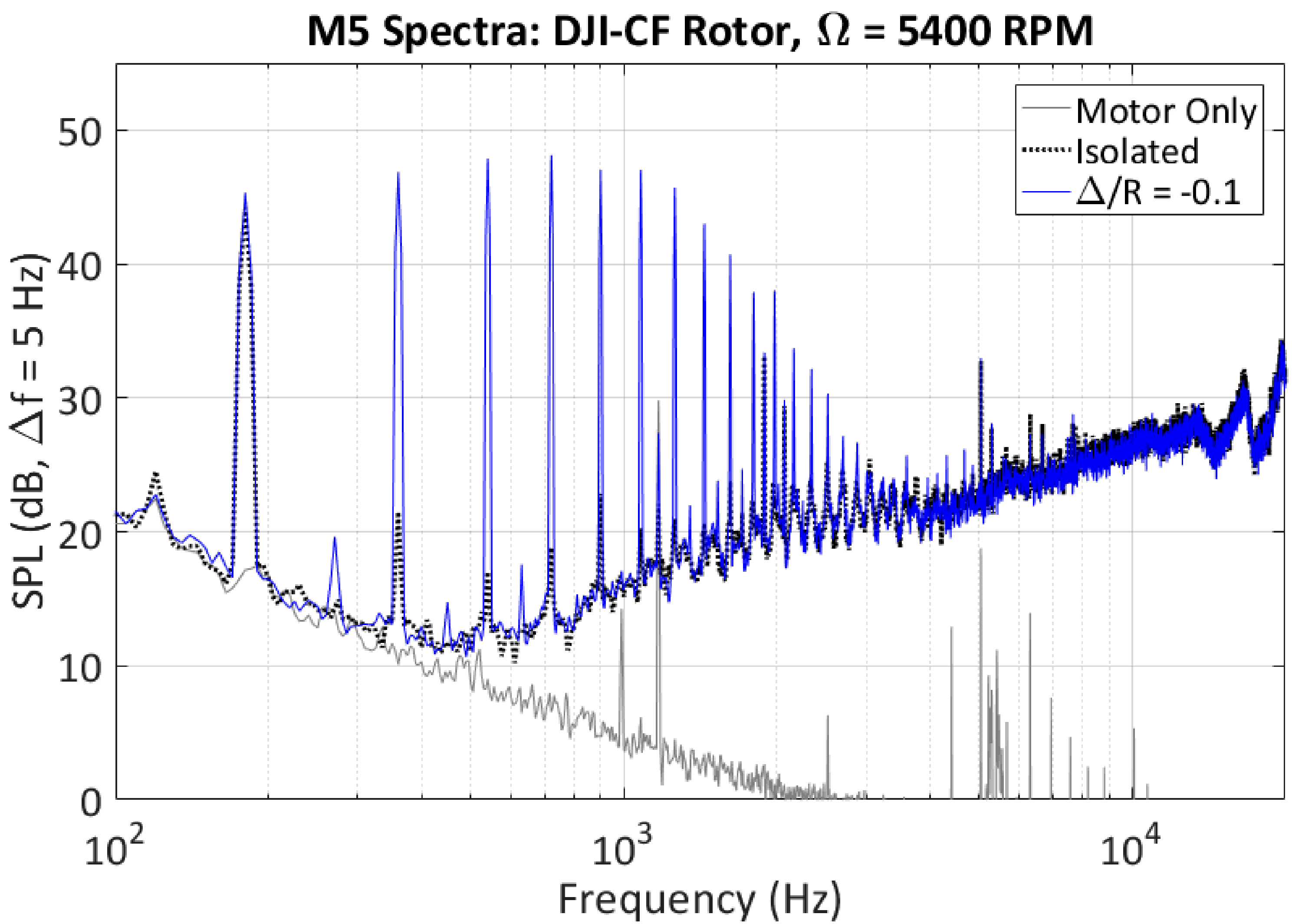
POC: Nik Zawodny

GROUND TESTING



POC: Nik Zawodny

GROUND TESTING

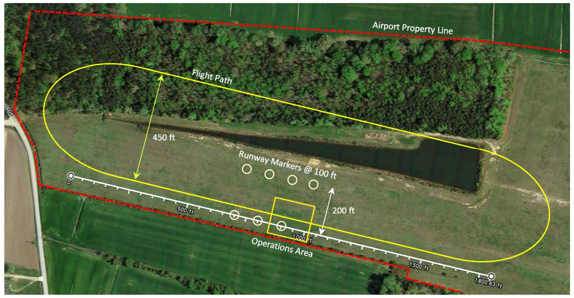


POC: Nik Zawodny

FLIGHT TESTING

Virginia Beach Airport (12/2014)

- Private grass airfield, 1500m x 60m
- 3 ground mics, 1 mic on 1.2m stand
- No on-site meteorological data



Fort A.P. Hill (8/2015)

- Paved 365m x 30m runway
- Shared test with separate NASA project
- 4 ground mics
- Weather station ~4m off ground

Oliver Farms, Smithfield, VA (Fall 2016)

San Diego, CA (December 2016)

- In conjunction with Straight-Up Imaging

POC: Ran Cabell

EXAMPLE FLIGHT VEHICLES

Edge 540 (Gas)
11.3 kg; 27 m/s

Phantom 2
1.6 kg; 15 m/s

- Fixed-pitch propellers
- All vehicles flown manually
- Flight data acquisition system with two GPS systems mounted on each vehicle

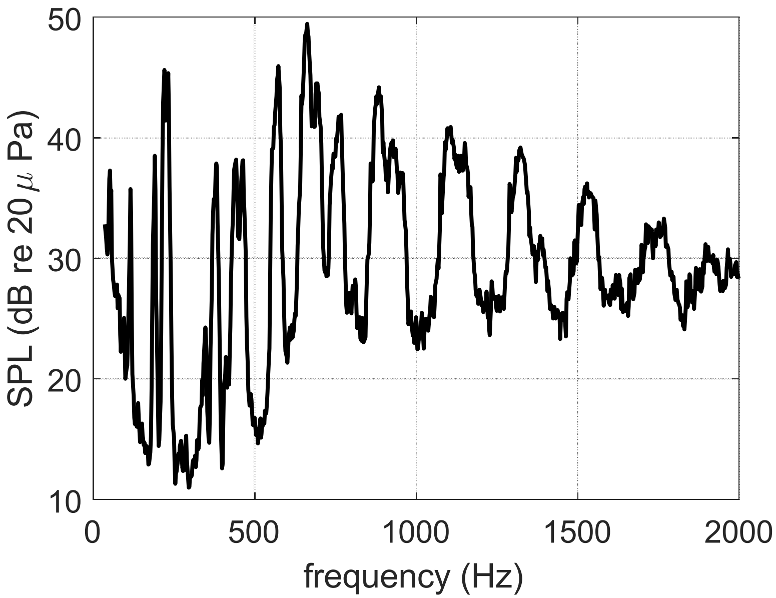
3DR Y6
2.5 kg; 15 m/s

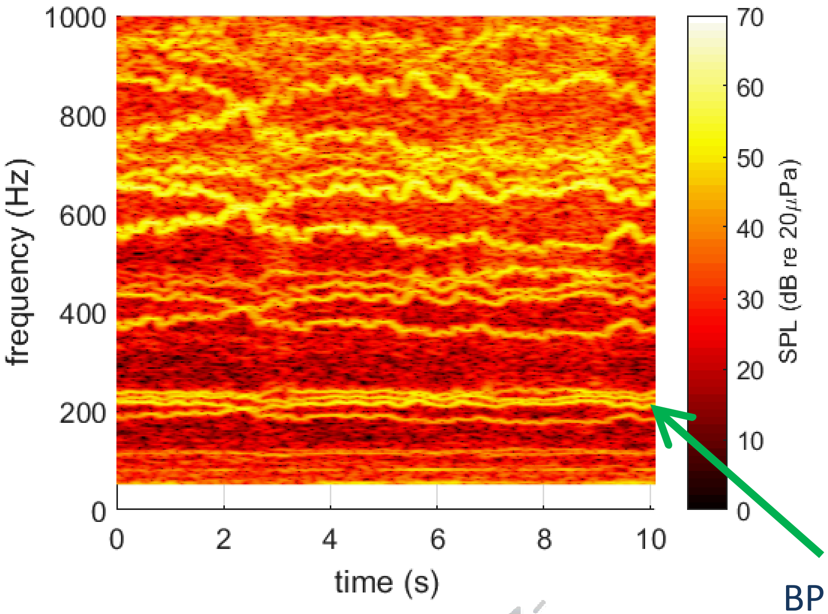
Prioria Hex
7.3 kg; 15 m/s

POC: Ran Cabell

SPECTROGRAMS: HOVER

Phantom 2 Quadcopter





BPFs

“Unsteady loading can be the dominant noise source, particularly for low-tip-speed propellers.”
(Magliozzi, Hanson, Amiet, NASA TR)

POC: Ran Cabell

AURALIZATION AND PSYCHOACOUSTICS

- Work toward the goal of understanding human annoyance that results from the sound of UAS has fallen (/will fall) into 3 categories:
  - Synthesis:

    Generating the capability to produce an auralized UAS flyover.
    - Work done Winter 2015, presented Summer 2015.
  - Simulation:

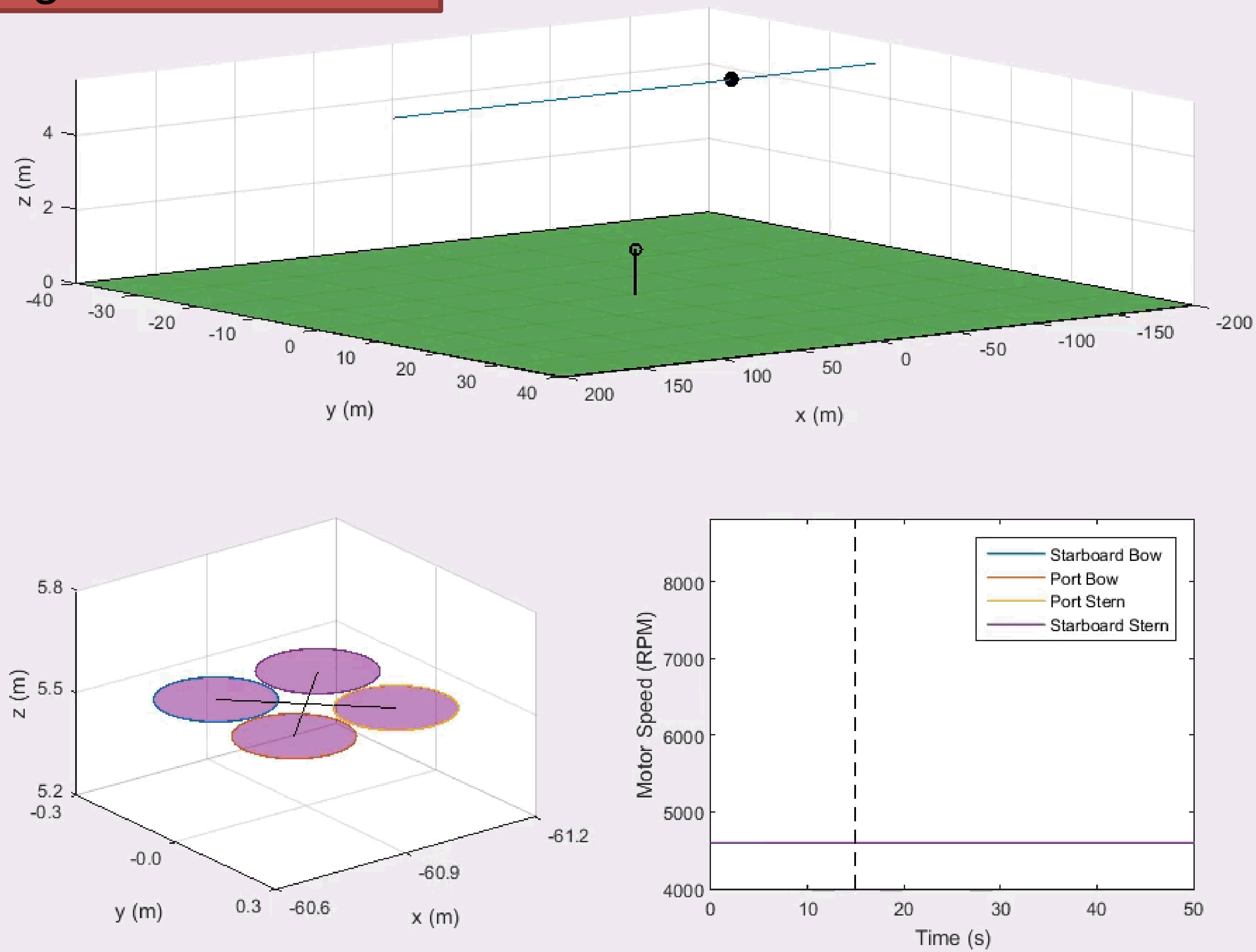
    Producing vehicle dynamics histories (distance, attitude, etc.) that can be used for auralization.
    - Work done Summer 2015, presented Summer 2016.
  - Psychoacoustic Testing:

    Presenting recorded and auralized sounds to human subjects in order to get direct measurements of the effects these sounds may have on a general population.
    - Work done Spring 2017, preliminary results indicate annoyance penalty with small UAS compared to road vehicle

POC: Steve Rizzi, Andrew Christian

AURALIZATION AND PSYCHOACOUSTICS

Auralizing a basic model:



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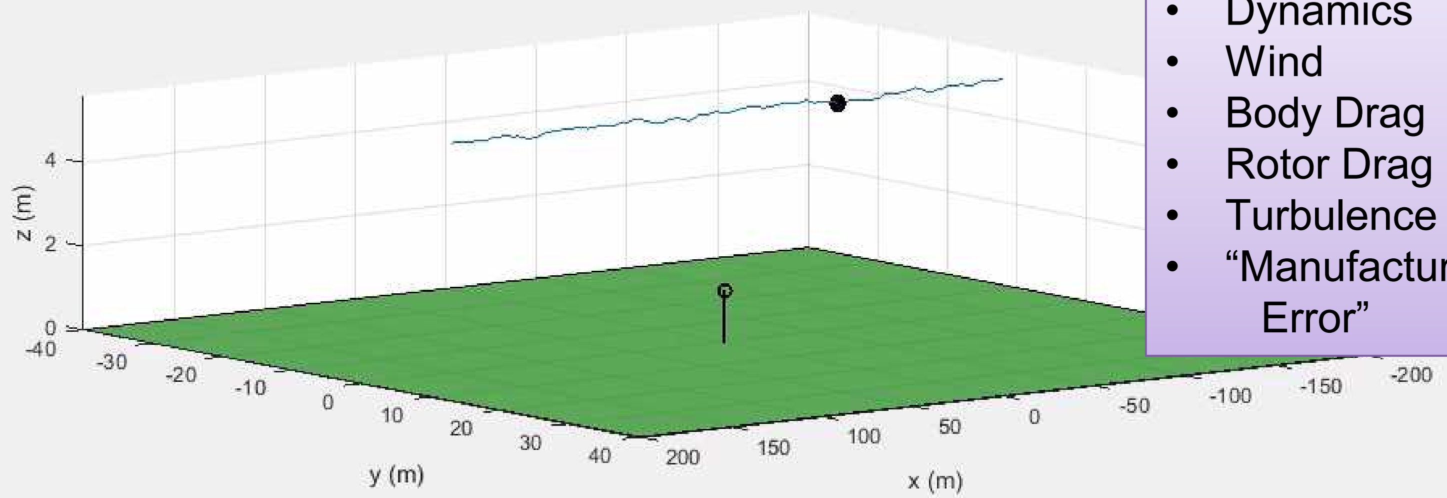
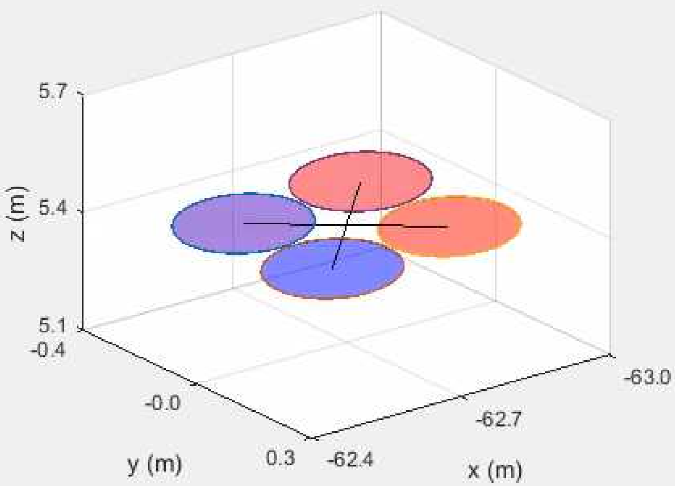
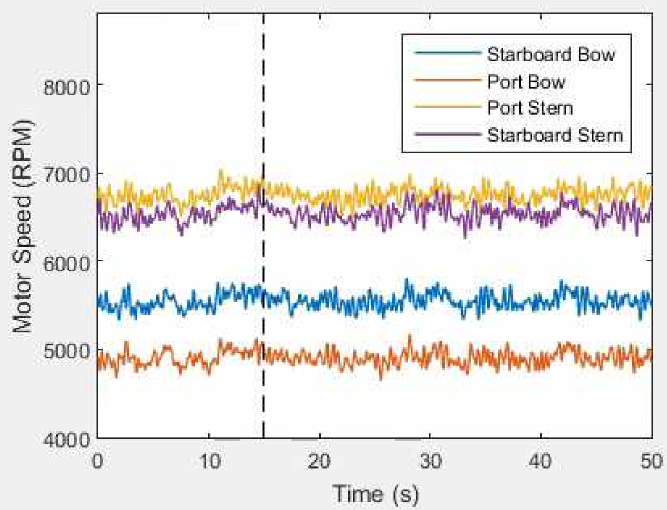
AURALIZATION AND PSYCHOACOUSTICS

Included Effects:
- Dynamics
- Wind
- Body Drag
- Rotor Drag
- Turbulence
- “Manufacturing Error”







POC: Steve Rizzi, Andrew Christian

CONCLUDING REMARKS

- Important to understand the acoustic impacts of current UAS and whether existing tools can successfully predict and auralize the noise
- Application of high (CFD) and low (PAS) fidelity methods to isolated rotor noise compare favorably with measurements from ground testing
- Acoustic implications of propeller/airframe interaction can be significant at small spacings from the rotor tip
- Flight tests have revealed the unsteady loading on the rotor(s) can increase the noise and change its character
- Auralizations from test data or predictions can reproduce realistic UAS noise when accounting for various free flight effects
- These auralizations can be presented to sound juries to measure the effects they might have on the general population

POC: Steve Rizzi, Andrew Christian

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Backup Slides

CONFERENCE PUBLICATIONS

- Christian, Boyd, Zawodny, Rizzi, “Auralization of tonal rotor noise components of a quadcopter flyover,” Inter-Noise 2015, San Francisco CA, August 9-12, 2015.
- Rizzi, Christian, “A method for simulation of rotorcraft fly-in noise for human response studies,” Paper 192, InterNoise 2015, San Francisco, CA, August 9-12, 2015.
- Zawodny, Boyd, Burley, “Acoustic Characterization and Prediction of Representative, Small-Scale Rotary-Wing Unmanned Aircraft System Components,” AHS Forum-72, West Palm Beach, FL, May 17-19, 2016.
- Christian, Lawrence, “Initial Development of a Quadcopter Simulation Environment for Auralization,” AHS Forum-72, West Palm Beach, FL, May 17-19, 2016.
- Cabell, McSwain, Grosveld, “Measured Noise from Small Unmanned Aerial Vehicles,” Noise-Con 2016, Providence, RI, June 13-15, 2016.
- Zawodny, Boyd, “Investigation of Rotor-Airframe Interaction Noise Associated with Small-Scale Rotary-Wing Unmanned Aircraft Systems,” abstract submitted to AHS Forum-73, 2017.
- Christian, Cabell, “Initial Investigation into the Psychoacoustic Properties of Small Unmanned Aerial Vehicles,” abstract submitted to AIAA Aviation 2017.
- Zawodny, Haskin, “Small Propeller and Rotor Testing Capabilities of the NASA Langley Low Speed Aeroacoustic Wind Tunnel,” abstract submitted to AIAA Aviation 2017.