AIAA Pacific Northwest
Virtual Tech Talk
Measuring the Noise of Urban Air Mobility Vehicles

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University of Washington Aeronautics and Astronautics
and
OptiNav, Inc.

April 30, 2020

Quantifying machinery noise

Noise regulation in the US vs. Europe

Contours of aircraft noise immission

Aircraft noise certification: airport centric

Urban Air Mobility: distributed noise

Potential for local regulation

Providing information: sound spheres

- Compute
- Measure in laboratory
- Measure in flight
    - Proposed innovation using an acoustic camera

Main References

Technology for a Quieter America
National Academy of Engineering
2010

Aeroacoustics of Flight Vehicles: Theory and Practice. Volume 2: Noise Control
Hubbard, Harvey H. [Editor]
https://ntrs.nasa.gov/search.jsp?R=19920005561

NASA Acoustics Technical Working Group Meetings 2018-2020

NASA Urban Air Mobility Noise Working Group Meetings

IMMISSION VERSUS EMISSION

Emission is how much noise something produces

Immission is how much noise someone is exposed to

Both are important for the present context

Noise Units

p = RMS sound pressure (Pa), usually limited to a frequency band

$L_p = 20\log_{10}\left(\frac{p}{p_0}\right)$ = Sound Pressure Level, SPL (dB)

$p_0 = 20\times10^{-6}$ Pa = Reference Pressure

dBA

A-Weighted Sound Pressure Level (dBA):

$$L_A = 10\log_{10}\left(\sum_f 10^{\frac{L_p(f)+w_a(f)}{10}}\right)$$

$w_a(f)$

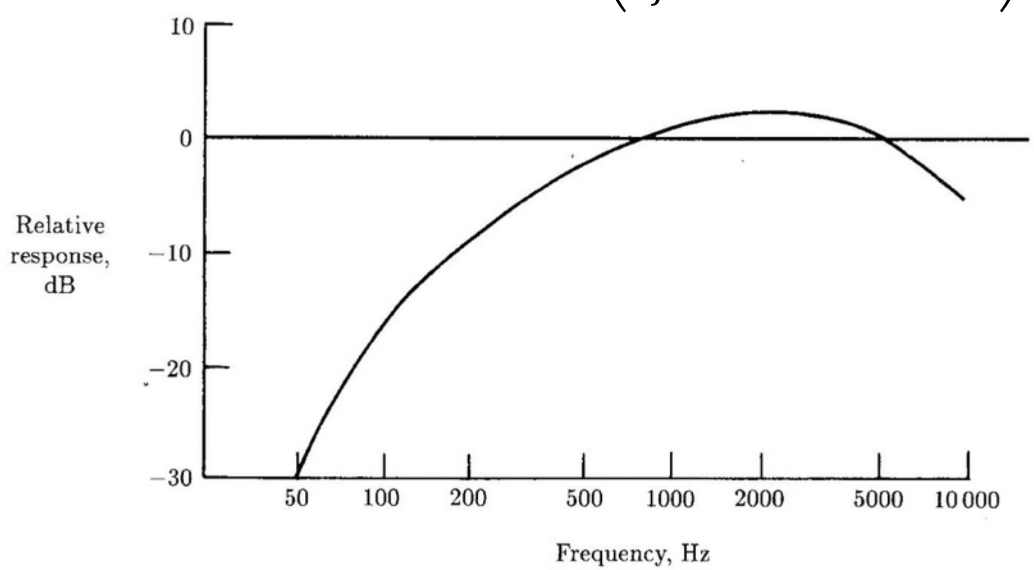


Figure 5. Relative response of the A-weighting filter.

Hubbard, Vol 2., p 8-9

LEQ

Equivalent Continuous Sound Level, LEQ (dBA):

$$L_{EQ} = 10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_A(i)}{10}}\right)$$

Hubbard, Vol 2., p 16

DNL

(LEQ with 10 dB penalty for night)

Day-Night Average Sound Level, DNL (dBA):

$$L_{dn} = 10\ \log_{10}\left[\frac{1}{24}\left(15\ 10^{\frac{L_d}{10}} + 9\ 10^{\frac{L_n}{10}}\right)\right]$$

Where

L_d= LEQ for 7 am – 10 pm = LEQ for day
L_n= LEQ for 10 pm – 7 am = LEQ for night

Hubbard, Vol 2., p 16

EMISSION REGULATION

US

Noise Control Act (NCA) of 1972 (codifed in 49 U.S. 4901-4918), EPA's newly established Office of Noise Abatement and Control (ONAC)

1982 it was defunded by Congress at the request of the Reagan administration

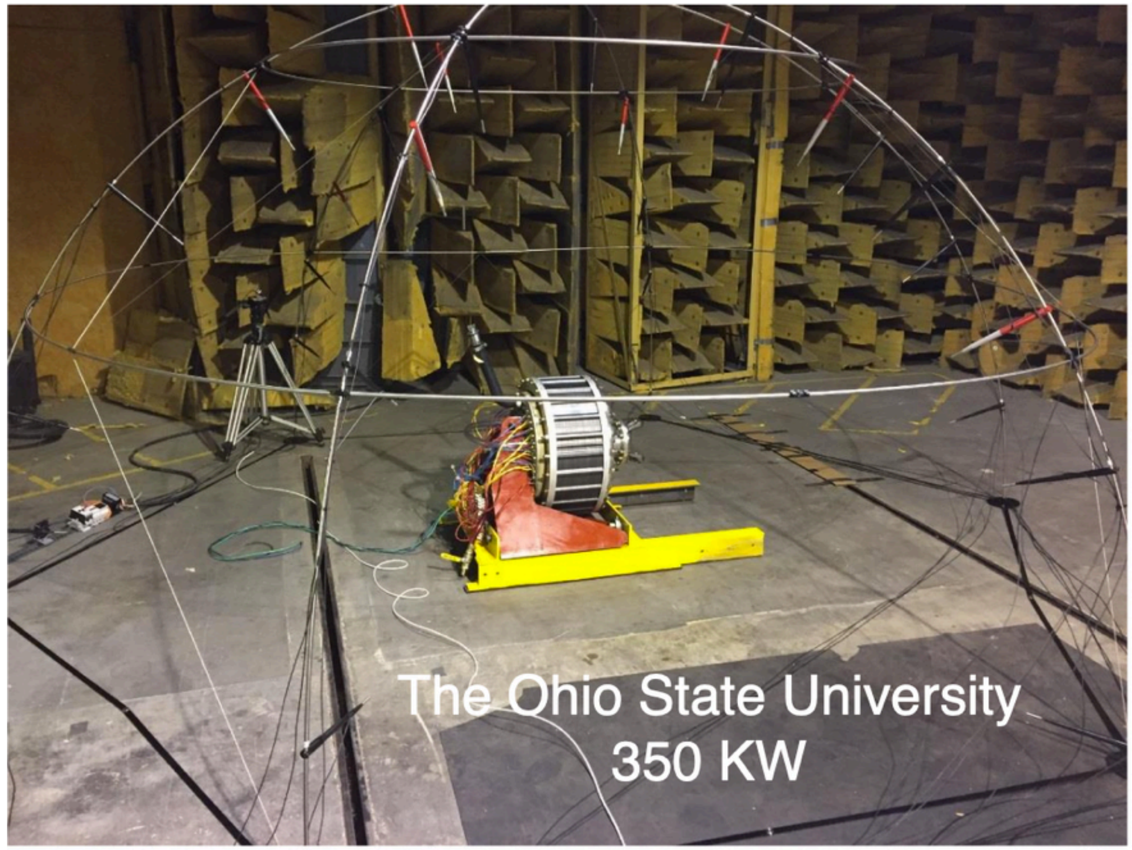
By retaining its authority under the NCA without the funding to execute it, EPA has effectively preempted state and local governments from adopting updated noise emission and labeling standards of their own for the sources and products that EPA has already regulated…

EMISSION REGULATION

Europe

Unlike in the United States, however, European regulation of product noise emissions based on standards developed by regional and international standards bodies has been very active and expansive in recent decades.

Example of sound power measurement



Electric Motor Noise Status

April 11 – 12, 2017
NASA Acoustics Technical Working Group

Dr. Brenda S. Henderson Dennis L. Huff
NASA Glenn Research Center

EMISSION REGULATION

Europe

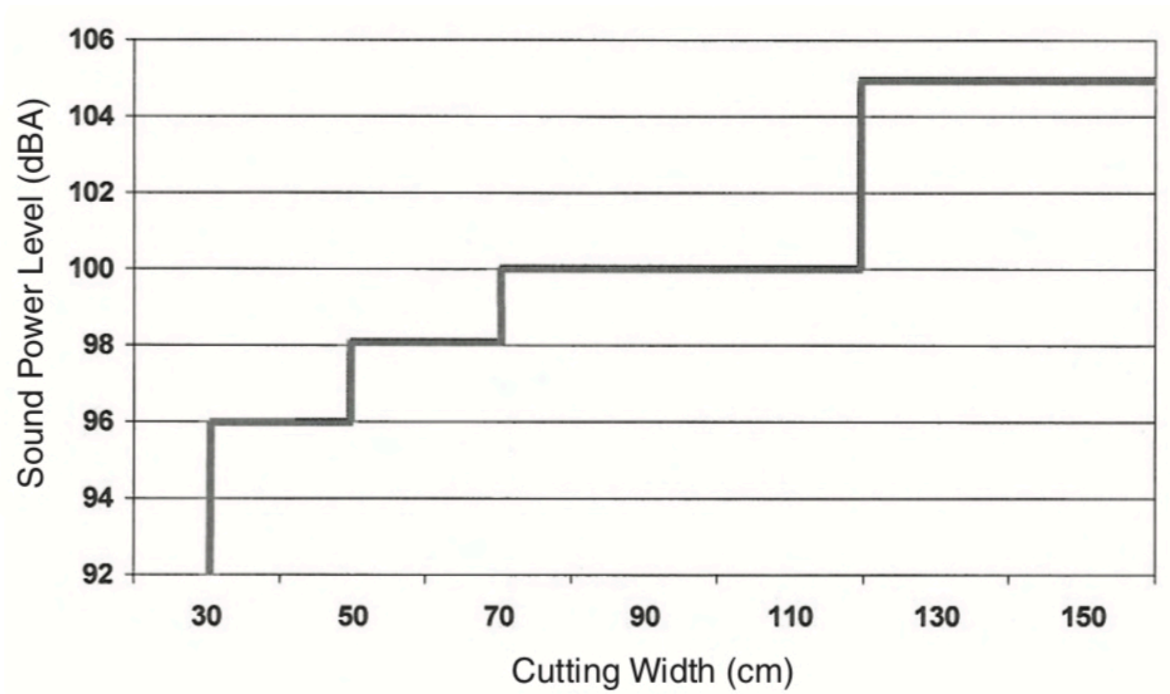


FIGURE 6-1 Permissible sound power levels (dB(A)) for lawn mowers, based on width of cut. Source: Directive 2000/14/EC of the European Parliament (EU, 2000).

Technology for a Quieter America

Immission Noise metrics

Occupational noise exposure

(b)(1) When employees are subjected to sound exceeding those listed in Table G-16, feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of Table G-16, personal protective equipment shall be provided and used to reduce sound levels within the levels of the table.

TABLE G-16—PERMISSIBLE NOISE EXPOSURES[1]

Duration per day, hours	Sound level dBA slow response
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

eCFR 1910.95(b)(2)

Immission Noise metric example

National Transportation Noise Map

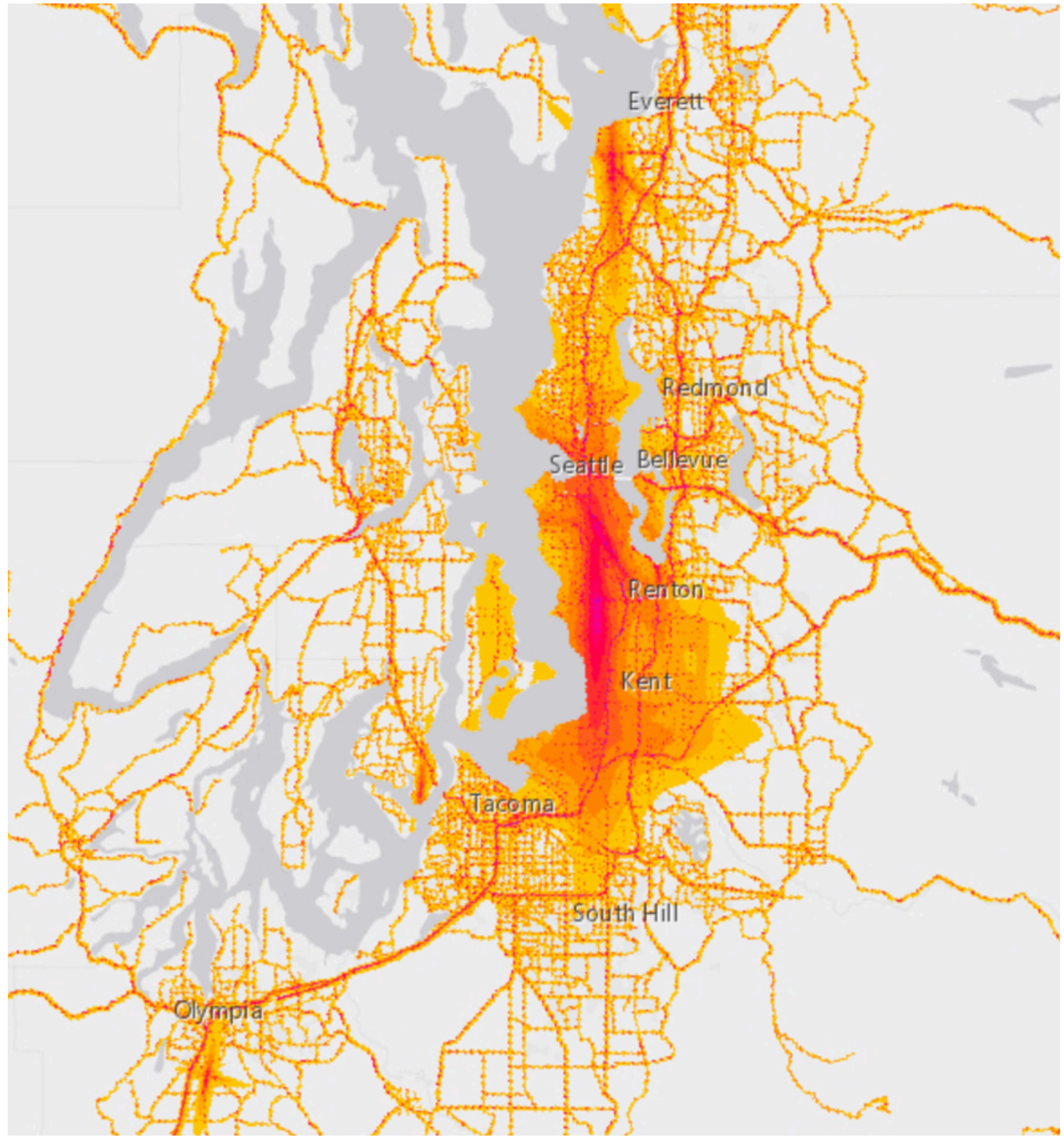
US road and aviation noise

CONUS Road and Aviation Noise - Decibels

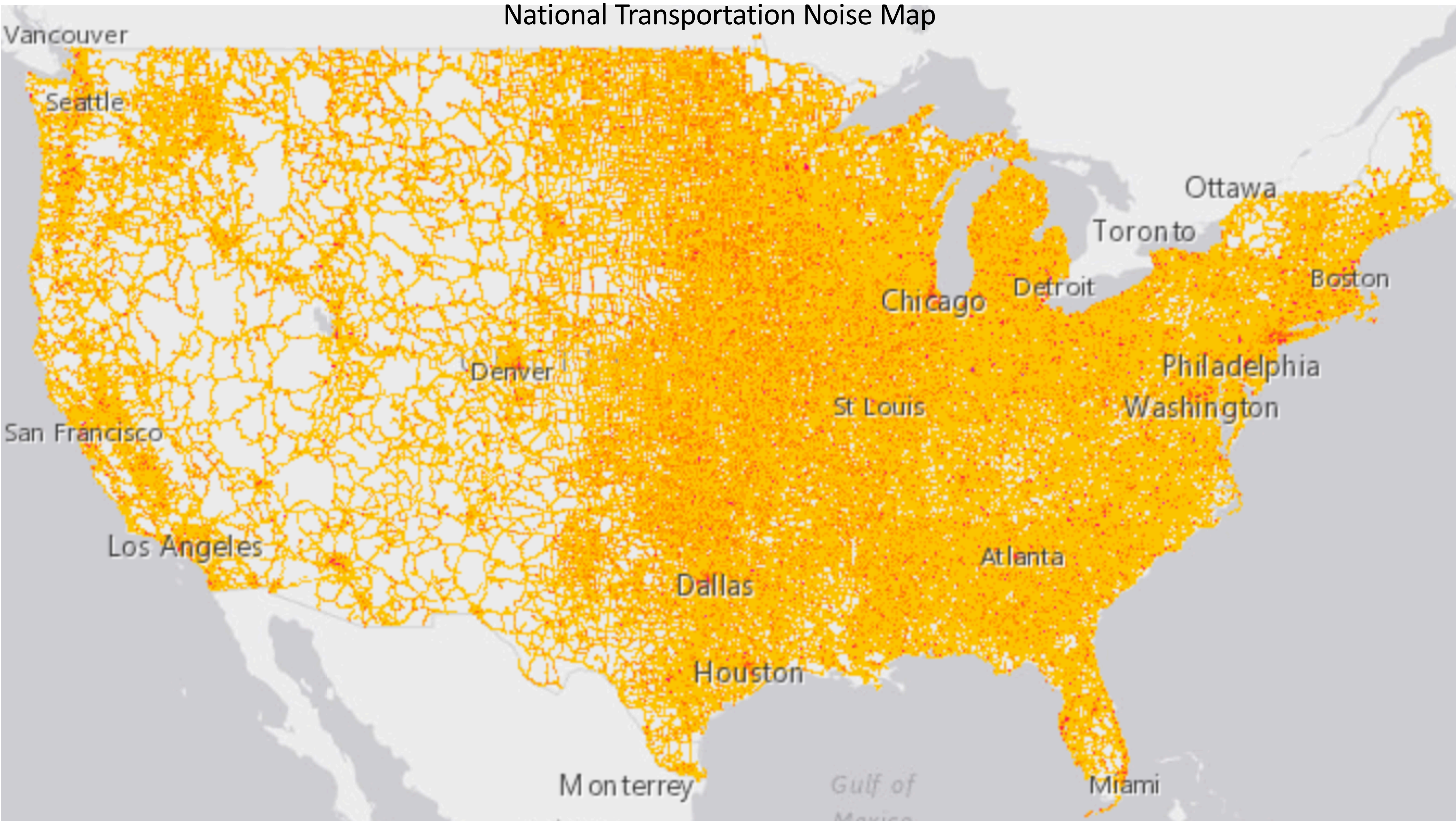
- 35 - 40
- 40.01 - 45
- 45.01 - 50
- 50.01 - 55
- 55.01 - 60
- 60.01 - 65
- 65.01 - 70
- 70.01 - 75
- 75.01 - 80
- 80.01 - 85
- 85.01 - 90
- 90.01 - 95

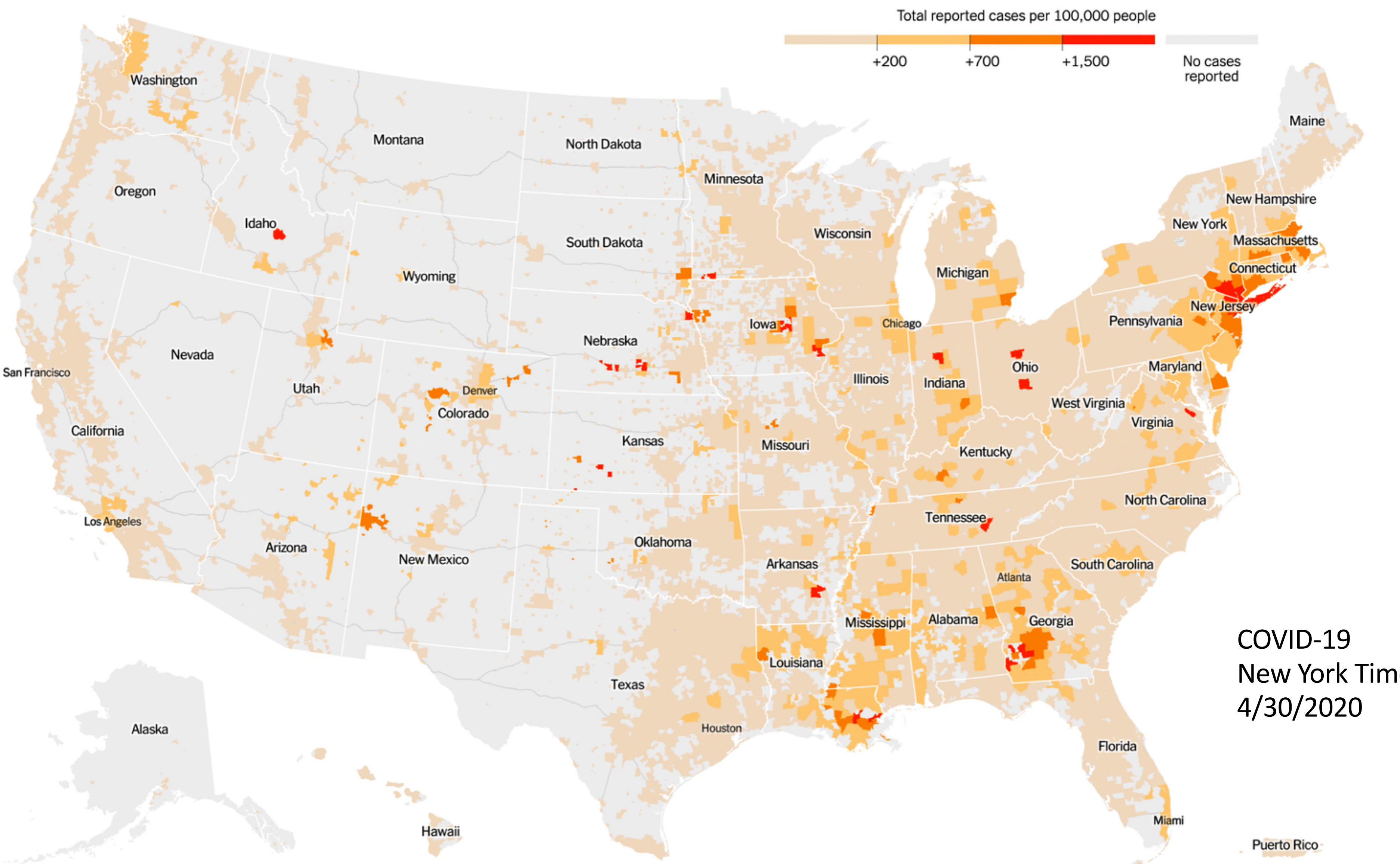
A-weighted 24-hour equivalent sound levels (LAEQ) (a-weighted, average sound level for the day) from aviation and Interstate road noise in the year 2014.

https://www.bts.gov/



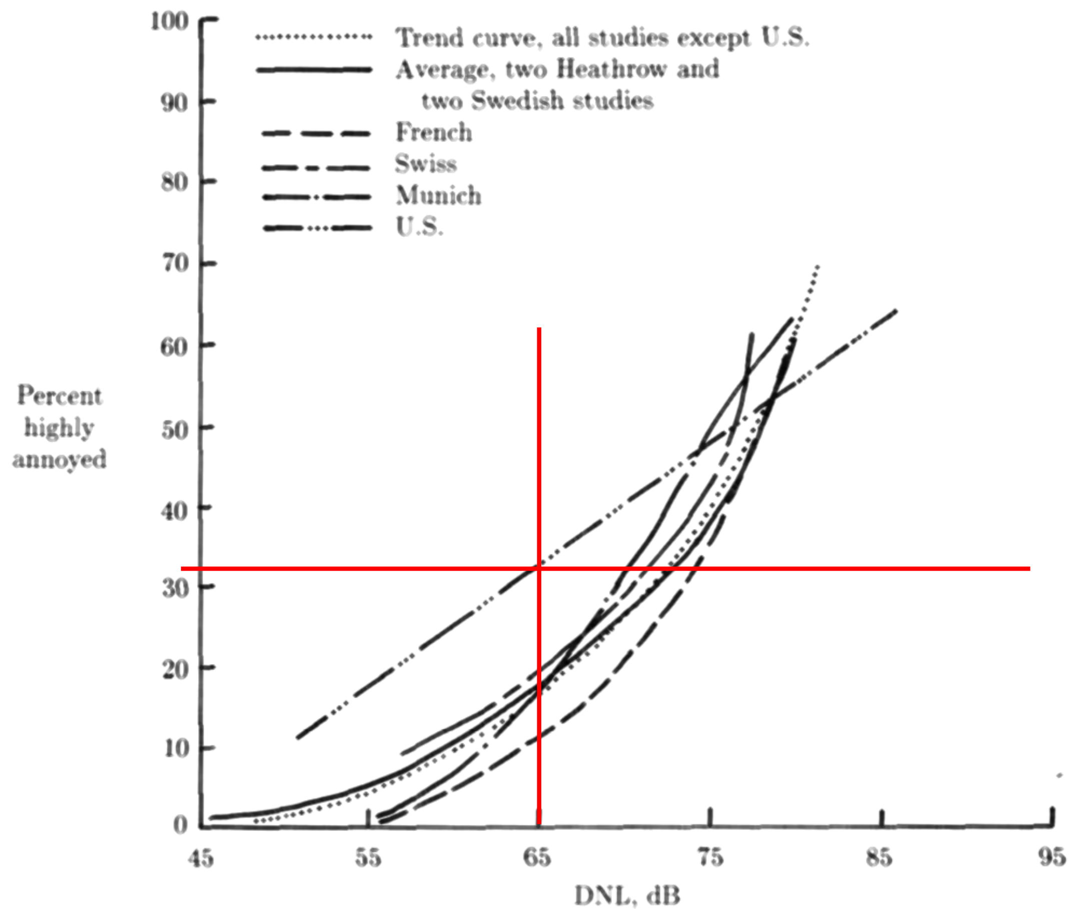
National Transportation Noise Map





COVID-19
New York Times
4/30/2020

Percent Highly Annoyed

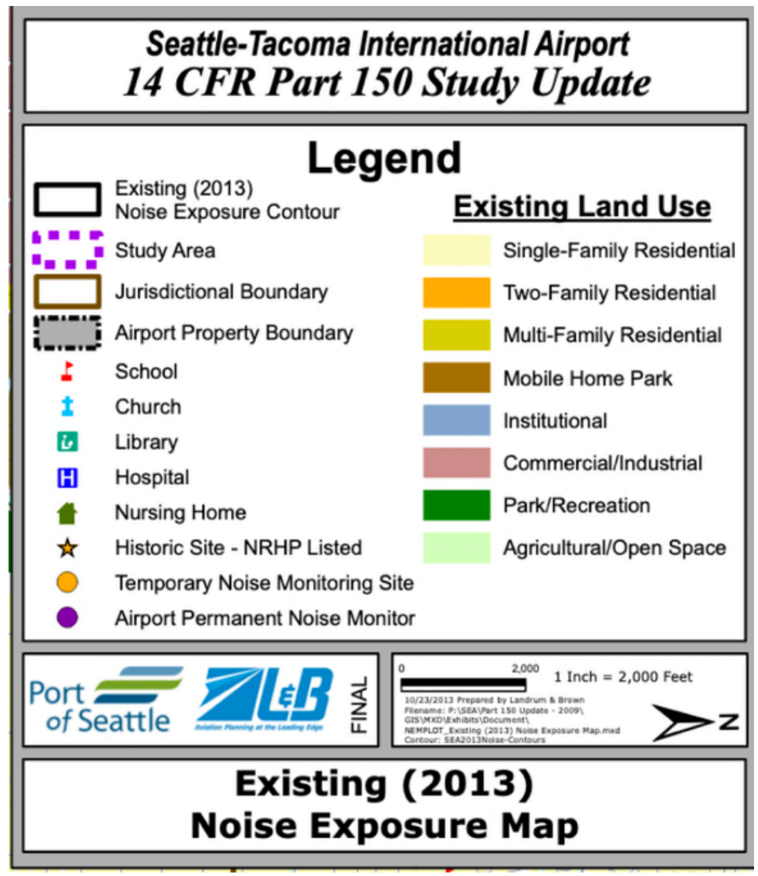


Hubbard, Vol 2. p38

Immission Noise metric example

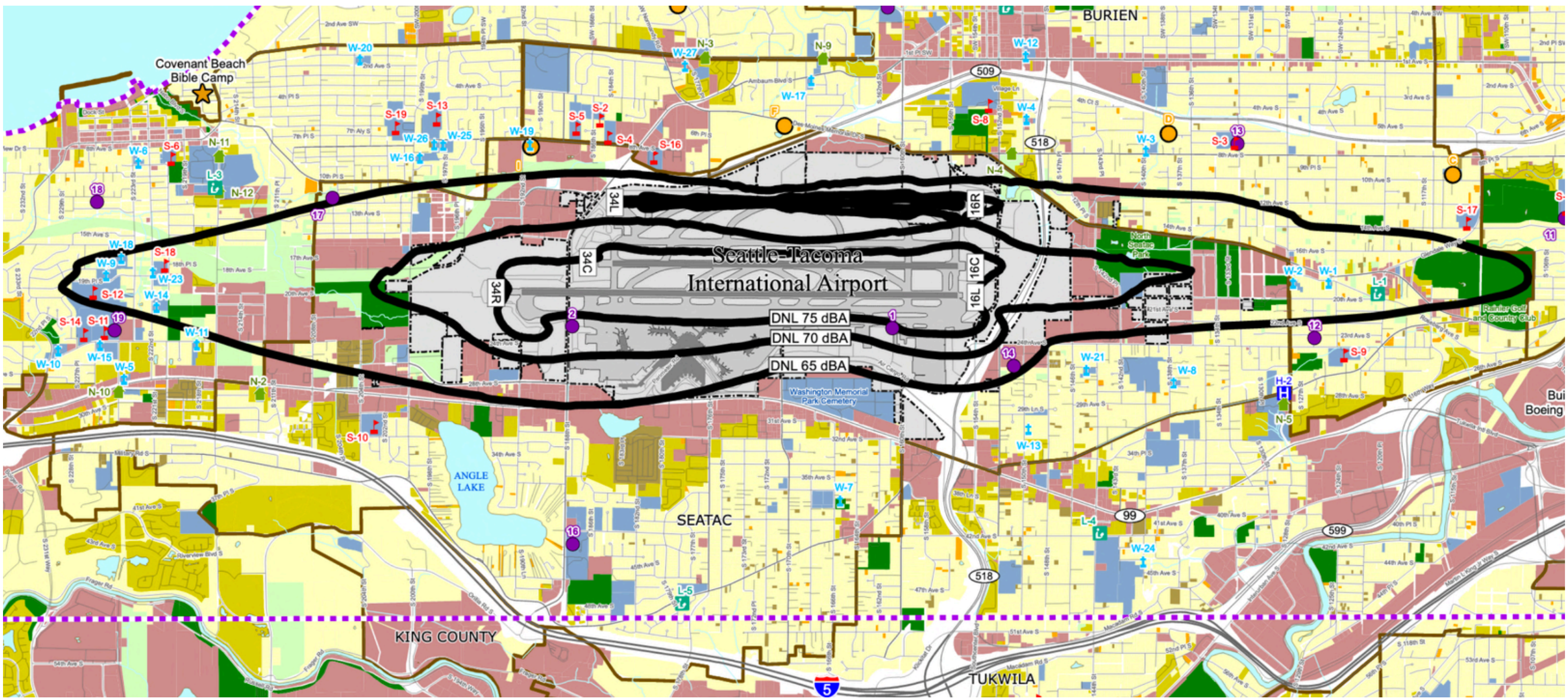
DNL values > 65 dB <-> 30% “highly annoyed” <-> “threshold for negative health effects”
Criterion for Residential Sound Insulation Programs around airports (FAA-funded)

http://www.airportsites.net/SEA-Part150/documents/final/x1-NEMPLOT_Existing%20(2013)%20Noise%20Exposure%20Map.pdf



Immission Noise metric example

65 dBA DNL Contor



Aircraft Noise Certification

Equivalent Perceived Noise Level, EPNL

Flyover metric for aircraft noise certification, EPNdB

Title 14 Code of Federal Regulations, Chapter 1, Subchapter C, part 36

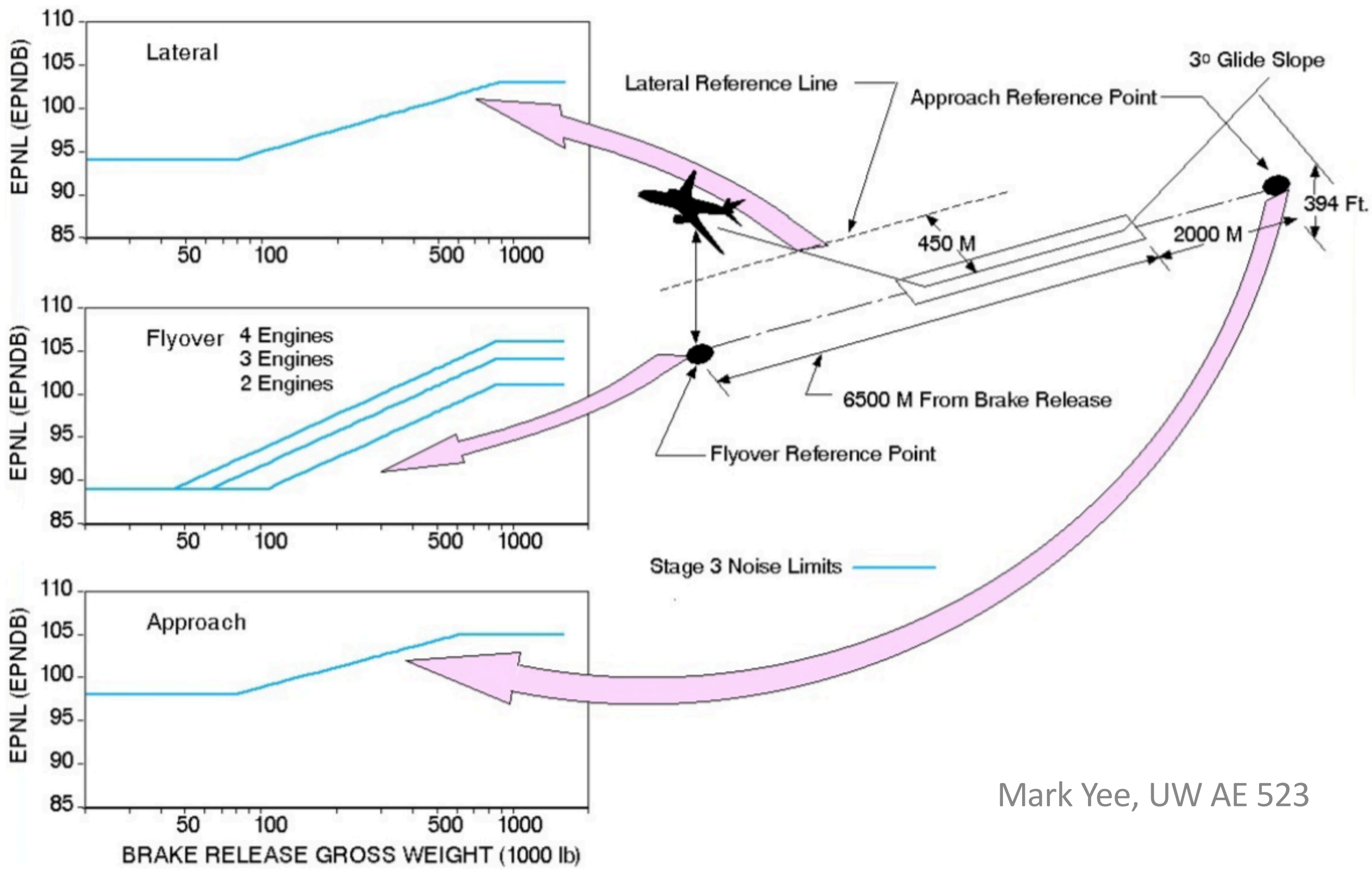
International Civil Aviation Organization, Annex 16 to the Convention on International Civil Aviation, Volume 1

Part 36

General Information (Subpart A)
Transport Category (Subpart B, Appx A & B)
– Includes any jet powered aircraft
Supersonic (Subpart D)
Propeller Driven (Subpart F, Appx F or G)
Helicopters (Subpart H, Appx H or J)
Tiltrotors (Subpart K, Appx K)
Documentation (Subpart O)

Noise Certification Rule Limits

Noise Certification Reference Points



Mark Yee, UW AE 523

Urban Air Mobility

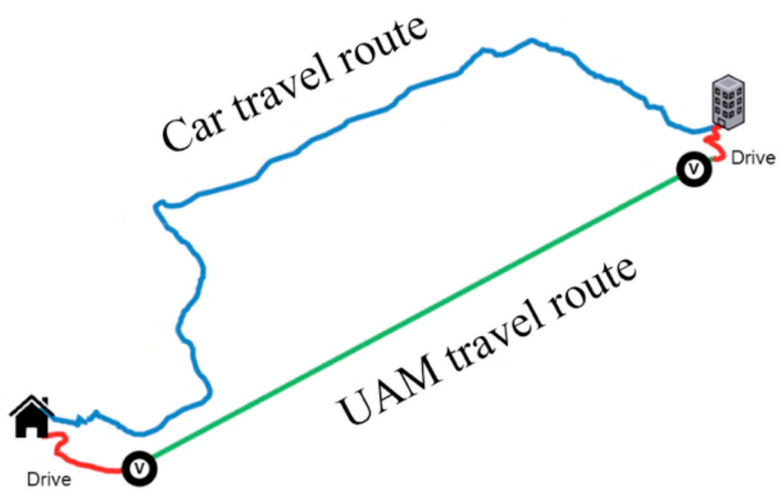
https://www.uber.com/info/elevate/

See also: white paper at https://www.uber.com/elevate.pdf

Electrically powered rotorcraft
Soaring over traffic
On demand mobility
(No pilot on board)
Children on swing set not disturbed by noise

Vision

- Replace automobile gridlock in urban areas that are underserved by public transportation, such as the Bay Area
- Trips of approximately 10 to 100 mi
- Operate from new “vertiport” infrastructure and/or existing heliports likely as a part of multi-modal transportation
- Approximately 1-9 passengers or up to ~2000 lb payload



Partially from Michael Patterson, Acoustics Technical Working Group, NASA, April 2018

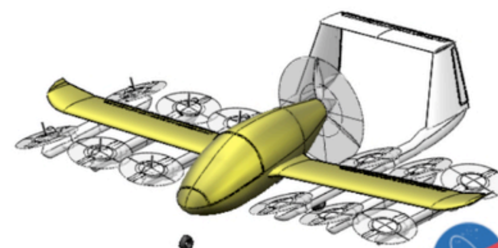
Convergence of technologies

- High energy-density batteries
- Fuel cells
- High power-density electric motors
- Additive (3D) manufacturing
- Hydrophobic material coatings
- Rich broadband air-to-ground, air-to-air, and orbit-to-air digital, bi-directional, IP connectivity
- Military-, or Bank-grade cybersecurity systems
- Trusted autonomous systems
- Multi-function materials and structures
- Advanced material systems (increased strength-to-weight properties)
- Artificial Intelligence
- Biometric identification, registration and authorization
- Wearable and virtual or enhanced reality display systems

See final report at http://www.nianet.org/ODM/roadmap.htm

There are many companies engaged in UAM with many different vehicle concepts

- Industry interest:
  - Existing operators (Blade, Voom, HeliJet)
  - Emerging operators (Uber, etc.)
  - Established manufacturers (Bell, Embraer, etc.)
  - Emerging manufacturers (Kitty Hawk, Joby Aviation, etc.)
- No dominant vehicle configuration or propulsion system type
  - Multi rotor, (multi) tilt wing, (multi) tilt rotor, fan-in-wing, separate lift + cruise, compound heli, tilt duct, blown flap/tilt duct, …
  - Propulsion: open props/rotors, shrouded props, ducted fans
- All are electric, hybrid-electric, or turboelectric
  - Therefore called "eVTOL" aircraft



michael.d.patterson@nasa.gov

From Michael Patterson, Acoustics Technical Working Group, NASA, April 2018

Prioritized Barriers to Successful ODM System Implementation from ODM Roadmapping Workshops

1. Ease of Certification	**2. Affordability**	**3. Safety**	**4. Ease of Use**	**5. Door-to-Door Trip Speed**
6. Average Trip Delay	**7. Community Noise**	**8. Ride Quality**	**9. Efficiency**	**10. Lifecycle Emissions**

Prioritized order, but any barrier can limit feasibility, utility, growth

michael.d.patterson@nasa.gov

http://www.nianet.org/ODM/roadmap.htm

From Michael Patterson, Acoustics Technical Working Group, NASA, April 2018

Why is UAM Noise Different?

	Conventional	UAM/eVTOL
Where is the aircraft?	distant airport	inside community
What does it sound like?	mostly broadband, low frequency, slow rise/fall	tonal components, rapid rise/fall rates
Distance to listener?	>5 miles	<1/2 mile
What metric?	integrated airport contibution to community noise exposure (DNL)	individual vehicle event audibility
Why measure?	identify homes for remediation	predict community acceptance
Design goals	manage noise	don’t notice noise

David Josephson
NASA ASTW, April 2018

Noise Certification Undetermined

- Uncertain if current noise certification metrics apply
- Concern that cities could ban the machines

Current Industry Noise Targets (2018)

- 15 dB decrease relative to small helicopters
- Outside of vertiport areas, noise below background noise levels today

From Michael Patterson, Acoustics Technical Working Group, NASA, April 2018

Sample NASA UAM Projects

- Concept vehicles
- Auralization
- Rotor noise ground testing
- Motor noise ground testing

NASA-developed Concept Vehicles for UAM

Objective: Identify NASA vehicles to serve as references to openly discuss technology challenges common to multiple concepts in the UAM community and provide focus for trade studies and system analysis

Passengers	50 nm trips per full charge/ refuel	Market	Type	Propulsion
1	1 x 50 nm	Air Taxi	Multicopter	Battery
	2 x 37.5 nm			
2	2 x 50 nm	Commuter Scheduled	Side by Side (no tilt)	Parallel hybrid
4	4 x 50 nm	Mass Transit	(multi-) Tilt wing	Turboelectric
6	8 x 50 nm	Air Line	(multi-) Tilt rotor	Turboshaft
15			Lift + cruise	Hydrogen fuel cell

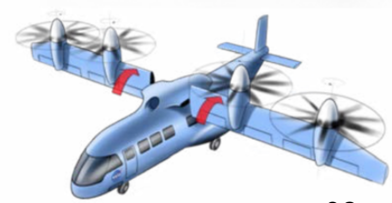
- Aircraft designed through use of NASA conceptual design and sizing tool for vertical lift, NDARC.
- Concepts described in detail in publications "Concept Vehicles for Air Taxi Operations," by Johnson, Silva and Solis. AHS Aeromechanics Design for Transformative Vertical Lift, San Francisco, Jan. 2018 and "VTOL Urban Air Mobility Concept Vehicles for Technology Development," by Silva, Johnson, Antcliff and Patterson. AIAA Aviation 2018, Atlanta, GA, June 2018.

Quadrotor "Air Taxi"

Side by Side "Vanpool"

Lift+Cruise Air Taxi

Tilt wing "Airliner"



From Susan A. Gorton, NASA

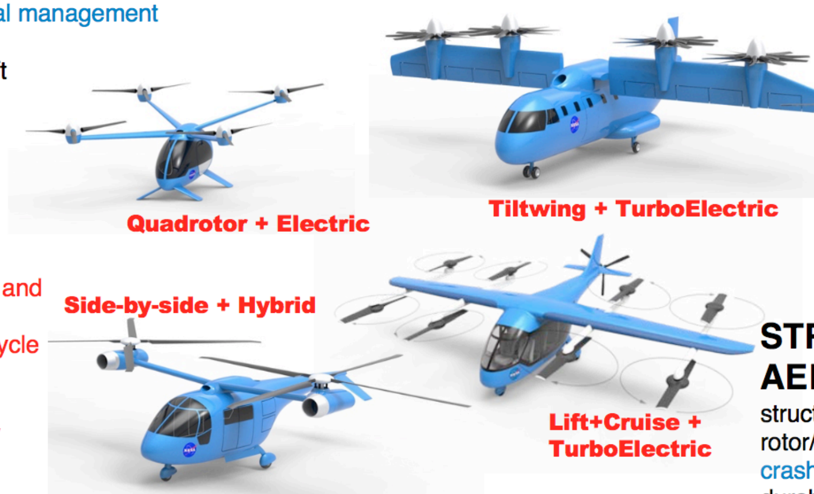
Research Areas Applicable to All Concept Vehicles

PROPULSION EFFICIENCY
high power, lightweight battery
light, efficient, high-speed electric motors
power electronics and thermal management
light, efficient diesel engine
light, efficient small turboshaft
efficient powertrains

PERFORMANCE
aircraft optimization
rotor shape optimization
hub and support drag minimization
airframe drag minimization

ROTOR-ROTOR INTERACTIONS
performance, vibration, handling qualities
aircraft arrangement
vibration and load alleviation

ROTOR-WING INTERACTIONS
conversion/transition
interactional aerodynamics
flow control



SAFETY and AIRWORTHINESS
FMECA (failure mode, effects, and criticality analysis)
component reliability and life cycle
crashworthiness
propulsion system failures
high voltage operational safety

STRUCTURE AND AEROELASTICITY
structurally efficient wing and rotor support
rotor/airframe stability
crashworthiness
durability and damage tolerance
high-cycle fatigue

OPERATIONAL EFFECTIVENESS
disturbance rejection (control bandwidth, control design)
Ops in moderate to severe weather
passenger acceptance/ ride quality
cost (purchase, maintenance, DOC)

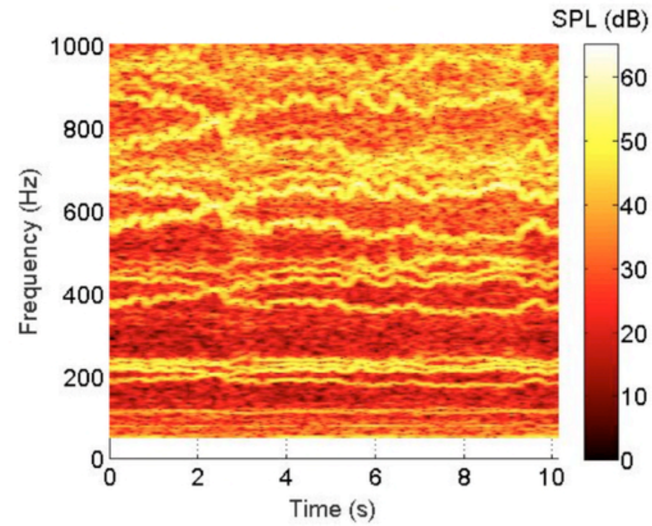
NOISE AND ANNOYANCE
low tip speed
rotor shape optimization
flight operations for low noise
aircraft arrangement/ interactions
cumulative noise impacts from fleet ops
active noise control
cabin noise
metrics and requirements

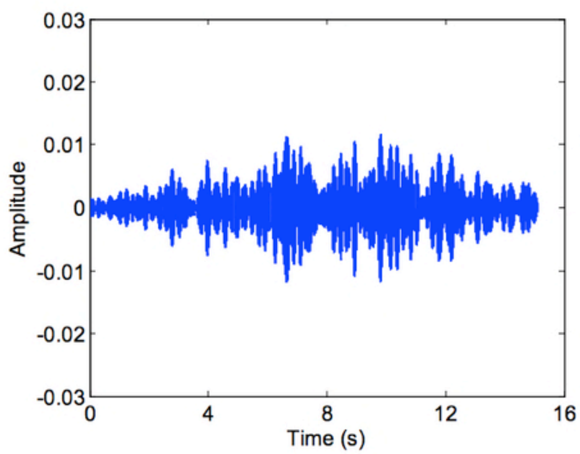
AIRCRAFT DESIGN
weight, vibration
handling qualities
active control

Red = primary focus
Blue = secondary focus

From Susan A. Gorton, NASA

Auralization





From Steven Rizzi, Fall 2017 Acoustics TWG Meeting

JOBY AVIATION

Joby's Perspective on Urban Air Mobility

NASA Acoustic Technical Working Group

Jeremy Bain

April 8, 2020

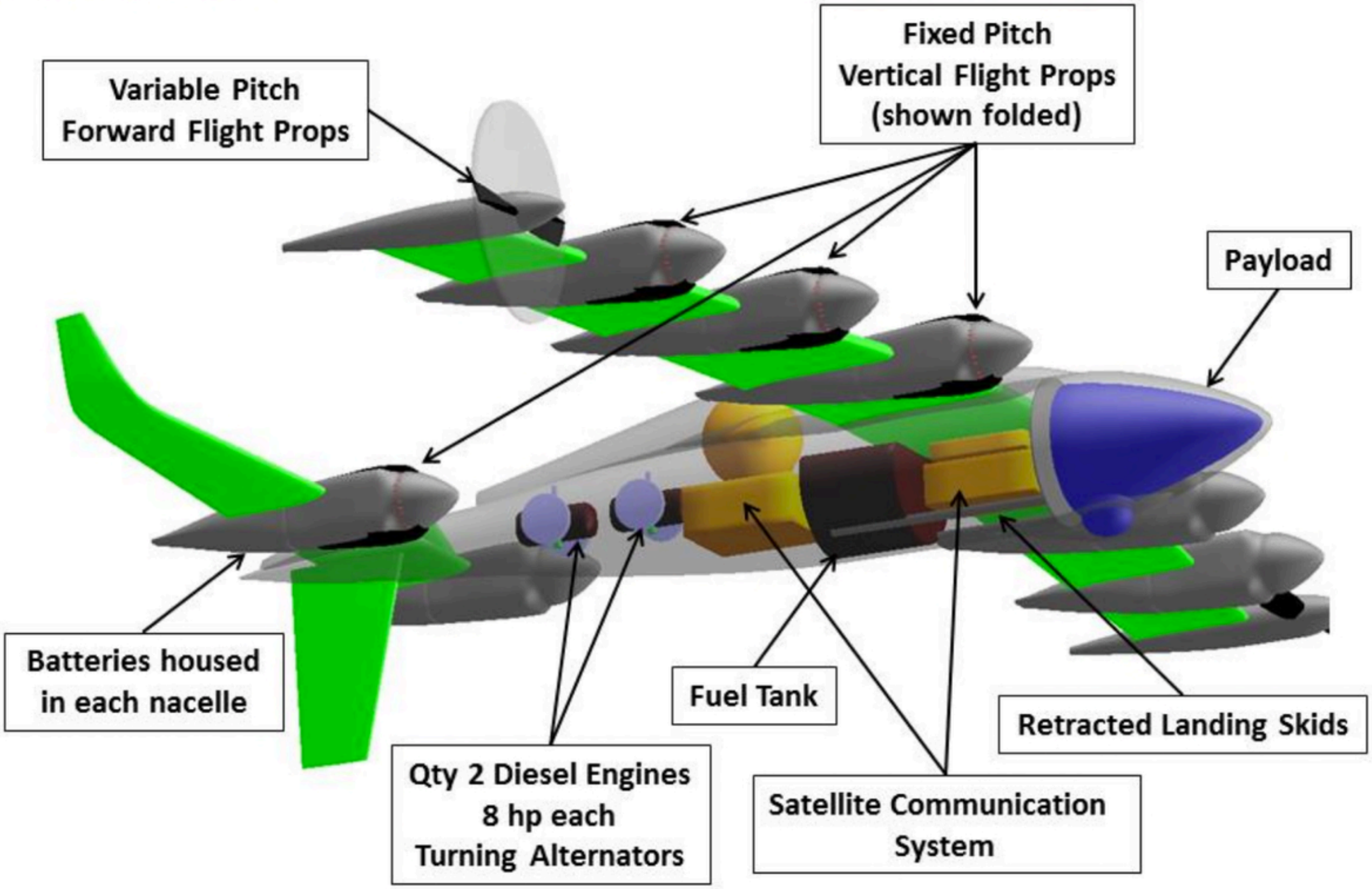

EXPERIMENTAL

Joby's Aircraft Details

- 6 all-electric tilt propellers
- 1 pilot, 4 passengers
- 200 MPH
- 150+ miles range
- 100x quieter than conventional aircraft and "near-silent cruise"
  - This is the key statement for this audience
  - Difficult to quantify since it depends on mode of flight, comparison aircraft, and noise metric
  - Low flyover noise is a key feature and another advantage of transitioning to wingborne flight
  - A 20 dB reduction is roughly the same as increasing the distance from the source by 10x.

Greased Lightning

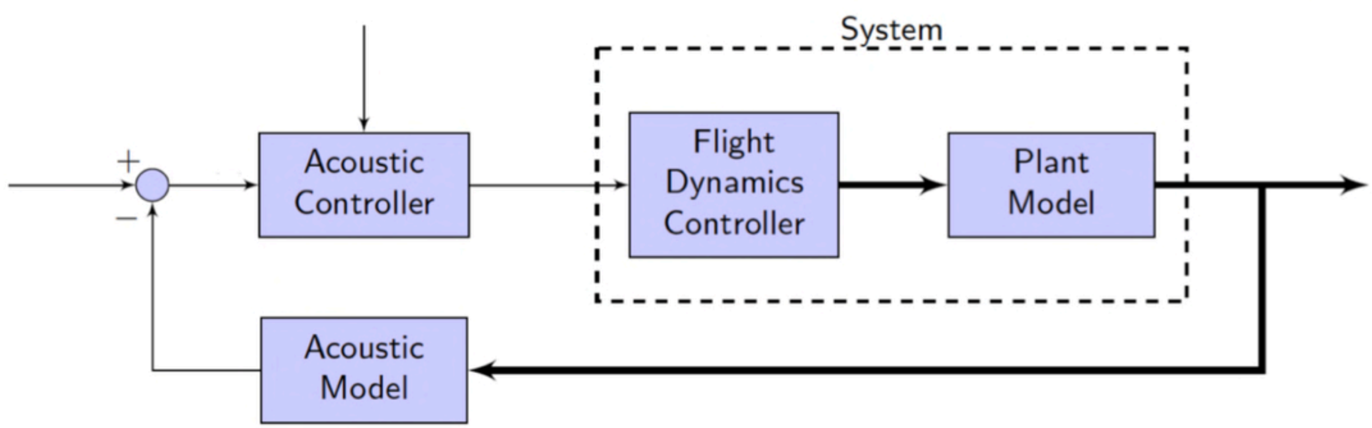
AERONAUTICS



Fredericks et at
AIAA Aviation 2015

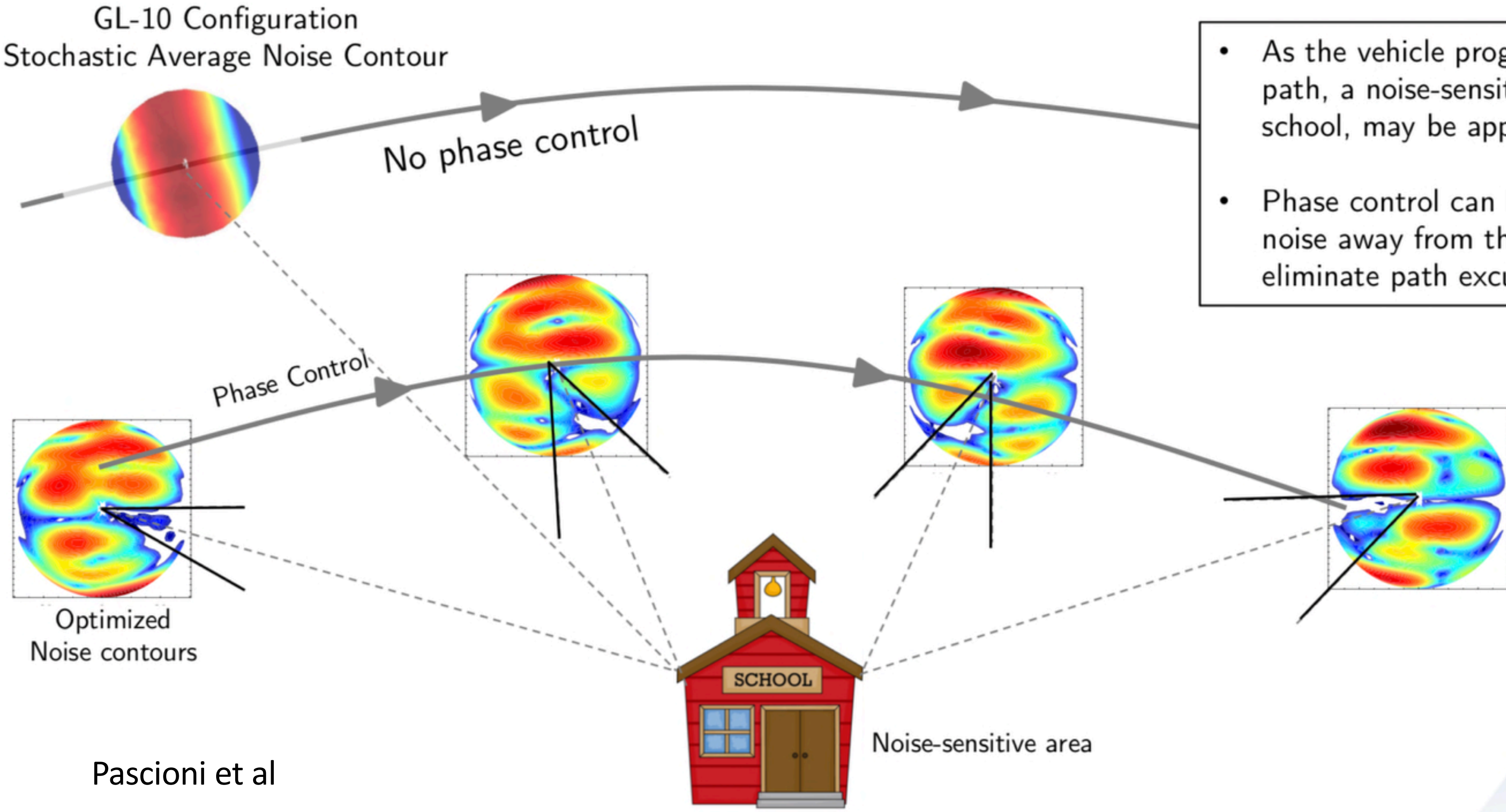
Directing noise by phase control of rotors

(not all UAMs have phase control)



Pascioni, Rizzi, Ackerman, Gales, Shiller and Gregory, Spring ATWG 2018

Phase Control Application: Community Noise Reduction



- As the vehicle progresses along its flight path, a noise-sensitive area, e.g., a school, may be approached.
- Phase control can be utilized to direct noise away from the area to minimize or eliminate path excursion.

Pascioni et al

UAM Noise Working Group

Kickoff and Status

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NASA Langley Research Center
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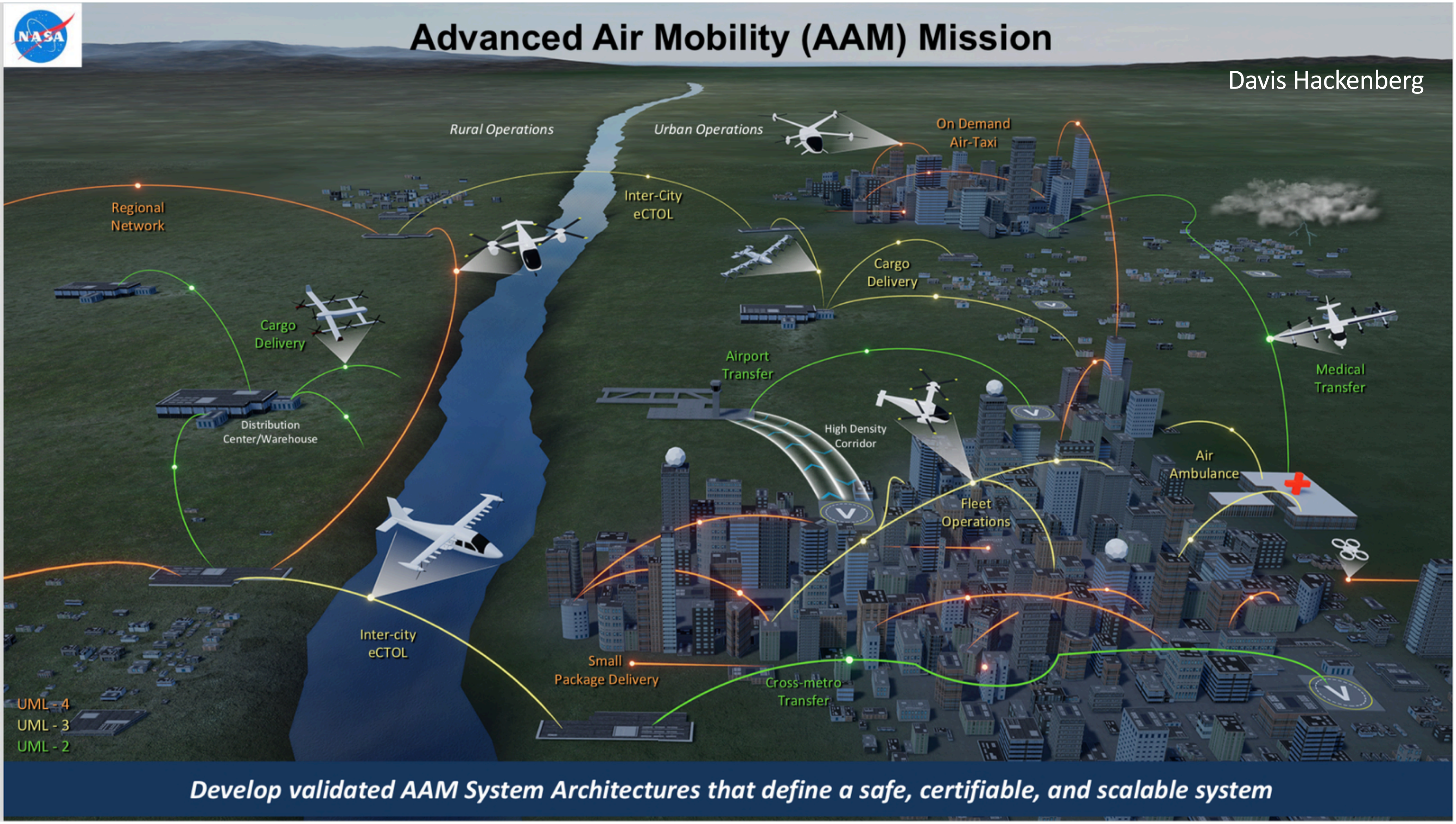
Dennis Huff
NASA Glenn Research Center
dennis.l.huff@nasa.gov

April 9 2020

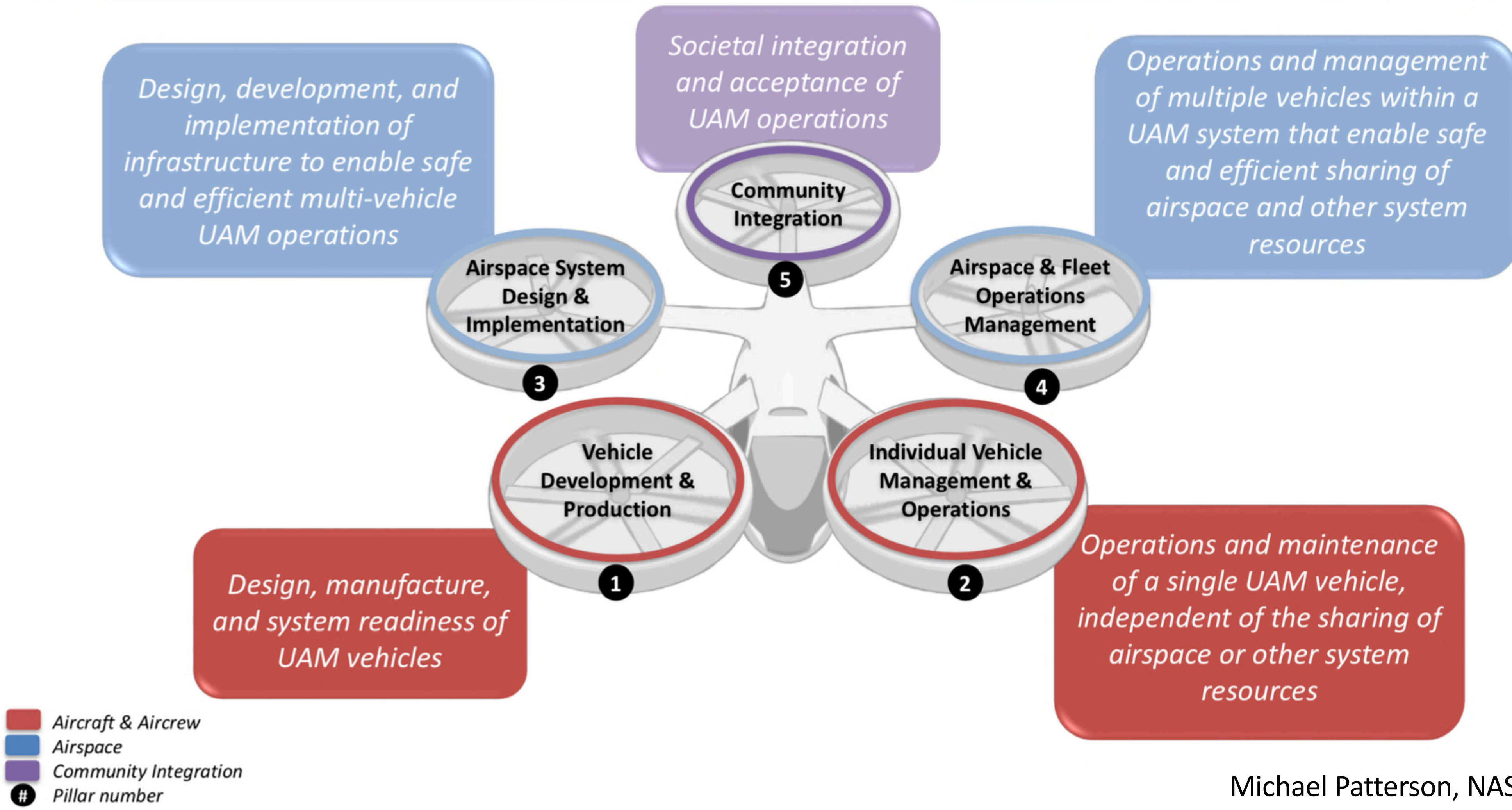
Agenda

9:00	Kickoff and status	Stephen Rizzi and Dennis Huff (NASA)
9:15	Advanced Air Mobility (AAM) Ecosystem Working Groups	Michael Patterson (NASA)
9:30	City of Los Angeles Policy-Making Framework of Transportation Noise	Todd Peterson (Ellis & Assoc.), Ryan Biziorek (Arup), Peter Falt (DesignWorks)
10:15	It's Not Just About Noise: An Introduction to the Community Air Mobility Initiative	Anna Dietrich (CAMI)
11:00	UAS and Community Outreach	Julie Marks (FAA)
11:30	Subgroup Updates	
	Subgroup 1 – Tools and Technologies	Doug Boyd (NASA)
	Subgroup 2 – Ground and Flight Testing	Kyle Pascioni (NASA)
	Subgroup 3 – Metrics	Stephen Rizzi (NASA)
	Subgroup 4 – Regulation & Policy	Bill He (FAA)
12:00	Adjourn	

4/2020: “Urban Air Mobility” -> “Advanced Air Mobility”


Advanced Air Mobility (AAM) Mission
Davis Hackenberg
Rural Operations
Urban Operations
On Demand Air-Taxi
Regional Network
Inter-City eCTOL
Cargo Delivery
Cargo Delivery
Airport Transfer
Medical Transfer
Distribution Center/Warehouse
High Density Corridor
Air Ambulance
Fleet Operations
Inter-city eCTOL
Small Package Delivery
Cross-metro Transfer
UML - 4
UML - 3
UML - 2
Develop validated AAM System Architectures that define a safe, certifiable, and scalable system

Framework



Michael Patterson, NASA

Regulatory

City of Los Angeles

What is LADOT doing differently?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  "rule_id": "8ad39dc3-…",
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    "scooter"
  ]
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    "available": [],
    "unavailable": []
  },
  "geographies": [
    "c0591267-…"
  ],
}
```

```
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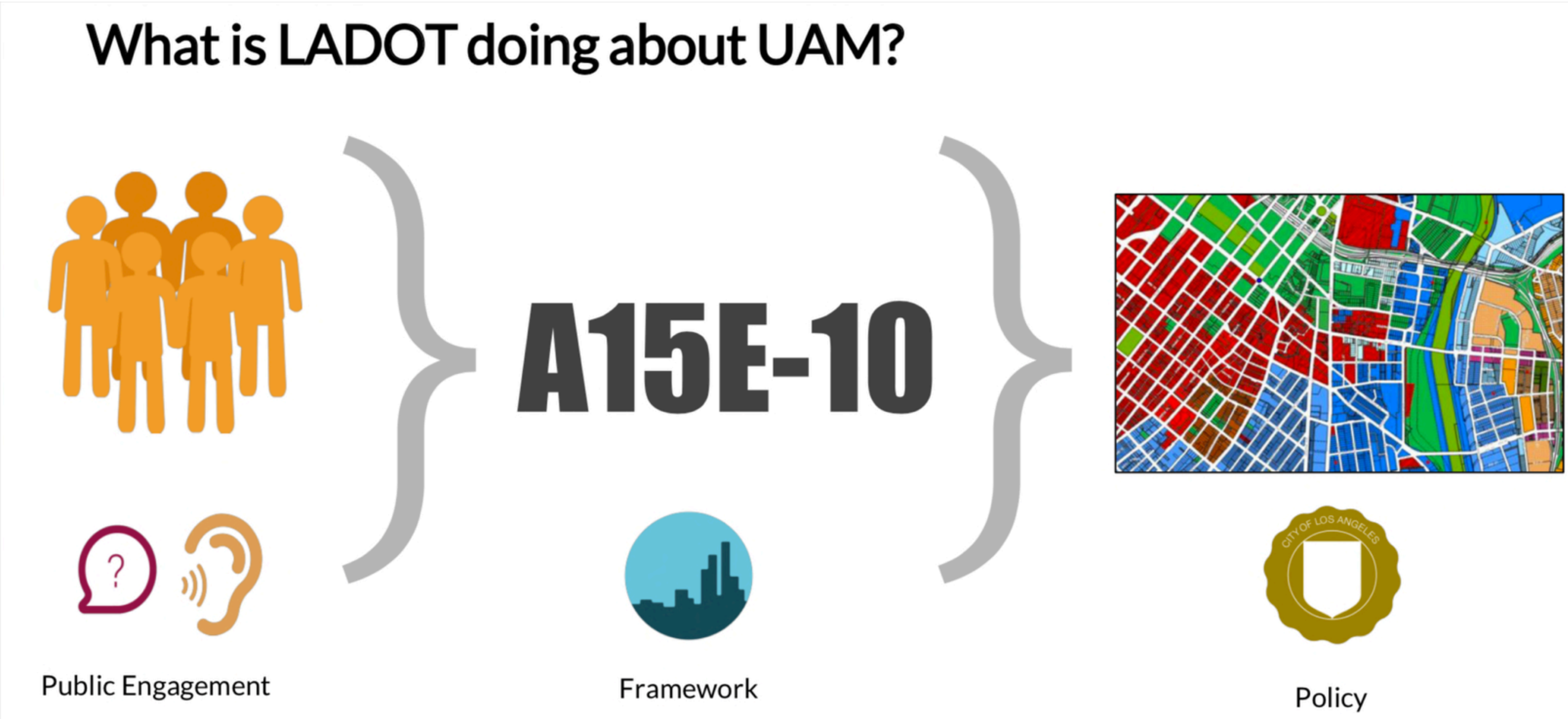
    … 22 removed …
    "e1d54dc4-…"
  ],
},
```


Analog APIs:
Coordination of city services and existing operators
Manual, reactionary enforcement

Digital APIs:
Integrating policy into new services and apps
Predictive, proactive enforcement


What is LADOT doing about UAM?
A15E-10
Public Engagement
Framework
CITY OF LOS ANGELES
Policy

UAM Policy Framework

A15E-10

Frequency

10 - Landing / Takeoff Events per hour
XX - Prohibited
NULL - Unlimited

Energy Class

E - Electric
P - Petroleum

Vehicle Weight Class (mass / 100)

05 - 500-599 lbs
25 - 2500-2599 lbs

Urban Vehicle Class (A-F)

A - Quietest, most acceptable aircraft (Modern Car)
F - Most Offensive, least quiet vehicle (2-blade helicopter w open tail-rotor)

Local Noise Regulation

Control of noise at the local level presents several challenges.

First, cities and towns in the United States have different needs.

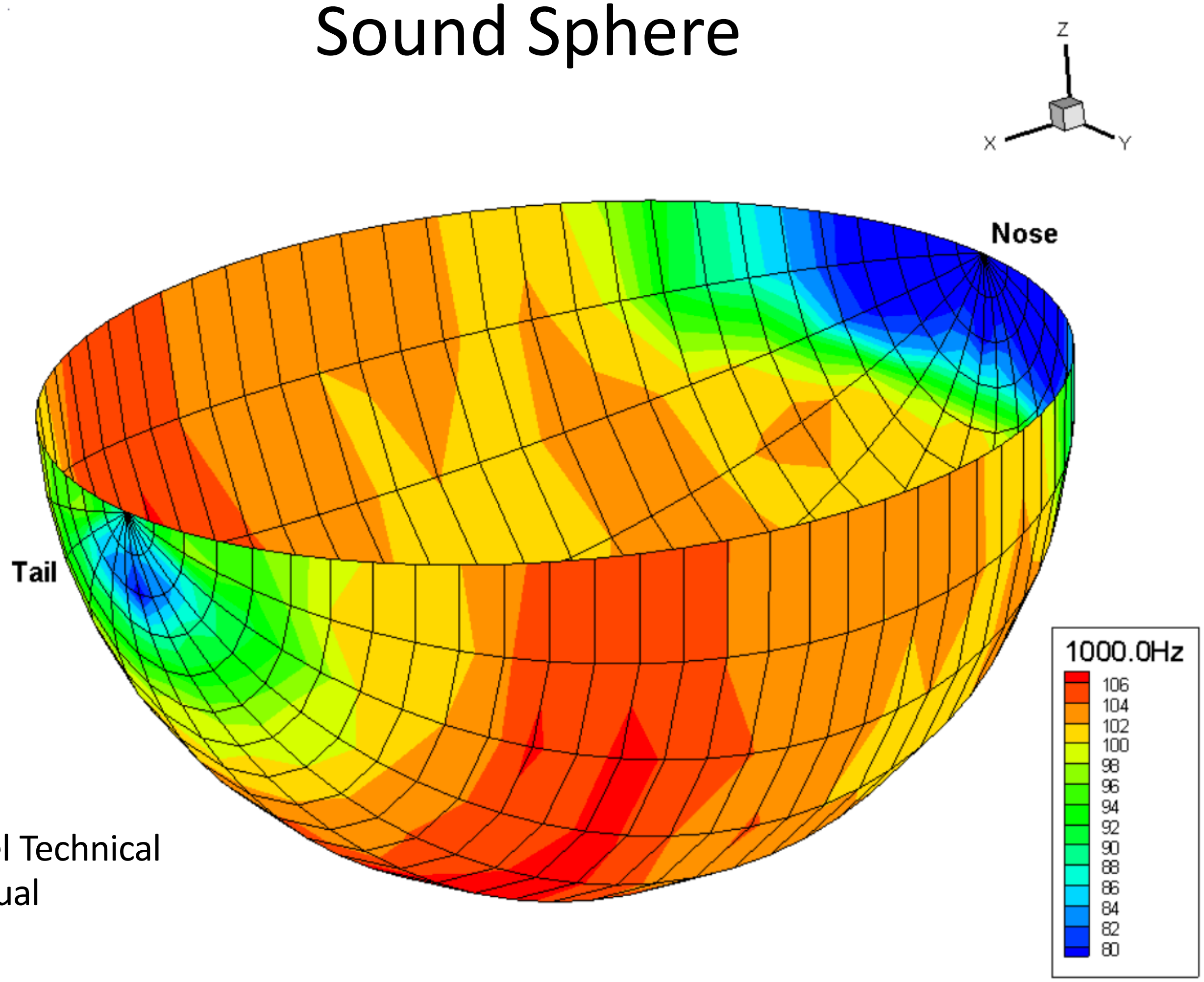
Second, many noise problems do not have engineering solutions.

Third, local officials often do not have the information they need to find the best methods of solving local problems.

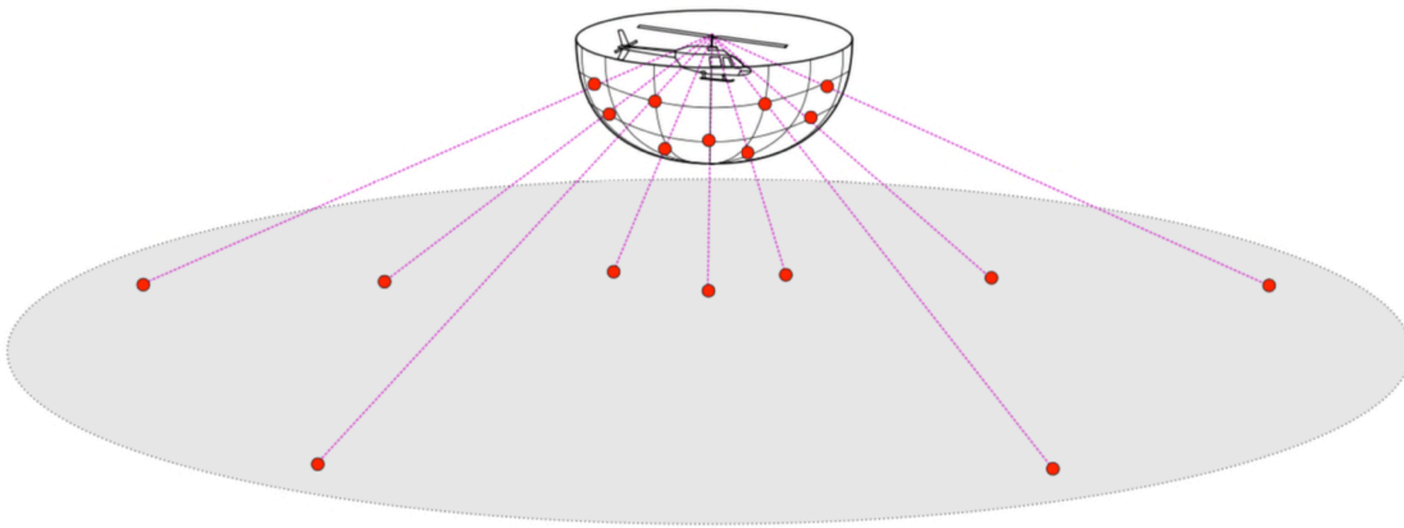
Technology for a Quieter America

Potential for Engineering and Information

Sound Sphere



Advanced Acoustic Model Technical
Reference and User Manual
SERDP Project WP-1304
Juliet Page et al



Eric Greenwood
Ph.D. Thesis
Penn State 2011

Obtaining Sound Spheres

- Compute
- Measure in laboratory
- Measure in flight

Compute Sound Spheres

Thickness and Loading Noise

Linear form of the Ffwocs Williams and Hawkins equation*

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\partial}{\partial t}\left[\rho_0 v_n |\nabla f| \delta(f)\right] + \sum_{i=1}^{3} \frac{\partial}{\partial x_i}\left[l_i |\nabla f| \delta(f)\right]$$

Thickness noise source

Loading noise source

$f(\boldsymbol{x}, t) = 0$ is the equation of the blade surface

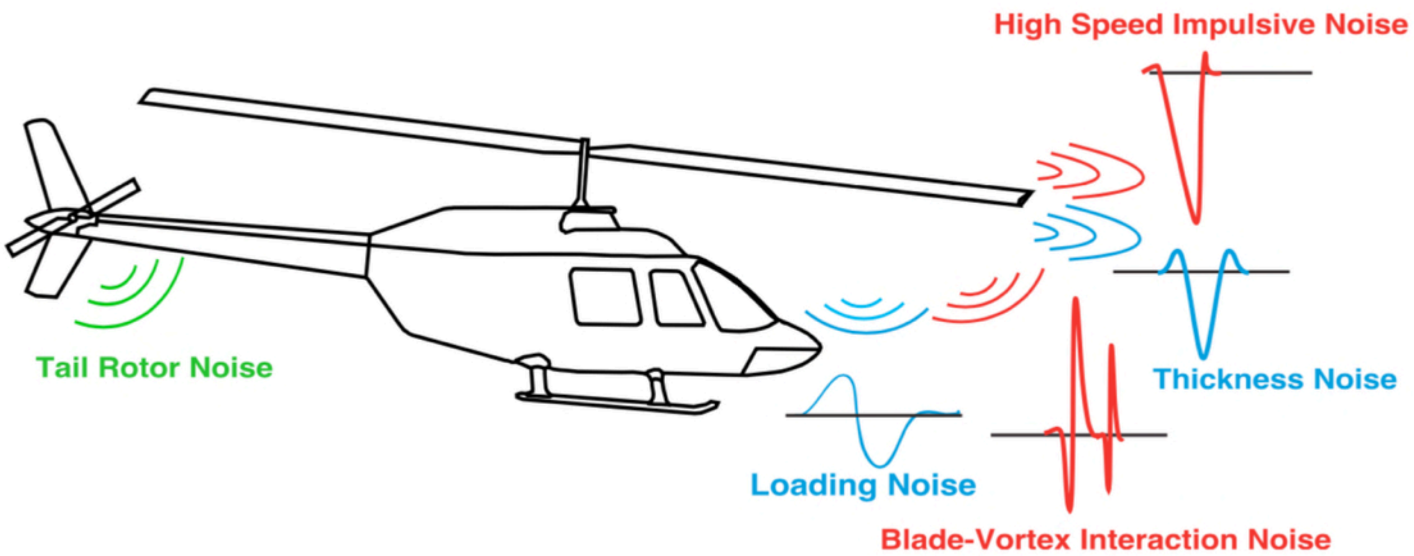
v_n is the local velocity of the surface normal to itself

l_i is the ith component of the surface force

$\delta(f)$ is the Dirac delta function

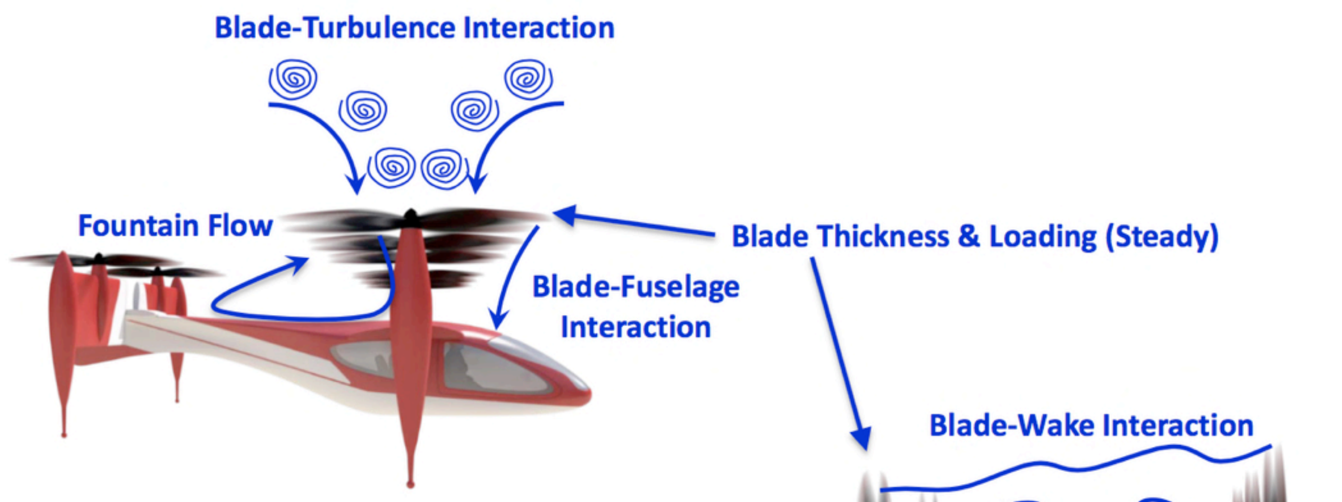
*Eq. (1) in Vol. 1 of Hubbard, from
Farassat, F., "Linear Acoustic Formulas for Calculation of Rotating Blade Noise", *AIAA J*. Vol. 19 No. 9, Sept. 1981, pp. 1122-1130.

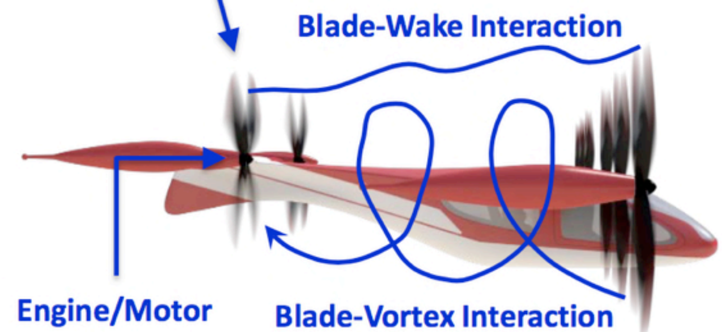
Helicopter Rotor Harmonic Noise



Eric Greenwood
Ph.D. Thesis
Penn State 2011

Possible Noise Sources





Expected Key Noise Sources

- Blade thickness
- Blade steady loading
- Blade unsteady loading
  - Blade-Vortex interaction
  - Blade-Turbulence interaction
  - Blade-Fuselage interaction
  - Blade-Wake interaction
- Engine/Motor

From Nik Zawodny and Nicole Pettingill, Spring 2018 Acoustics TWG Meeting

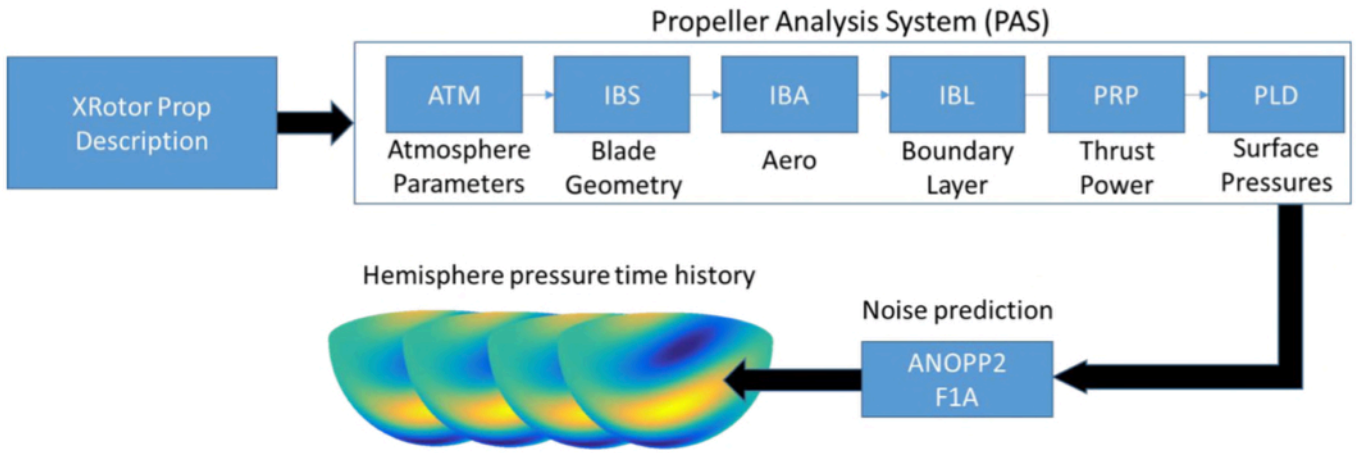
Compute Sound Spheres

ANOPP and ANOPP2
Leonard V. Lopes
NASA-Langley Research Center

Cetin Kiris
Computational Aerosciences Branch
NASA-Ames Research Center

Low-Fidelity Code for Rotor Noise

- ANOPP Propeller Analysis System – Tonal loading and thickness noise components



- Broadband Acoustic Rotor Code (BARC) – Airfoil self-noise components

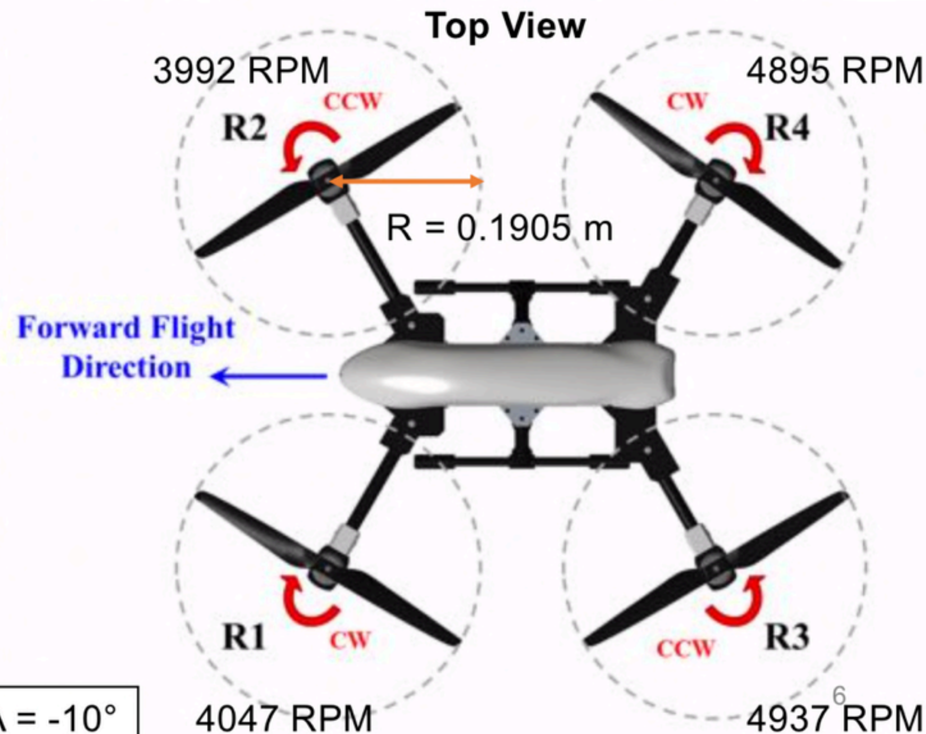
Steve Rizzi, 2017

High-Fidelity Example

Cetin Kiris 2020

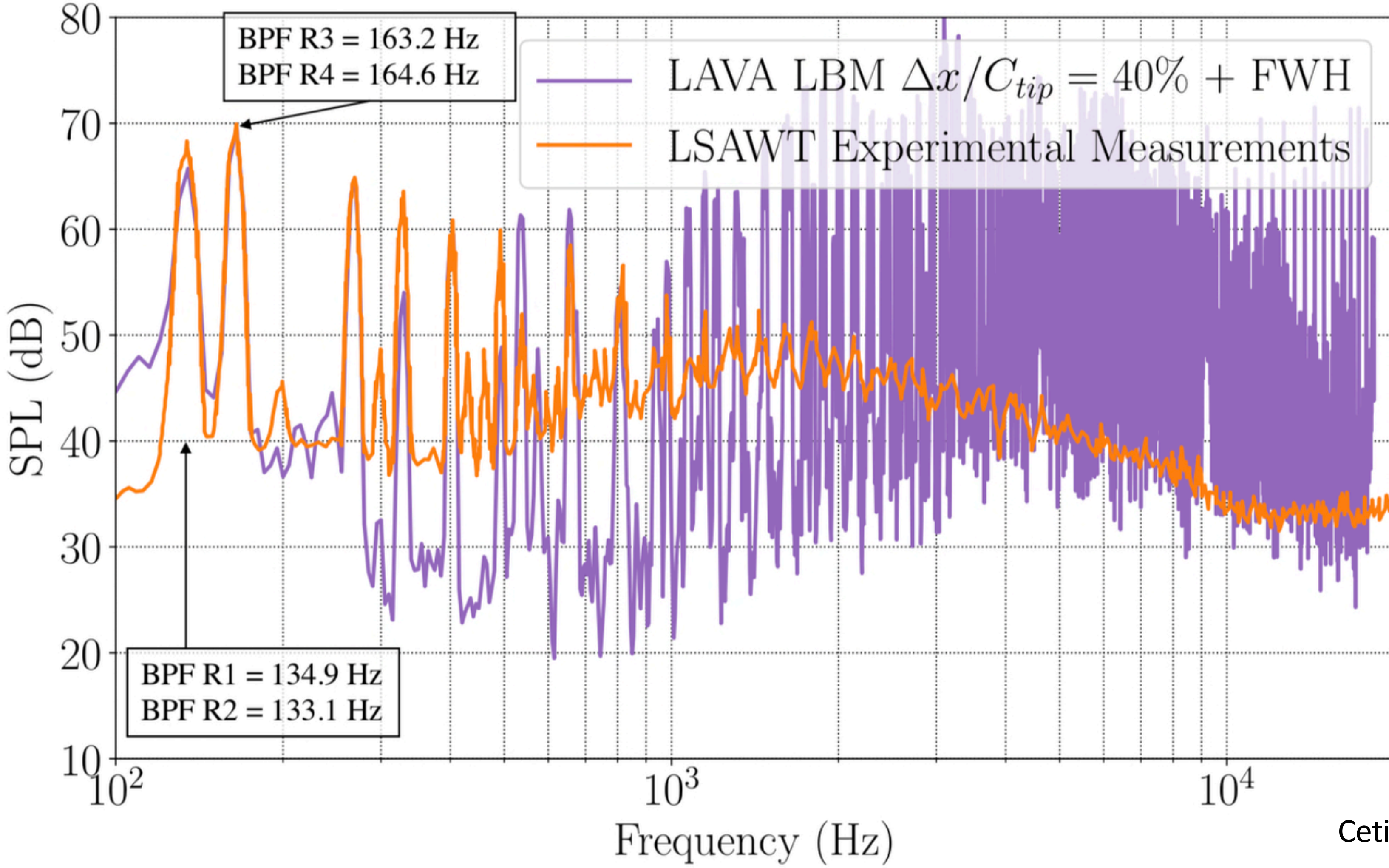
- Establish best practices for multi-rotor and vehicle interaction noise predictions, validate predictions, and assess accuracy/resources

Zawodny, Nikolas, and Nicole Pettingill. "Acoustic wind tunnel measurements of a quadcopter in hover and forward flight conditions." *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Vol. 258. No. 7. Institute of Noise Control Engineering, 2018.



Mach = 0.045, AoA = -10°

FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



Cetin Kiris 2020

Laboratory Measurement

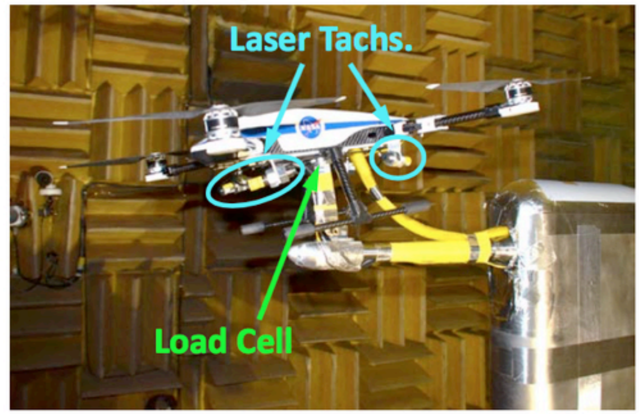
UAS Testing

- Tests performed in Low Speed Aeroacoustic Wind Tunnel (LSAWT)
  - Hover and forward flight conditions for different vehicle weight (thrust) conditions
  - Upright and flyover vehicle orientations tested

- Low-end facility speed ($M_\infty = 0.045$, $U_\infty \approx 15$ m/s) used for tests
  - Slightly higher than previous flight test conditions
  - Vehicle pitched slightly farther forward than flight tests

From Nik Zawodny and Nicole Pettingill,
Spring 2018 Acoustics TWG Meeting

Upright Orientation

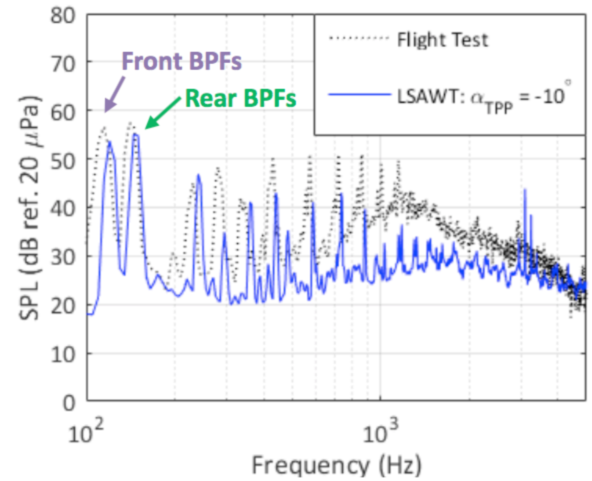


Flyover Orientation

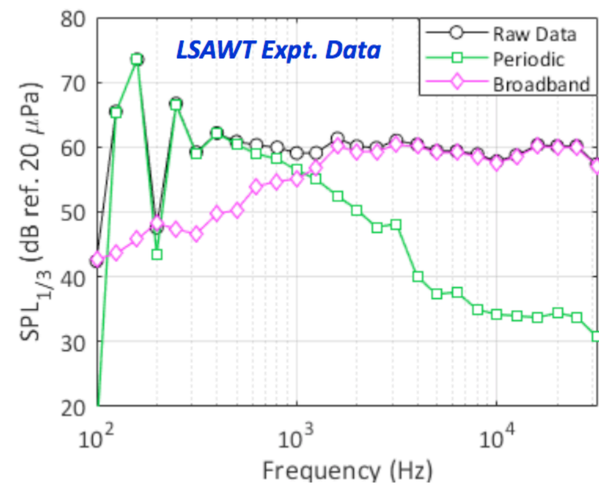
UAS Testing (contd.)

From Nik Zawodny and Nicole Pettingill, Spring 2018 Acoustics TWG Meeting

- Sample flyover acoustic data
  - Forward flight condition (all rotors operating)
  - Overall good match in spectral trends
  - Differences: atmospheric turbulence, forward flight speed, vehicle pitch



- Relative roles of periodic and broadband noise
  - Done using periodic averaging
  - Determined by analyzing cases of actuated rotor pairs (R1 & R3)
  - Broadband noise dominates at mid and high frequencies
  - A-weighted OASPLs indicate comparable contributions of periodic and broadband noise

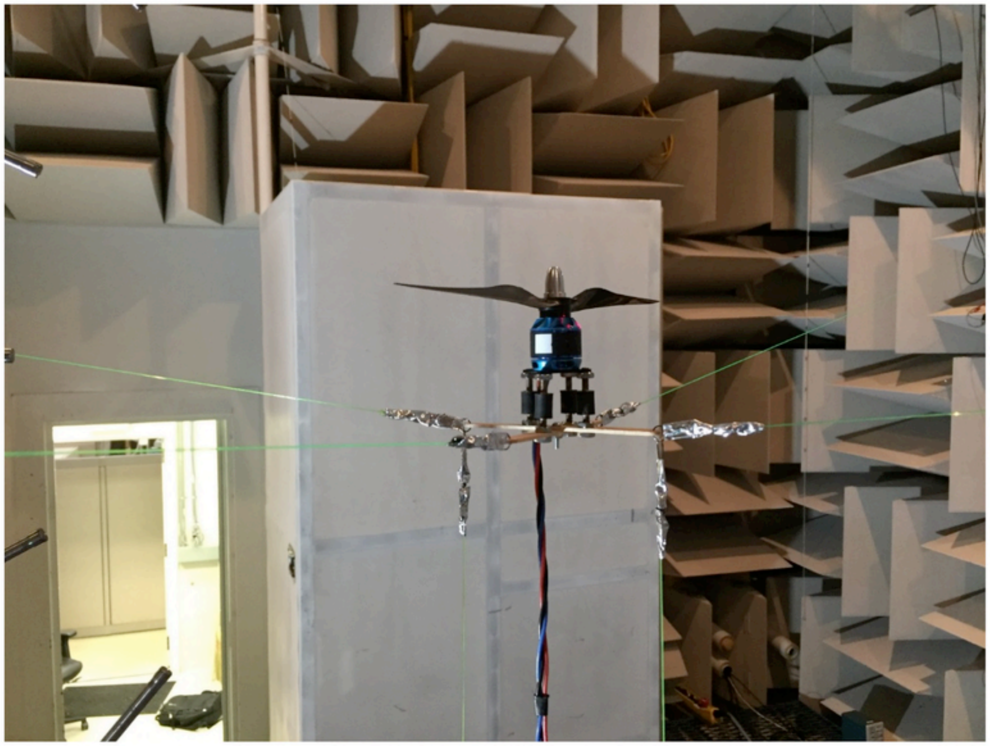


Motor Noise Ground Testing

Results from Brenda S. Henderson, Dennis L. Huff, and Jordan Cluts
NASA Glenn Research Center

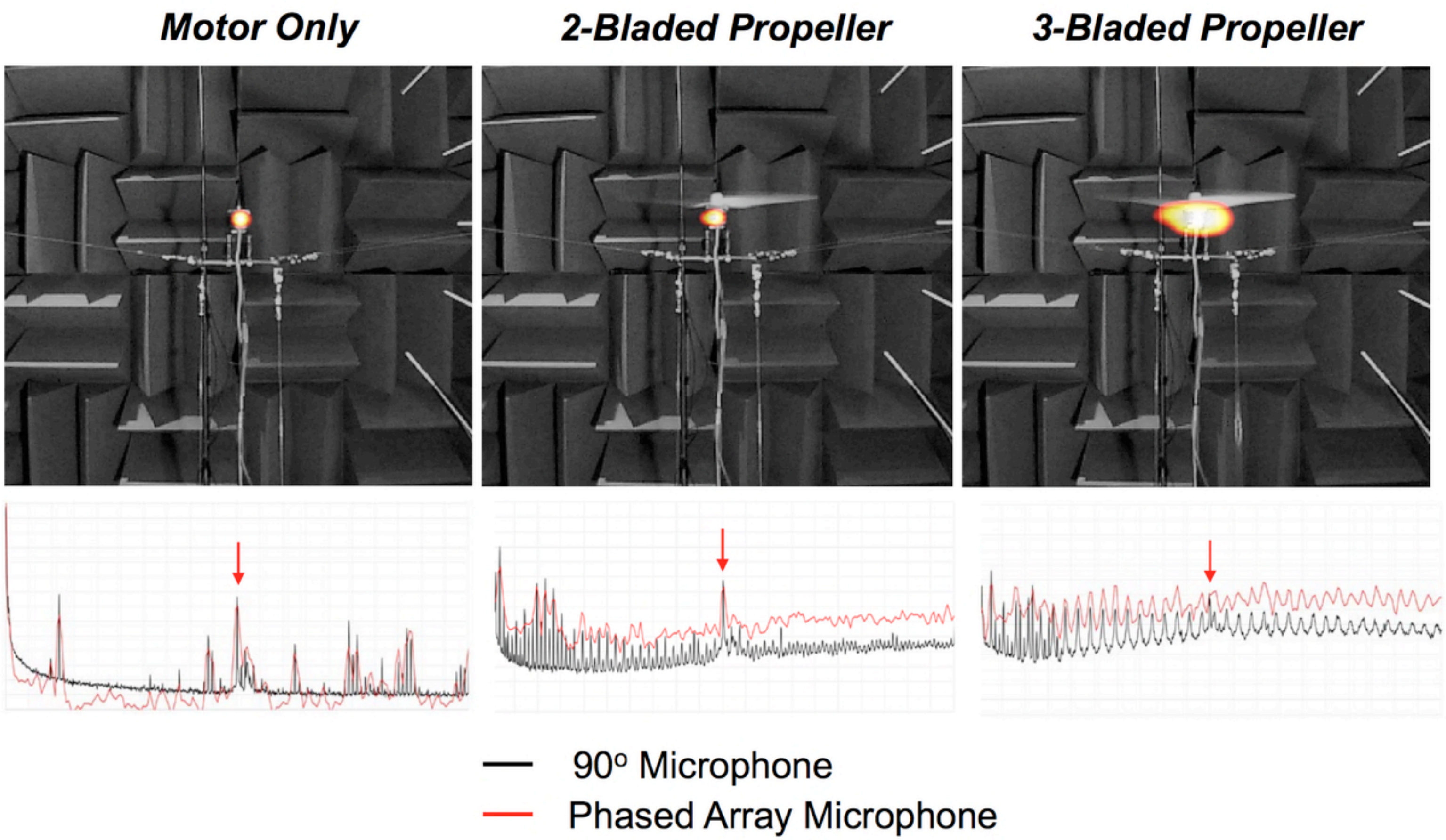
References
D.L. Huff and B.S. Henderson, “Electric Motor Noise from Small Quadcopters: Part I– Acoustic Measurements”, AIAA 2018-2952
and
B.S. Henderson, D.L. Huff, and C. Ruggeri, “Electric Motor Noise from Small Quadcopters: Part II– Source Characteristics”, AIAA 2018-2953

Motor and Propeller with Tether



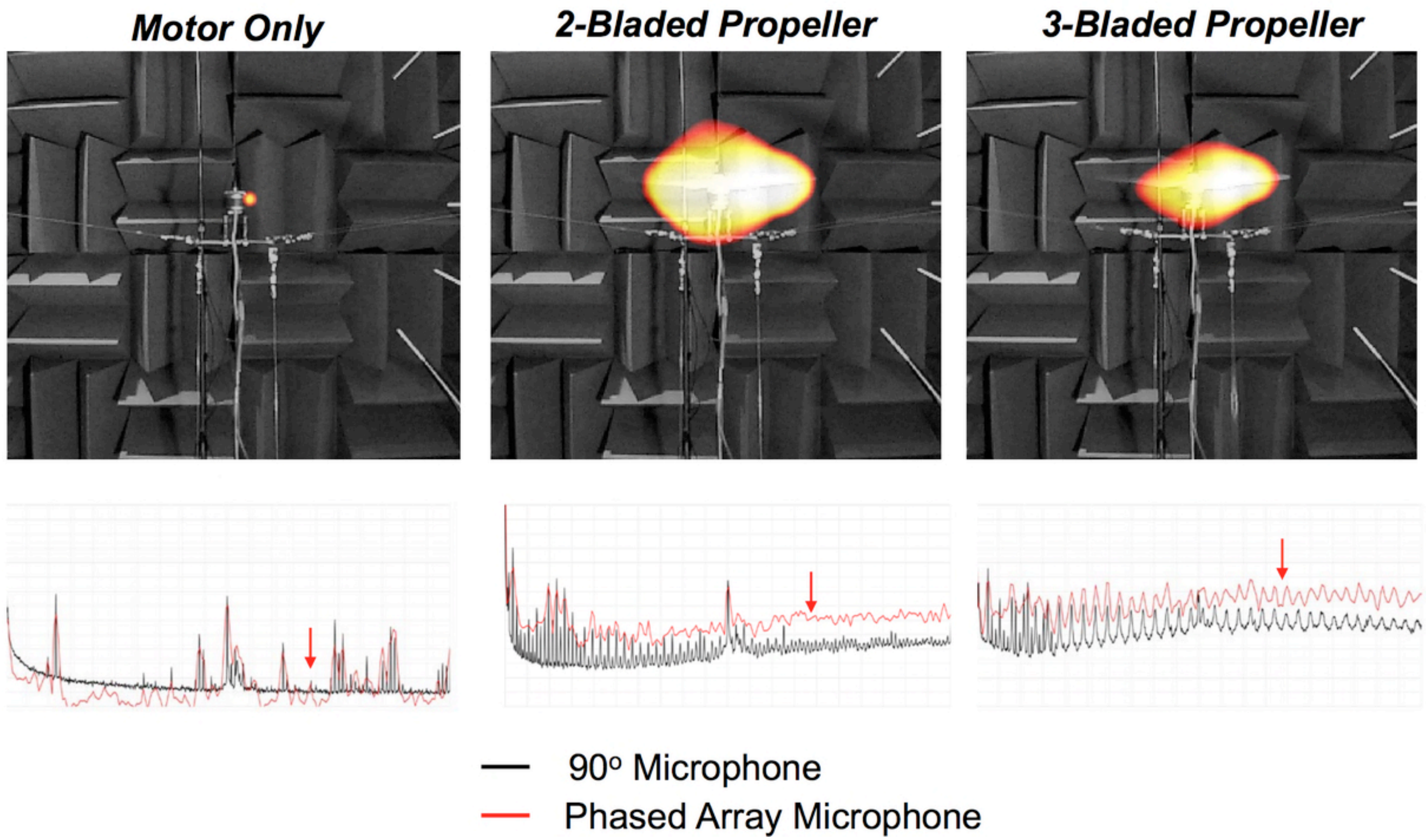
From Brenda Henderson, Dennis Huff, and Jordan Cluts, Spring 2018 Acoustics TWG Meeting

Phased Array Results - 5029 Hz



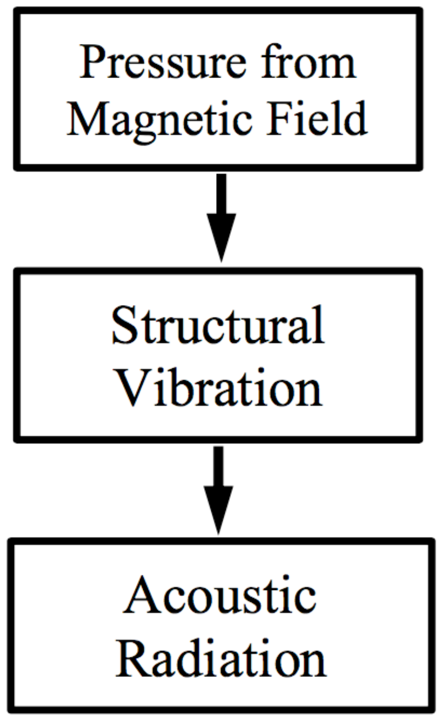
From Brenda Henderson, Dennis Huff, and Jordan Cluts, Spring 2018 Acoustics TWG Meeting

Phased Array Results - 6885 Hz



From Brenda Henderson, Dennis Huff, and Jordan Cluts, Spring 2018 Acoustics TWG Meeting

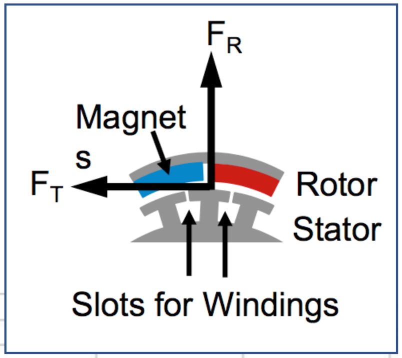
Why Motor Noise at 5 kHz?



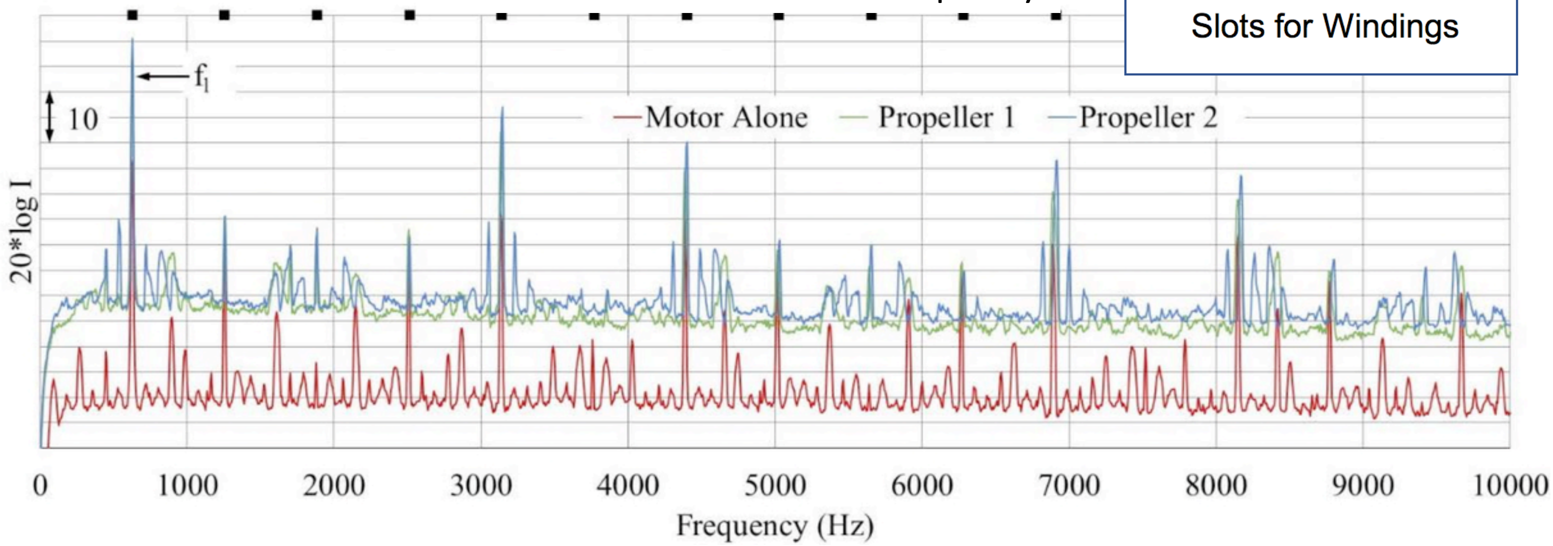
Results from Brenda S. Henderson, Dennis L. Huff, and Jordan Cluts
NASA Glenn Research Center

Pressure from Magnetic Field

Current -> Magnetic Field -> Radial force on (outside) rotor shell



Motor controller current vs. frequency

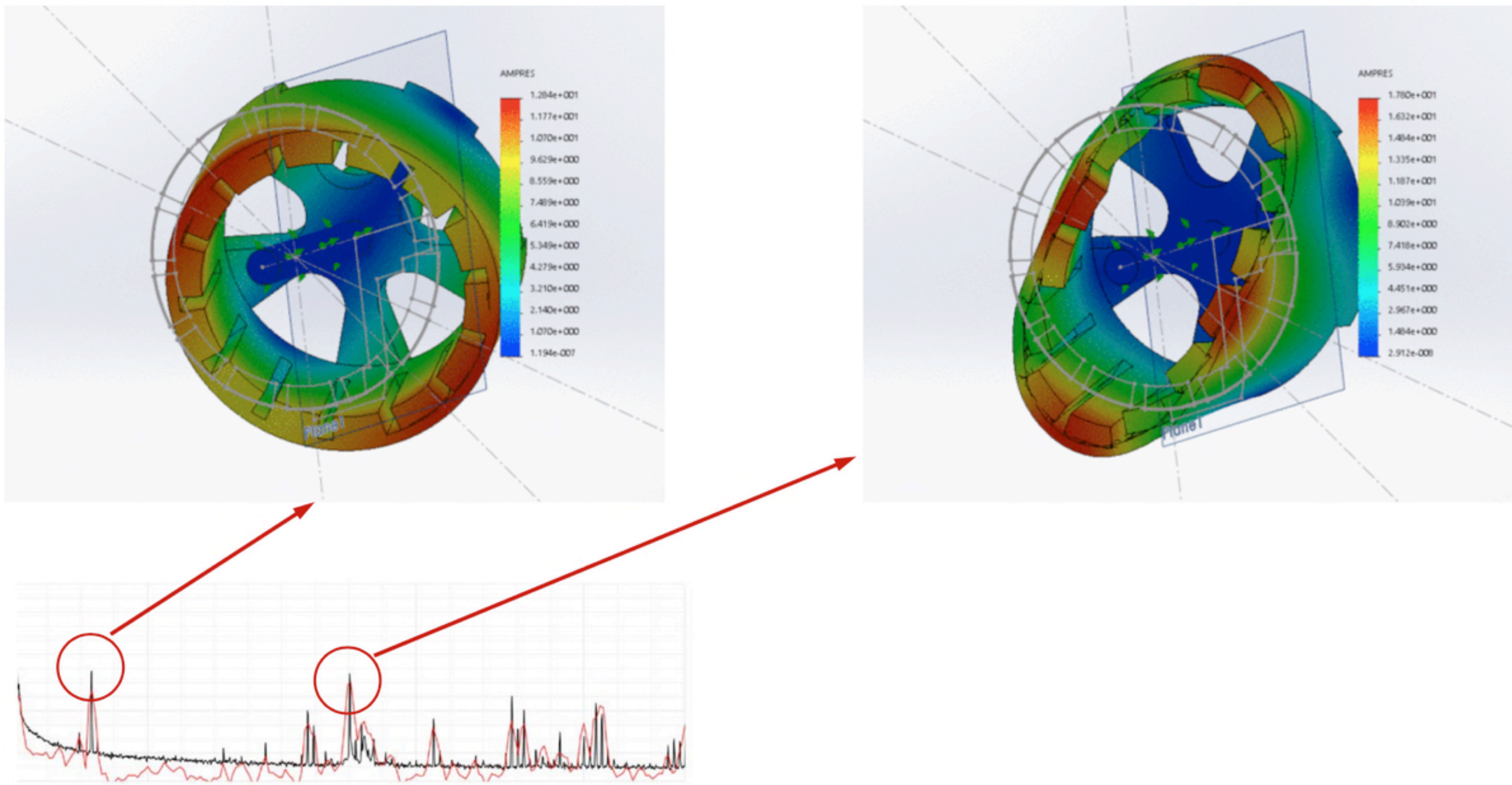


Adapted from Brenda Henderson, Dennis Huff, and Jordan Cluts, Spring 2018 Acoustics TWG Meeting

Structural Vibration: Finite Element Analysis

Mode 1 ~ 1.5 kHz

Mode 2 ~ 4 – 5 kHz

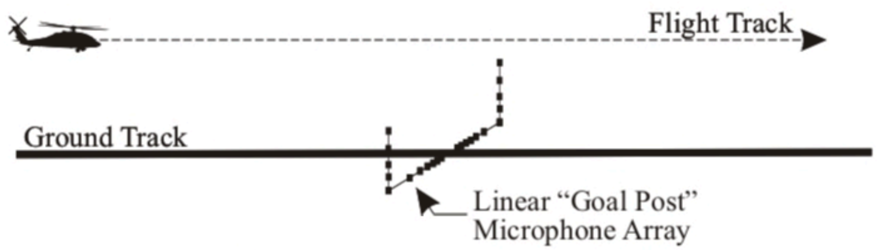


From Brenda Henderson, Dennis Huff, and Jordan Cluts, Spring 2018 Acoustics TWG Meeting

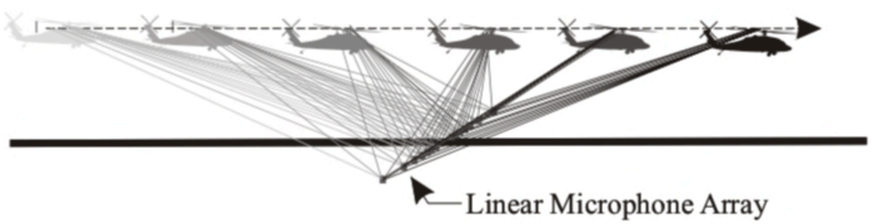
Flight Measurement of Sound Spheres

- Goal post array
- Acoustic Camera

Source Noise Measurement With A Goal Post Array



a) Source flyover of a linear microphone array.



b) Acoustic data measured during flyover.

c) Single source location transformation.

d) Source noise hemisphere.

D.A. Conner, C.L. Burley and C.D. Smith, “Flight Acoustic Testing and Data Acquisition For the Rotor Noise Model (RNM),” American Helicopter Society 62nd Annual Forum, Phoenix, AZ, May.2006.

Figure 9. Photo of MH-53E flying through the goal-post microphone array.

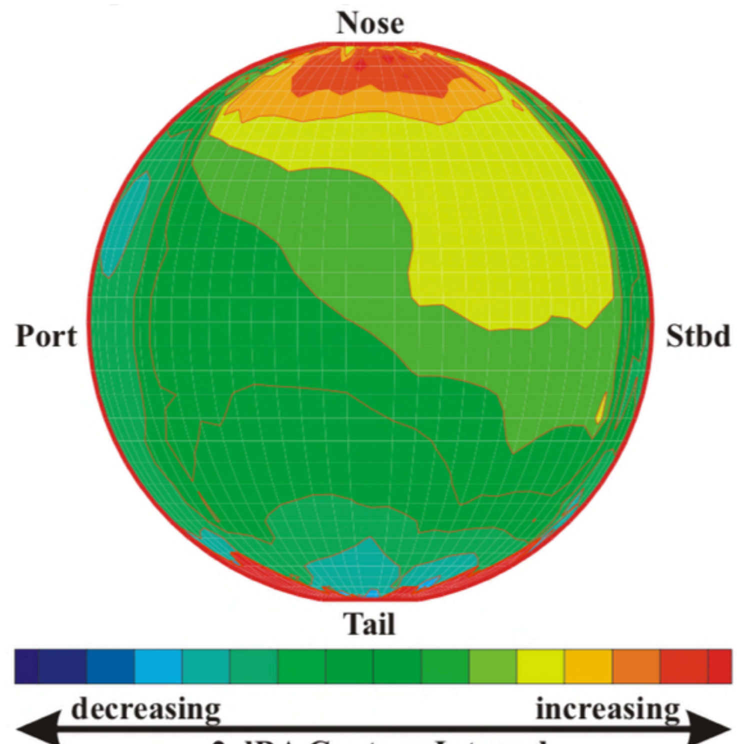
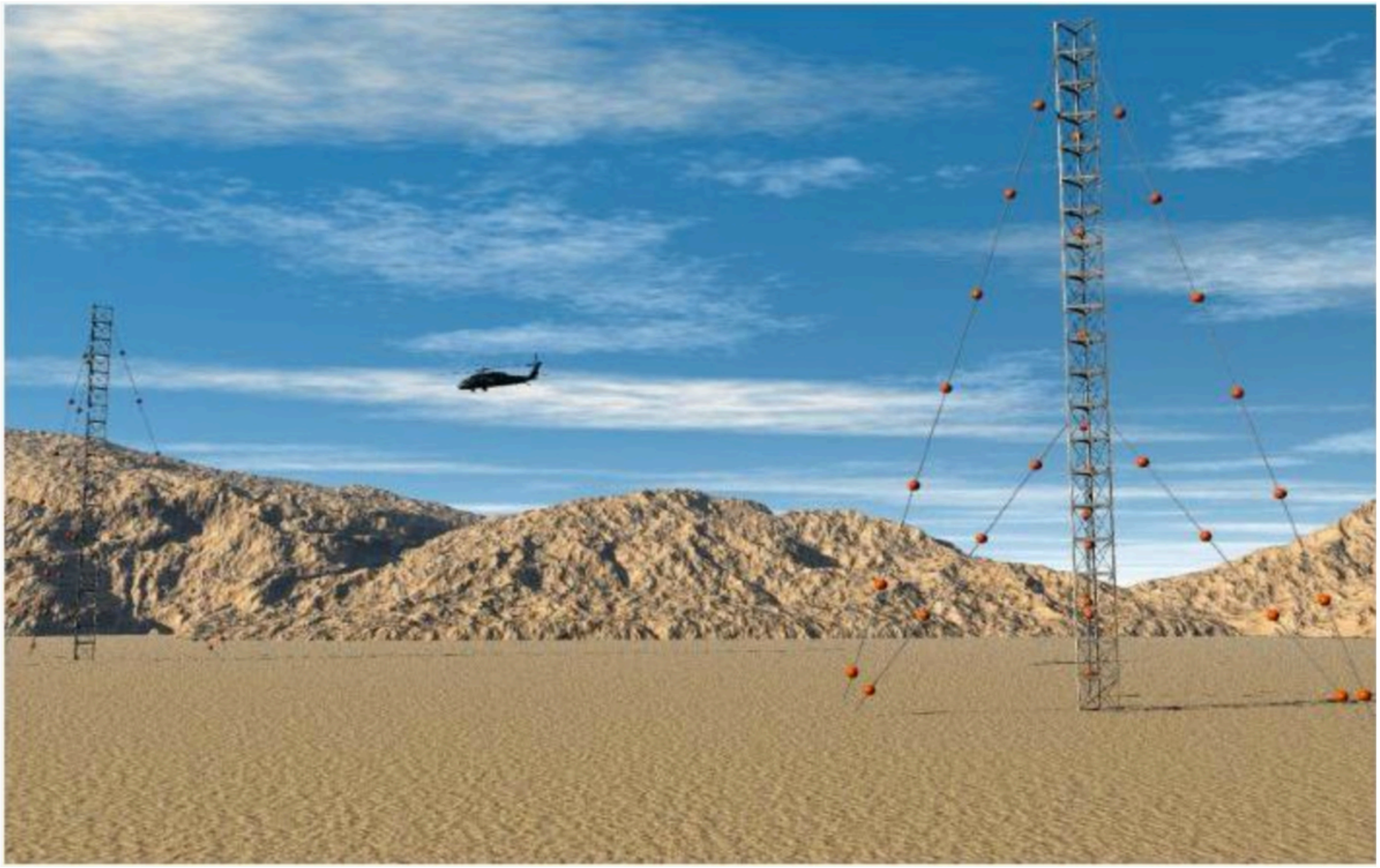


Figure 21. L_A semi-sphere created using measured vehicle fuselage orientation data; MD600N at 90 knots, 6° approach.

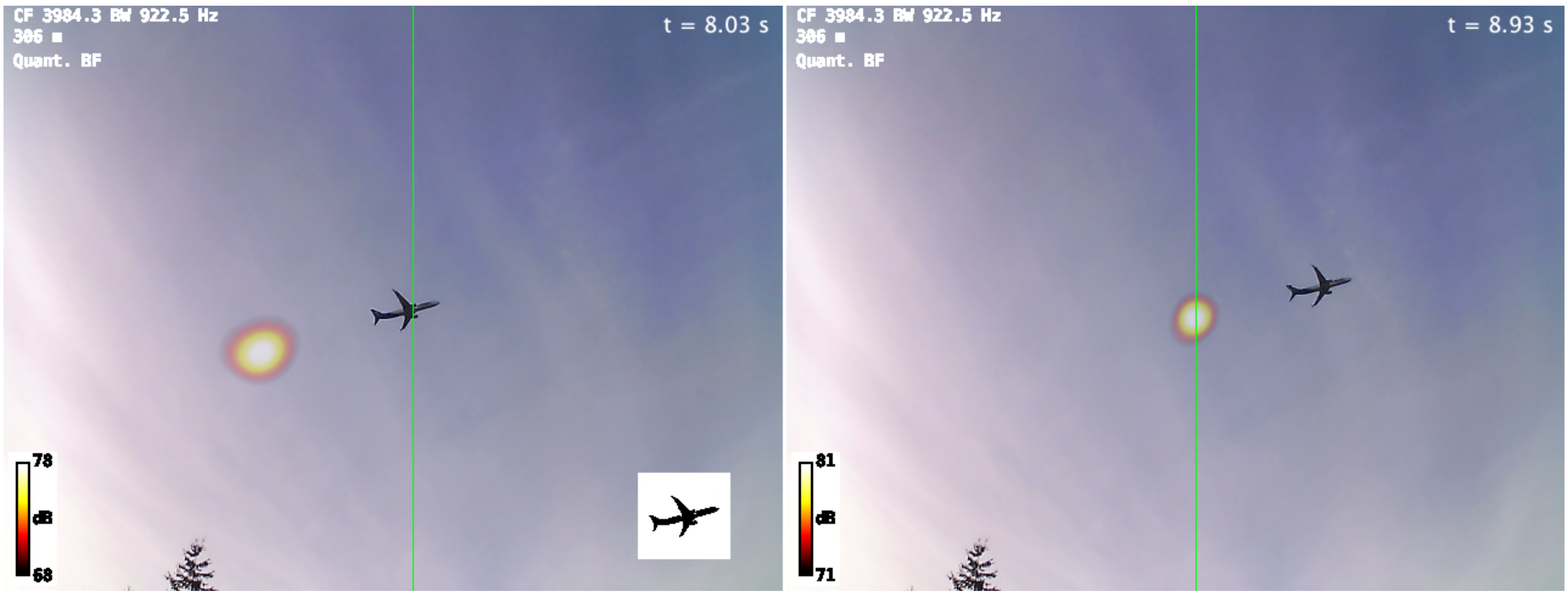
Acoustic Research Complex at the White Sands Missile Range

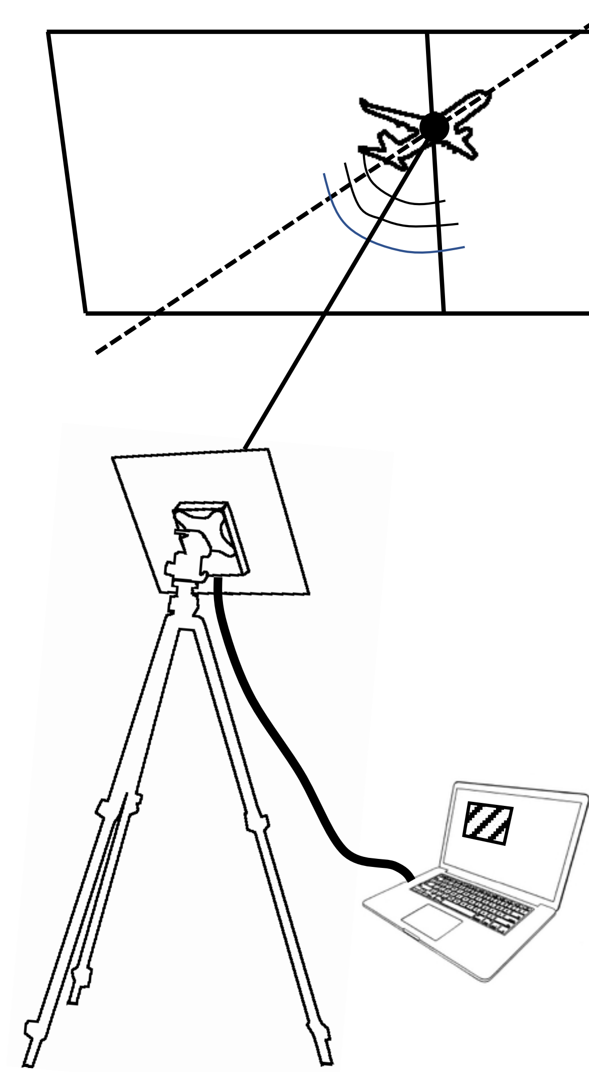


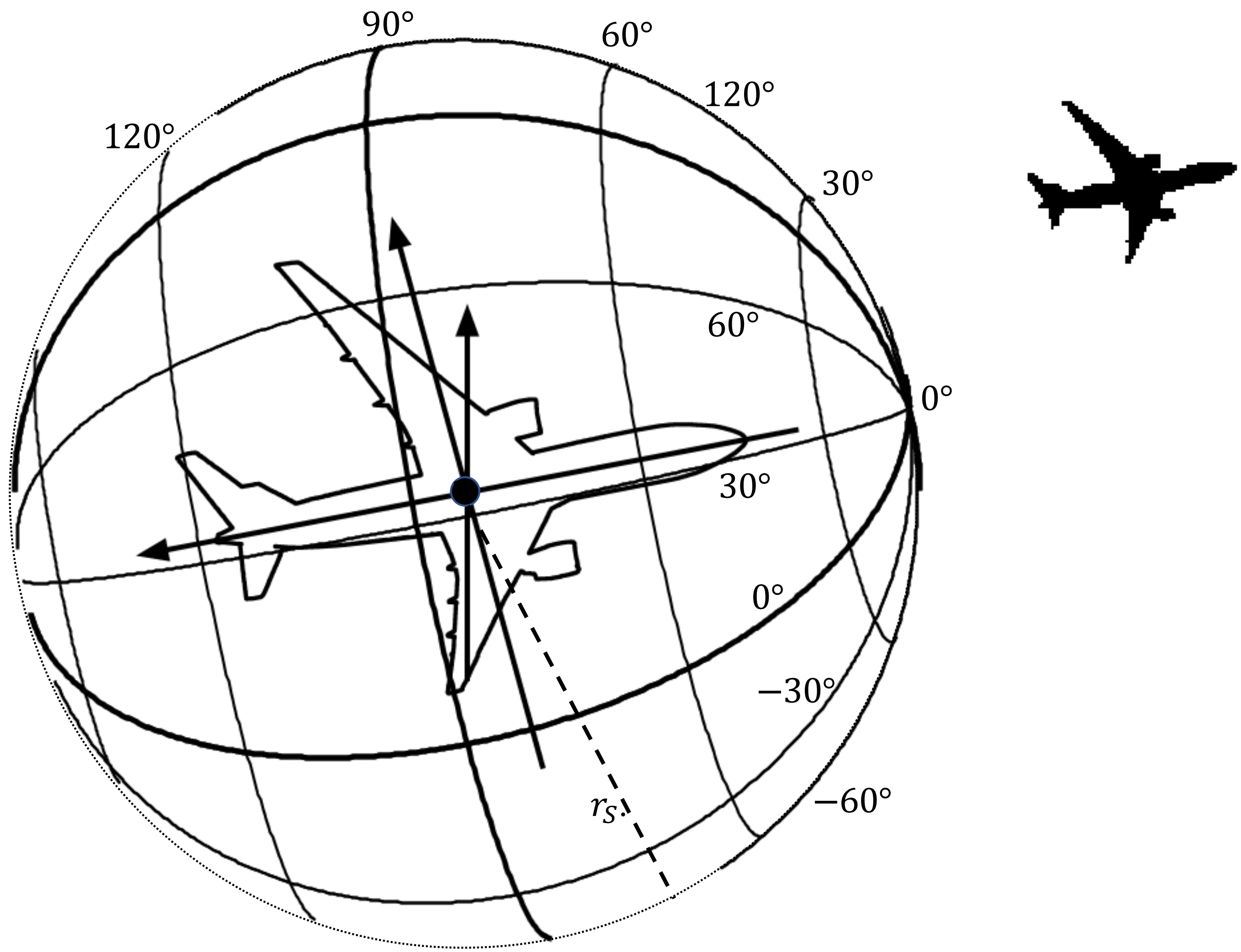
Difficulties of Goal Post Approach

- Remote location needed for SNR
- High cost for instrumentation and personnel
- Errors in “depropagaton” due to imperfect knowledge of wind over propagation path
- Ground bounce for elevated microphones

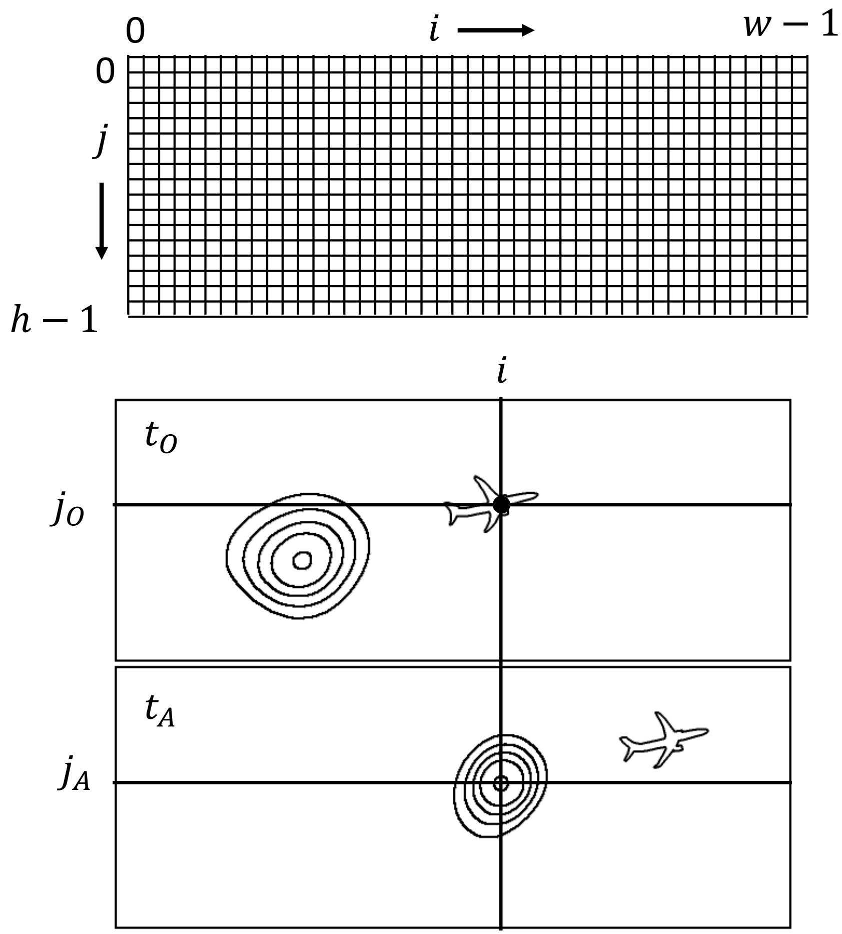
Acoustic Camera Approach


CF 3984.3 BW 922.5 Hz
306
Quant. BF
t = 8.03 s
78
dB
68
CF 3984.3 BW 922.5 Hz
306
Quant. BF
t = 8.93 s
81
dB
71



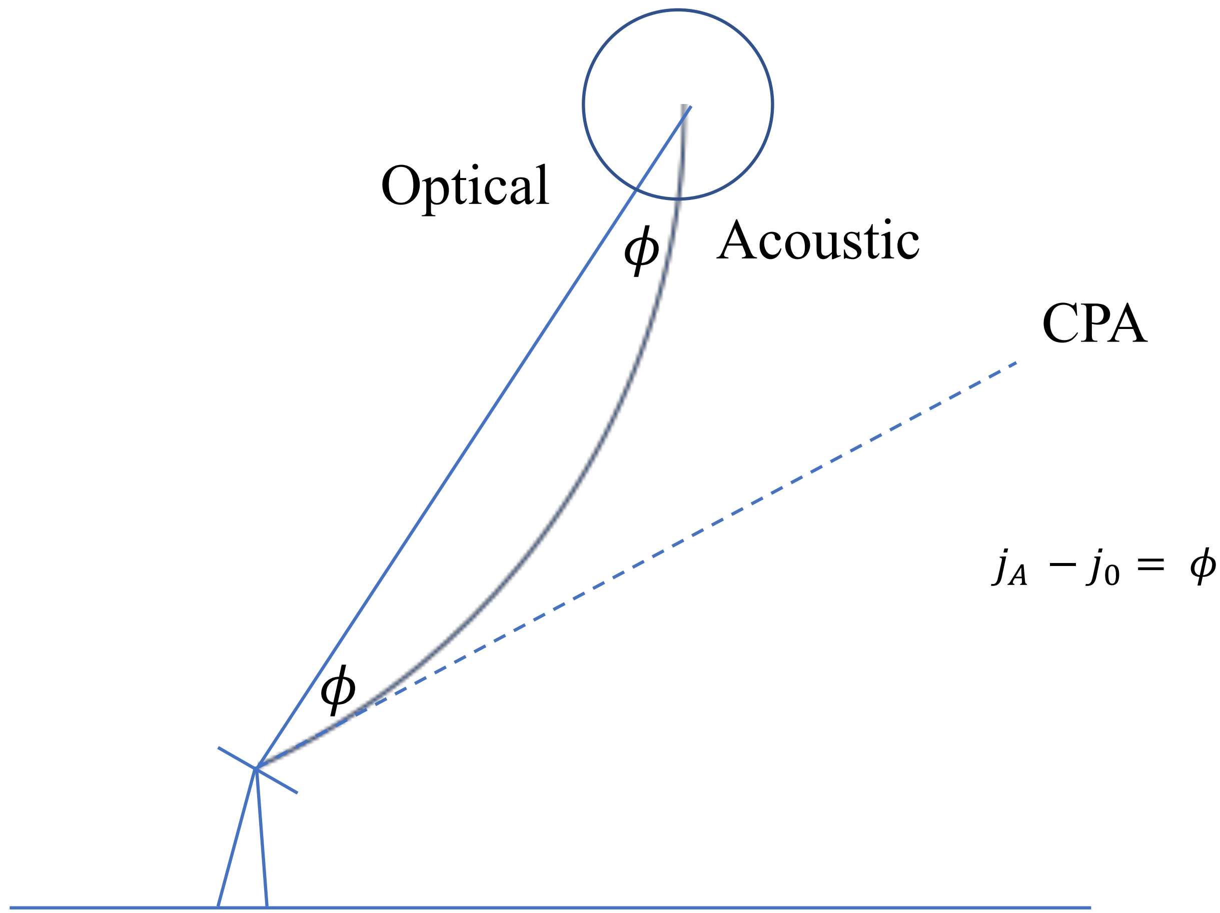


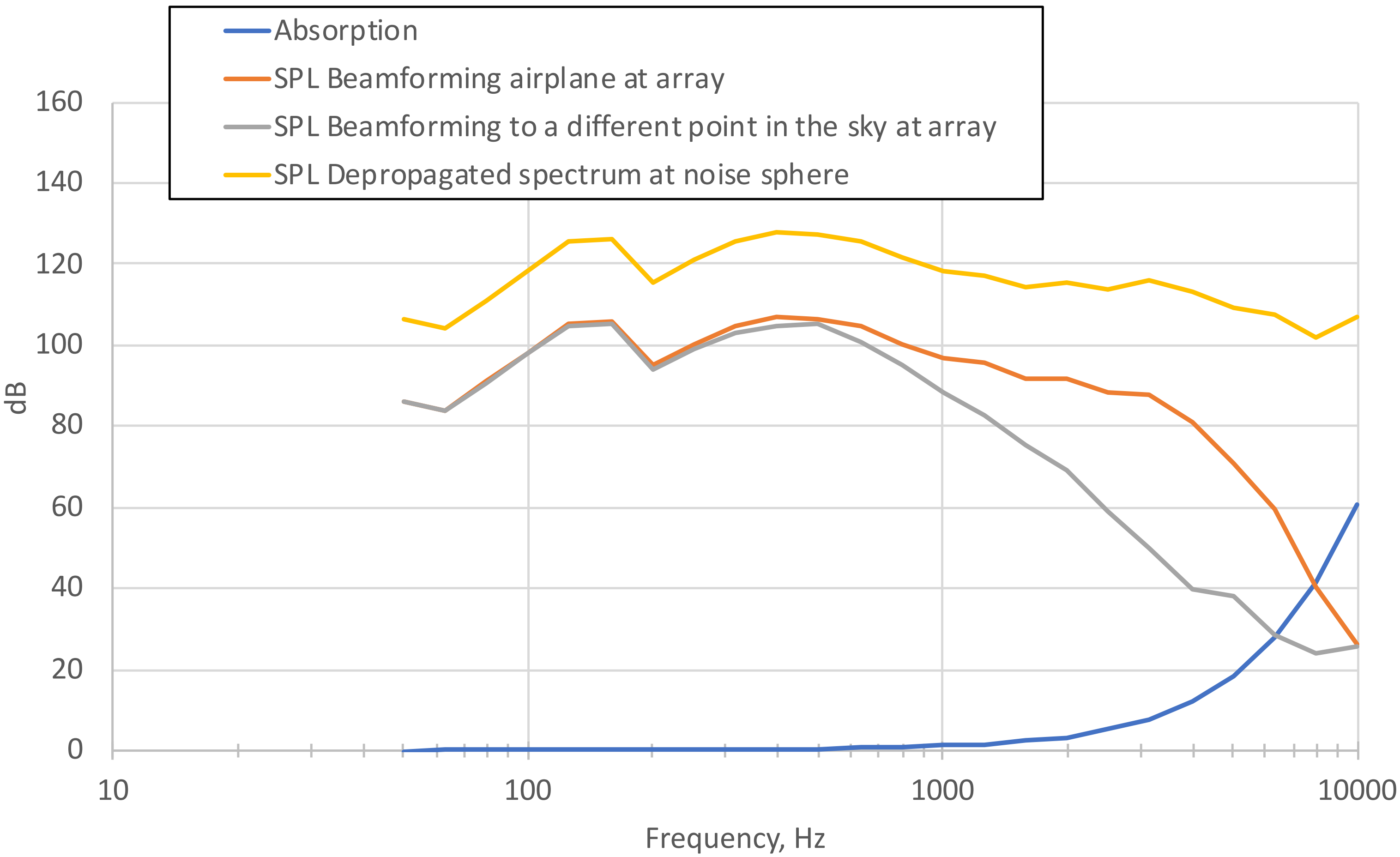
90°
60°
120°
120°
30°
60°
0°
30°
0°
−30°
r_S
−60°



$t_A - t_0$ determines the propagation distance

$j_A - j_0$ is used to correct the optical angle to the acoustic angle for wind


Optical
Acoustic
CPA
ϕ
ϕ
$j_A - j_0 = \phi$


Absorption
SPL Beamforming airplane at array
SPL Beamforming to a different point in the sky at array
SPL Depropagated spectrum at noise sphere
160
140
120
100
80
60
40
20
0
dB
10
100
1000
10000
Frequency, Hz

Summary

The acoustic camera approach should substantially reduce the cost and improve the accuracy of UAM sound sphere measurements.

This may provide information for efficient regulation of UAM noise, helping to remove a barrier to the acceptance of this technology.