Aural Effects of Distributed Propulsion

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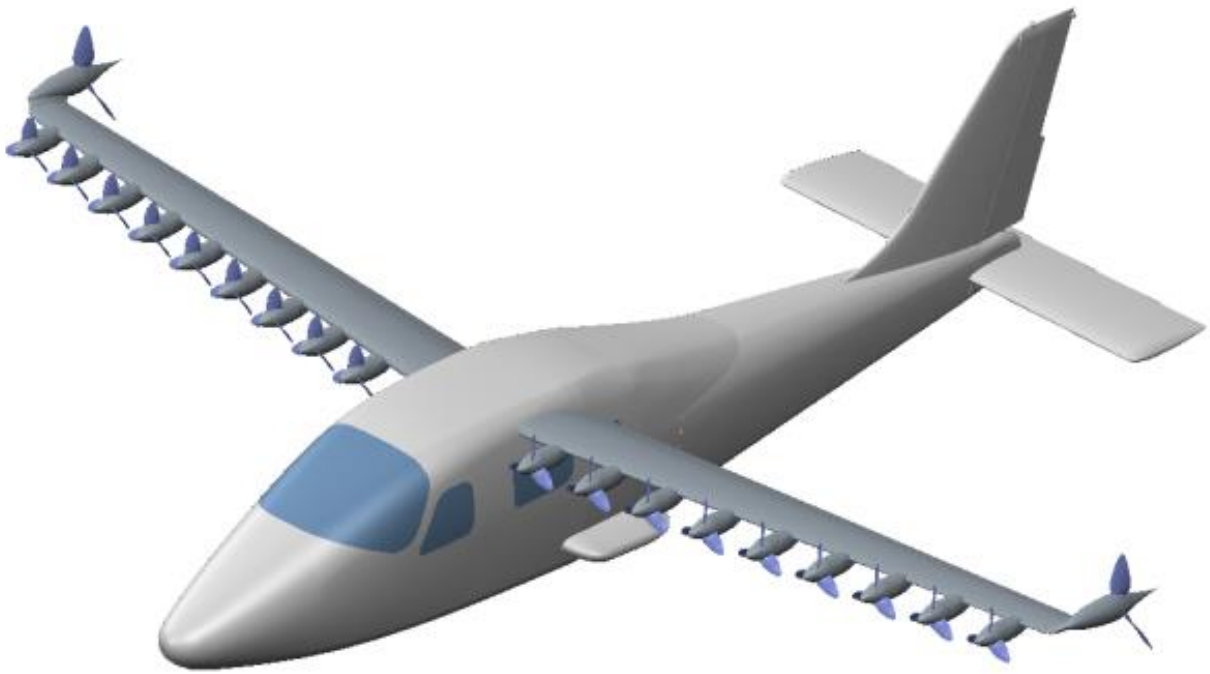

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Motivation

- Large potential noise reduction with Distributed Electric Propulsion (DEP) aircraft
- Use human perception of noise to influence early design process
  - Determine suitable metrics which correlate well with annoyance and/or detection for this unique noise source

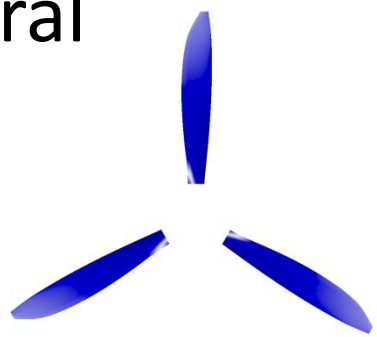
Outline

1. *Quick Look* estimates of noise reduction potential
   a. Reduced tip speed
   b. Spread spectrum

2. Auralization of DEP Configuration.
   a. Dataflow from design through auralization process
   b. Preliminary studies of leading edge prop DEP configuration

Quick Look Test Cases

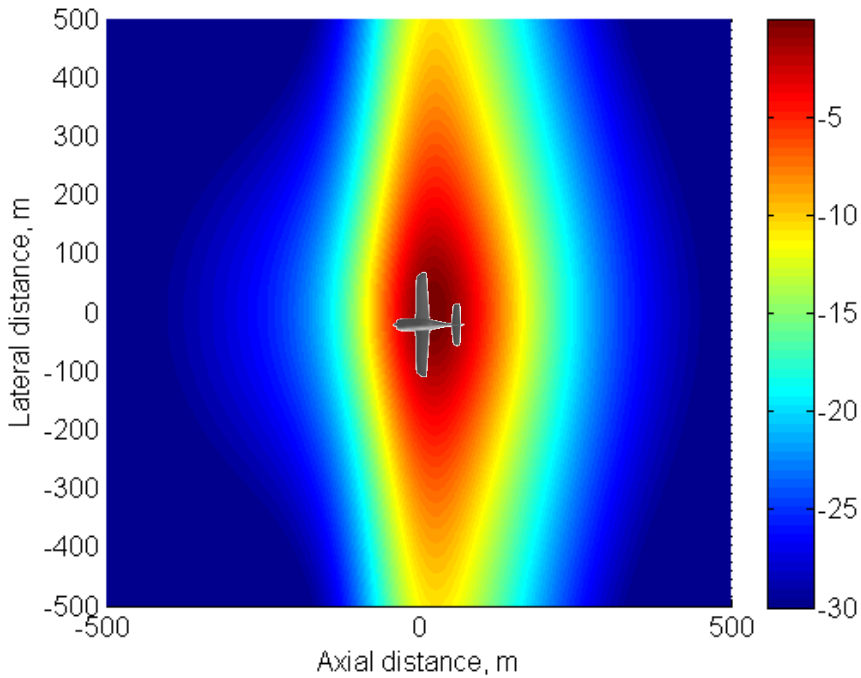
- Operating conditions based on general aviation propeller
- Pure tone at BPF
  - Directivity from prediction



# Props	# Blades	RPM	BPF (Hz)	Tip Speed (m/s)	Unit Thrust (lbs)	Scale	Diameter (m)
1	3	2500	125	262	480	100%	1.98
2	3	2500	125	249	240	95%	1.88
4	3	2500	125	236	120	90%	1.78
8	3	2500	125	223	60	85%	1.68
18	3	6500	325	170	26	25%	0.49

Context of Analysis

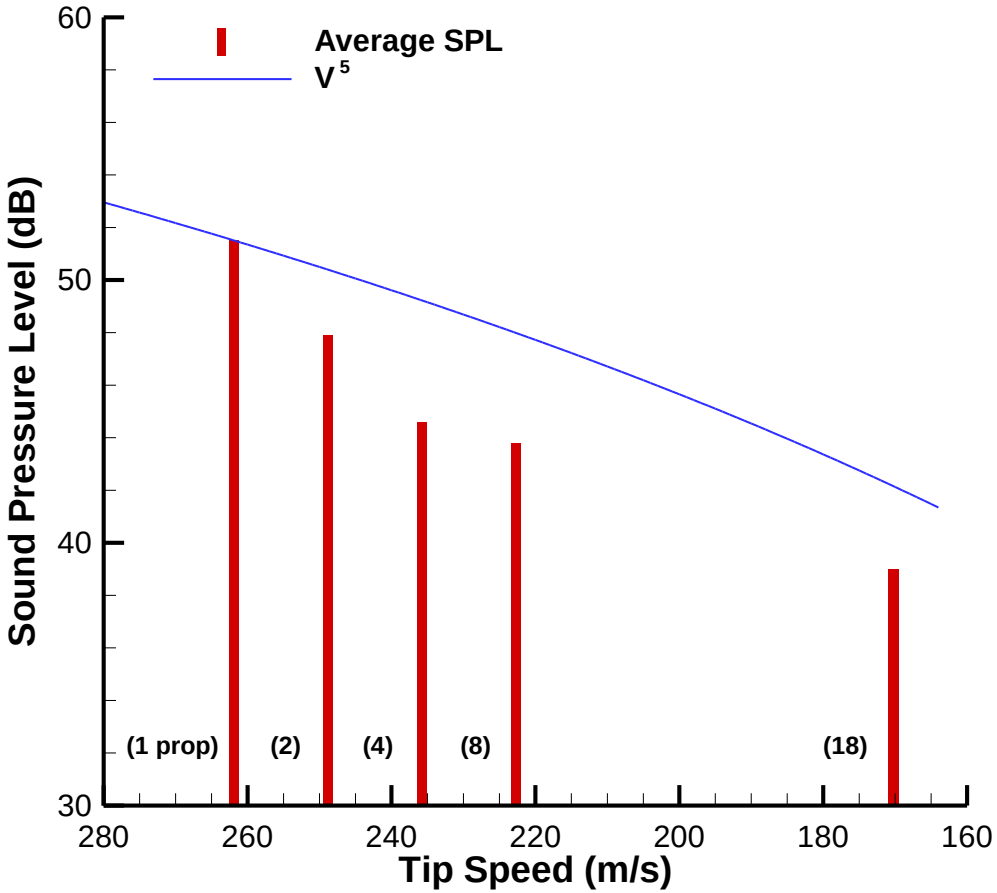
Single Propeller Radiation Pattern



- 1 km square surface
- Source located at center of surface
- Source altitude 150 m
- Source is stationary
- Color is SPL re: max

- Average SPL is determined over surface.
  - Used for estimating effects of reduced tip speed.
- Peak SPL is maximum over the surface.
  - Used for estimating effects of spread spectrum

Effects of Reduced Tip Speed



	Tip Speed	Constant	Noise Reduction (dB) (TS 262 m/s to 170 m/s)
QL Avg	Circumferential	N props at constant thrust	12.5
V^5 (*)	Helical	Single prop @ constant input power	9.4

*SAE AIR 1407, May 1977

Spread Spectrum

- Introduction to Terminology and Analyses
- Radiation patterns in time and space
- Source sounds (Quick Look)

Coherent vs Incoherent Sources

- N sources at the same RPM will be coherent.
- N sources at different RPMs, will be incoherent.

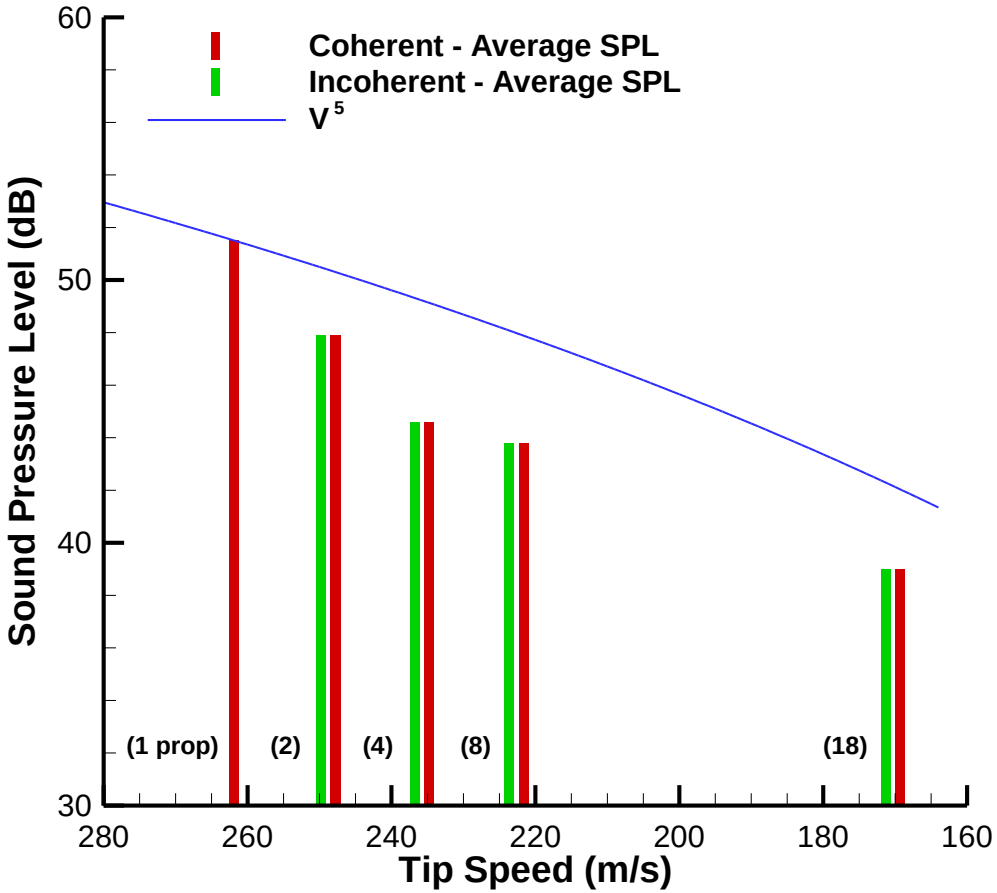
- Say we have two noise sources S_1 and S_2 emitting sound.
- At some point, the sound pressure from the sources is A and B respectively.
- The total sound power at this point is

$$S = (A+B)^2 = A^2 + B^2 + 2AB$$

Only coherent sources will include cross terms

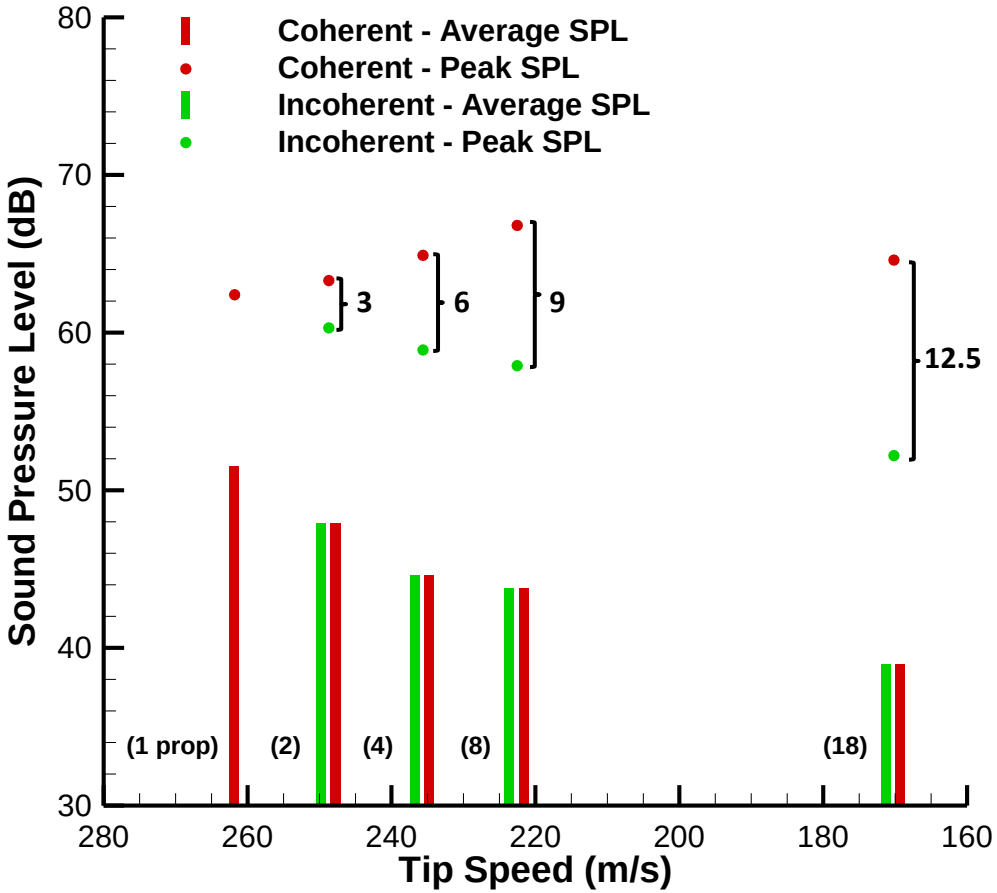
- If A=B=1 and A and B are coherent, the total power would be 4, a 6 dB increase
  - Coherent power increases as $10\log_{10}(N^2)$.
- If A is not coherent with B, the total power will be 2, a 3 dB increase.
  - Incoherent power increases as $10\log_{10}(N)$.
- Ideally, the noise power reduction of a spread spectrum configuration is $-10\log_{10}(N)$

Effect of Spread Spectrum



Spread spectrum has no effect on average SPL

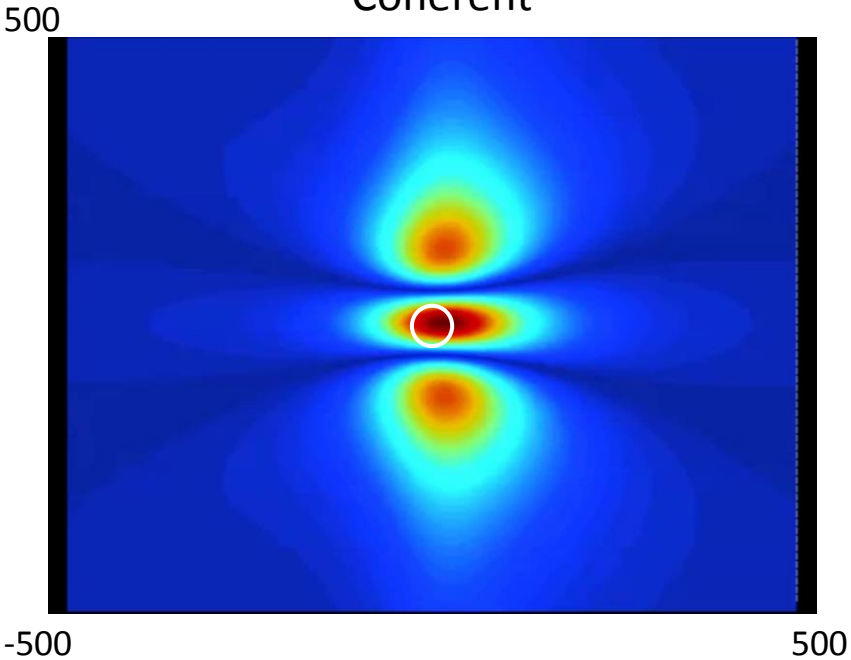
Effect of Spread Spectrum



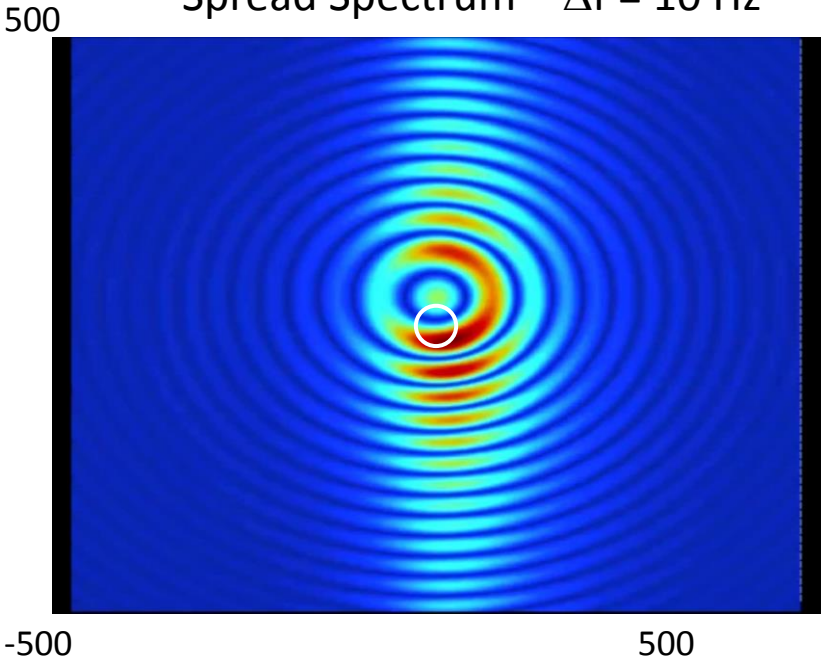
- Spread spectrum has theoretical peak SPL reduction of $-10\log_{10}(N)$
- Average SPL reduction due to tip speed <u>does not</u> add to peak SPL reduction due to spread spectrum

2 Sources – Quick Look

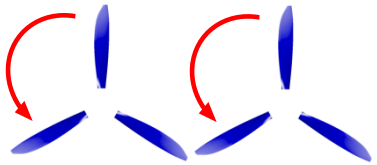
Coherent



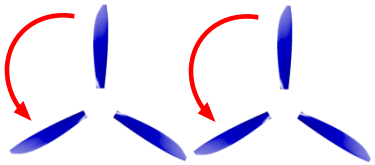
Spread Spectrum – Δf = 10 Hz



Both at 125 Hz and in phase



120 Hz 130 Hz

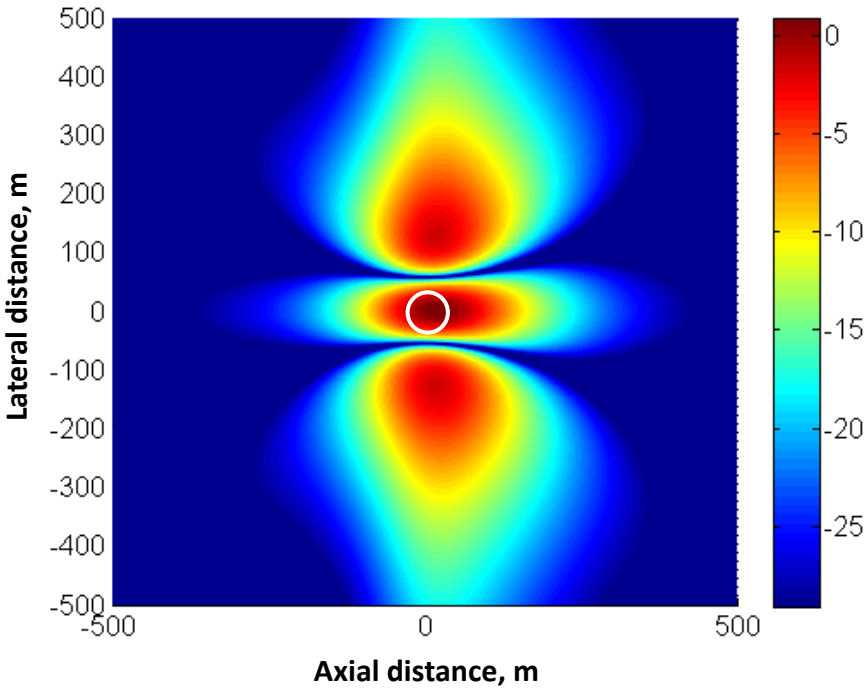


Stationary source, pure tone, altitude=150 m

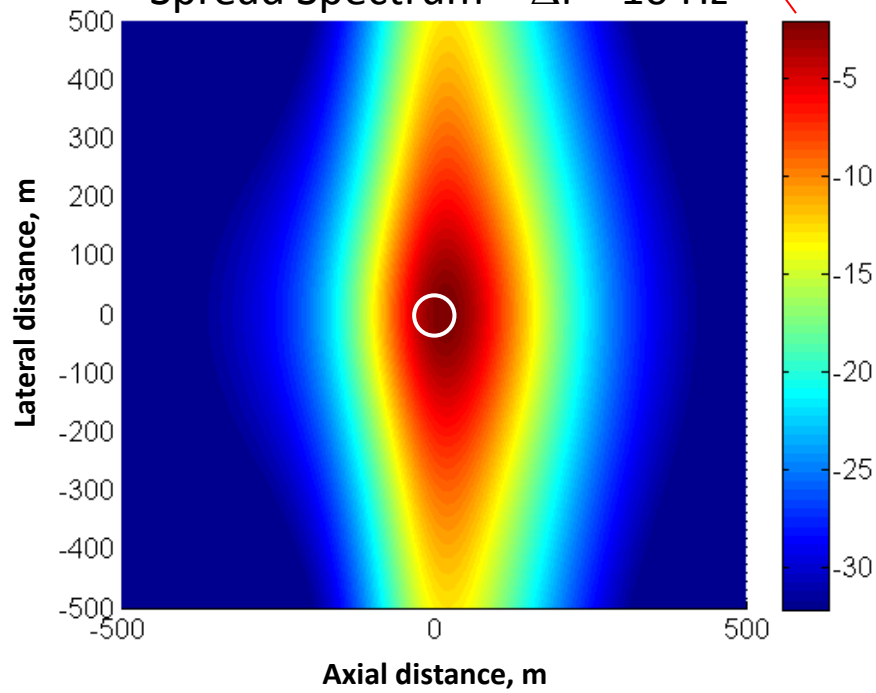
Time Averaged Radiation Patterns from Quick Look – 2 Sources

Peak power down 3dB

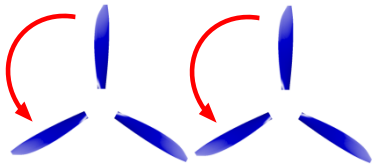
Coherent



Spread Spectrum – Δf = 10 Hz

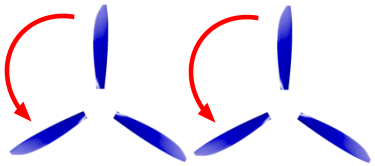


Both at 125 Hz and in phase



Same average radiated power

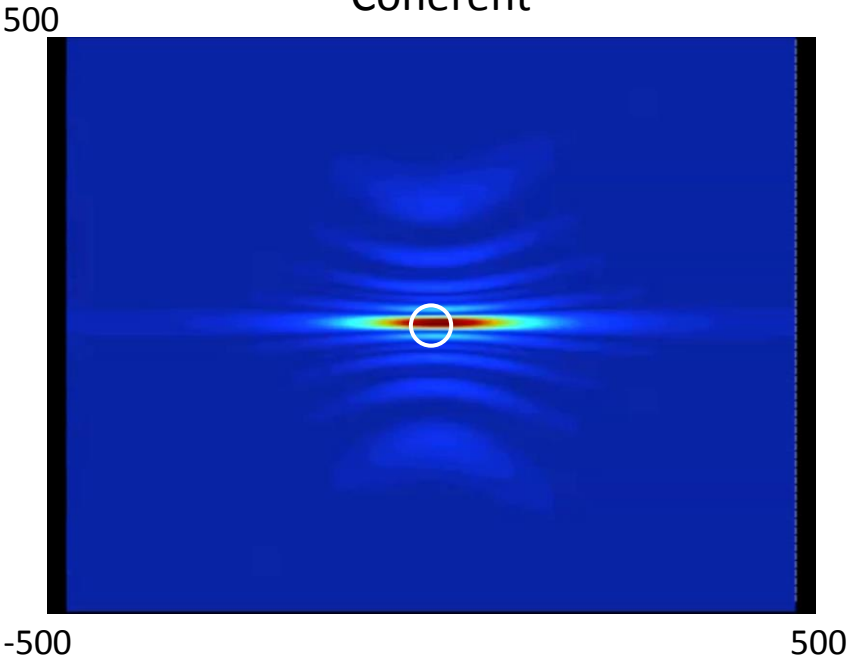
120 Hz 130 Hz



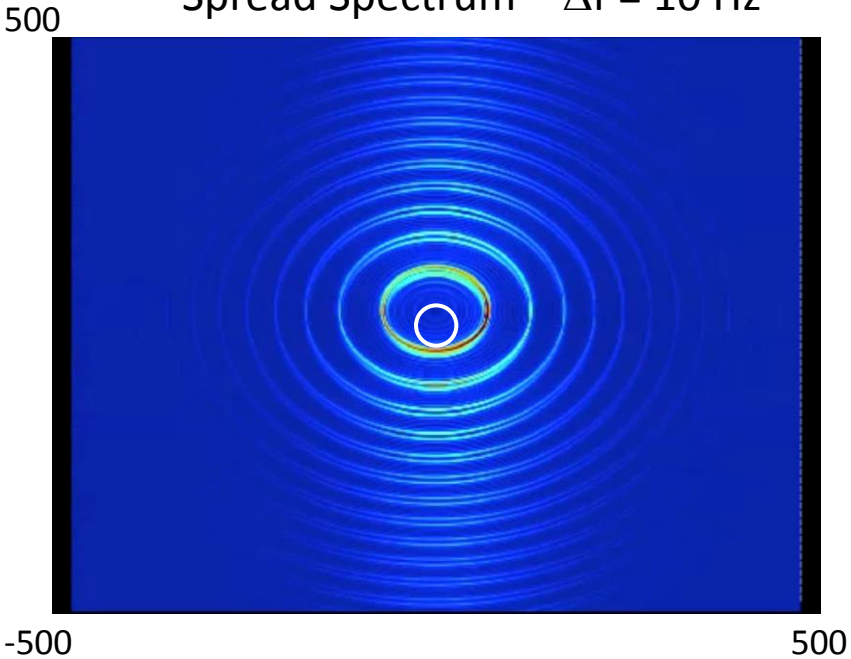
Stationary source, pure tone, altitude=150 m

18 sources – Quick Look

Coherent



Spread Spectrum – Δf = 10 Hz



All at 325 Hz and in phase

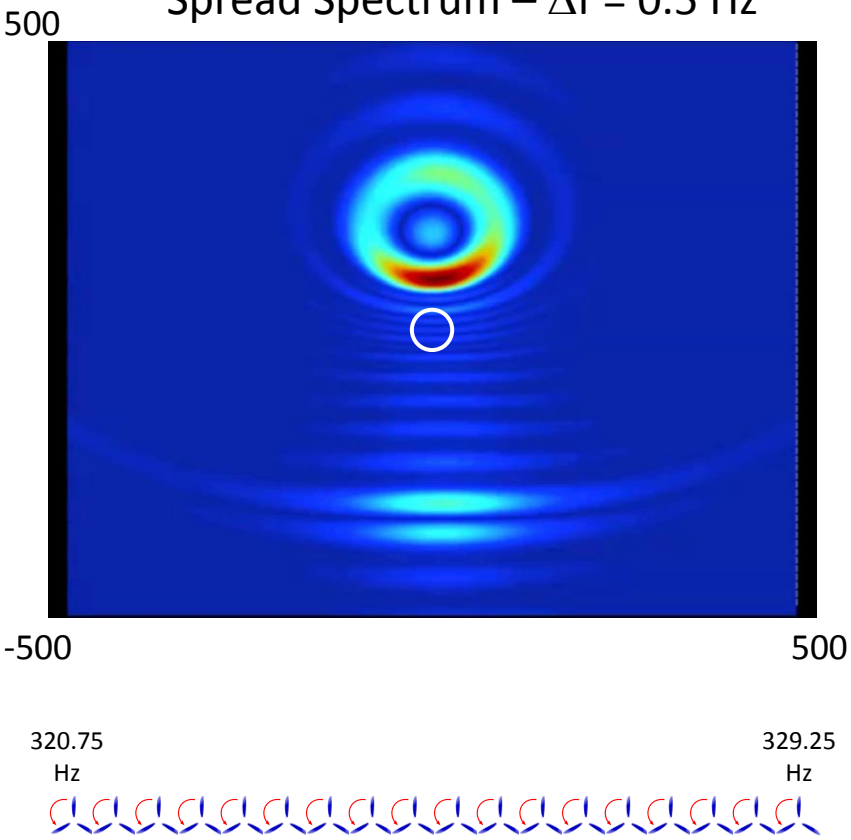
240 Hz

410 Hz

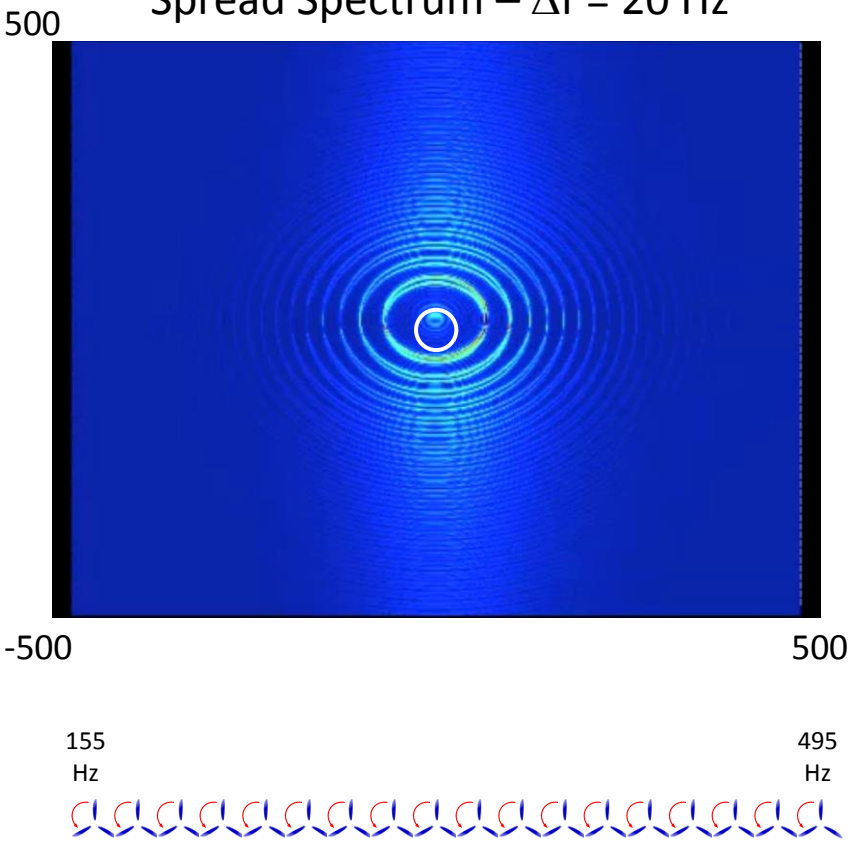
Stationary source, pure tone, altitude=150 m

18 Sources – Quick Look

Spread Spectrum – Δf = 0.5 Hz



Spread Spectrum – Δf = 20 Hz

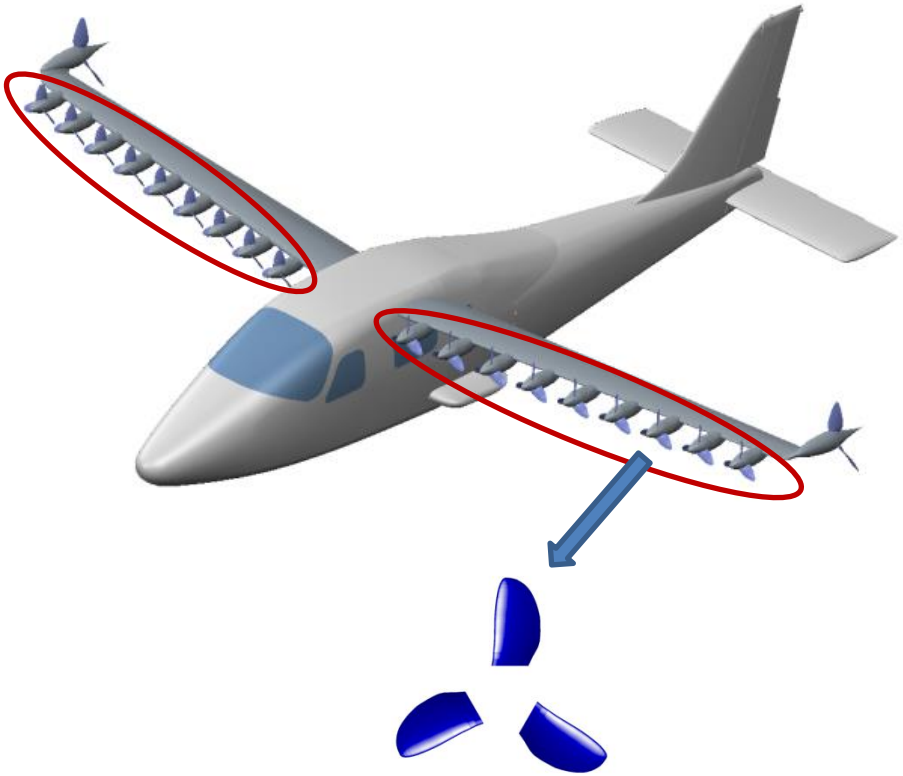


Stationary source, pure tone, altitude=150 m

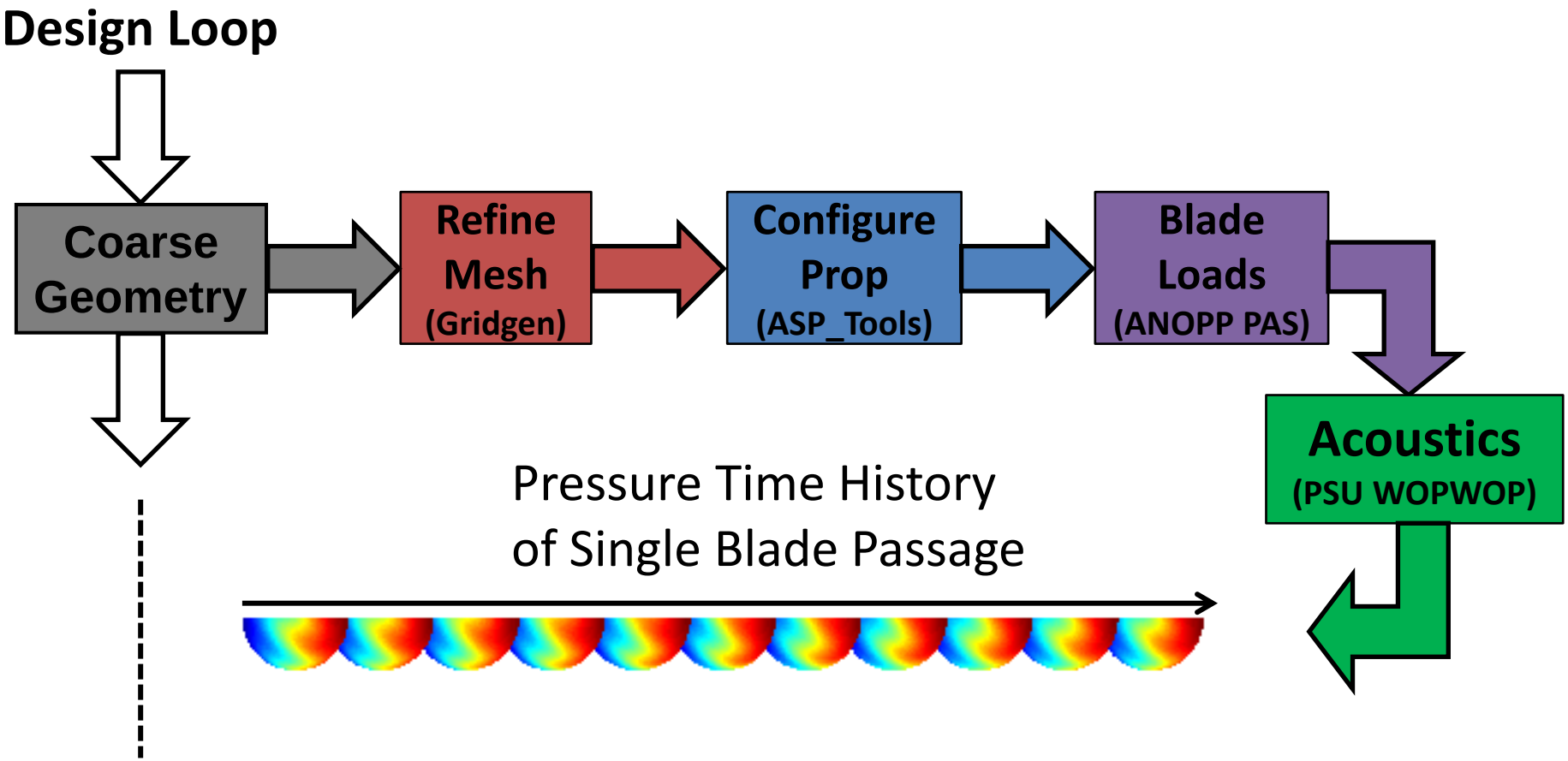
Auralization of DEP Configuration

- Auralization process
  - Source noise definition
  - Source noise synthesis
  - Propagation

- Preliminary studies of a GA prop and leading edge props (LEP) in DEP configurations
  - Coherent
  - Spread spectrum

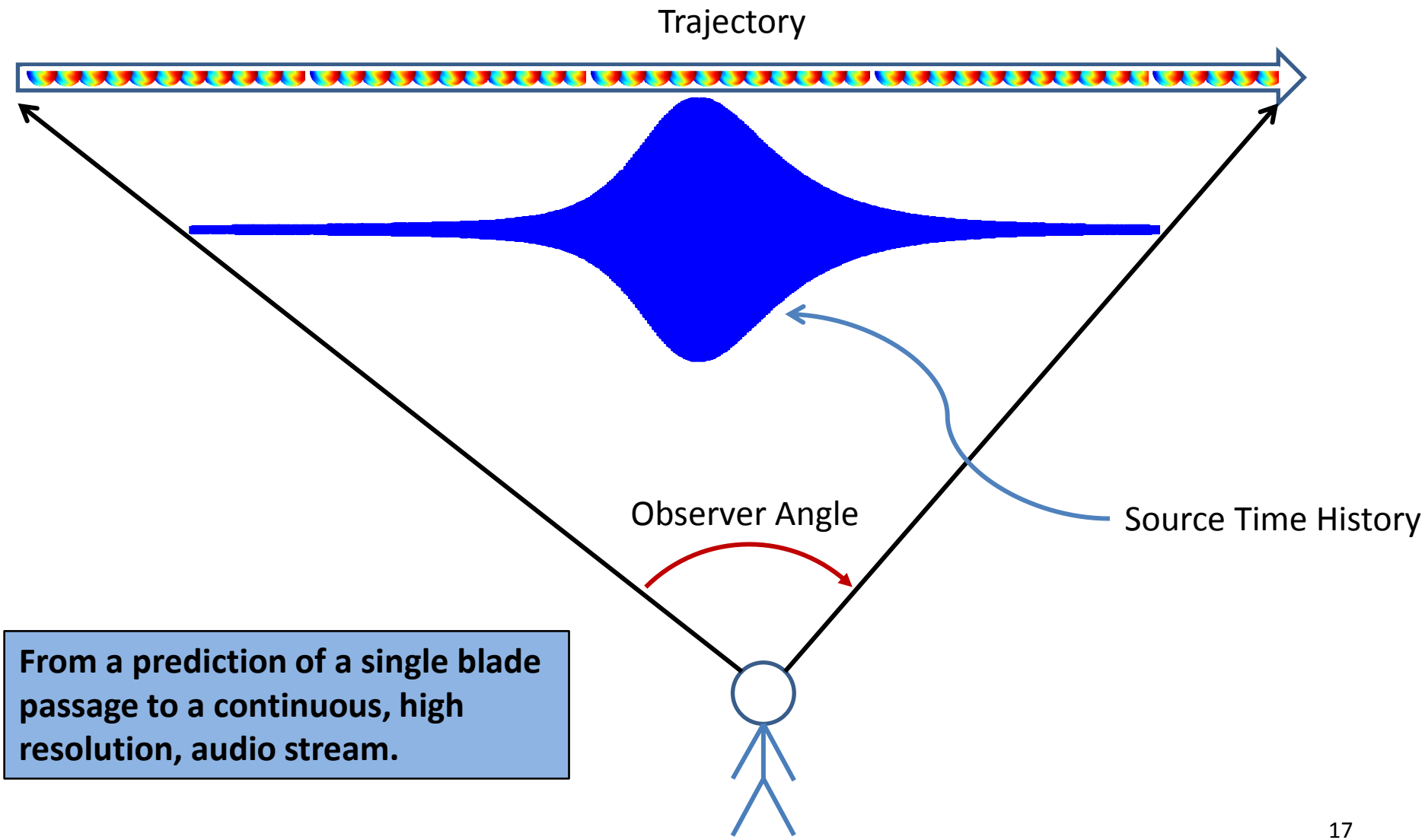


Propeller Source Noise Definition Process



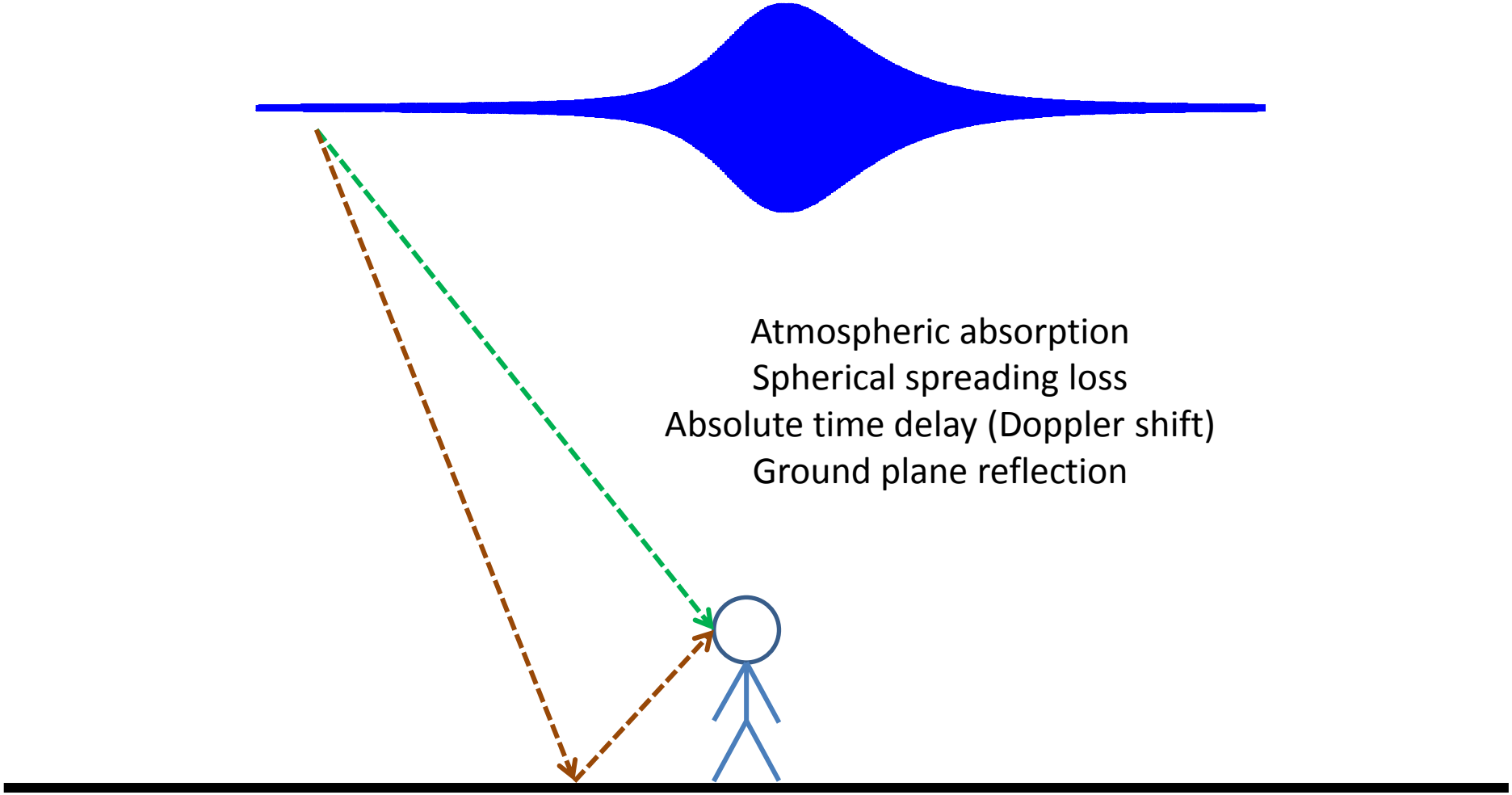
- Many steps from coarse prop geometry to sound pressure prediction.
- Each step now requires format translation and manual tracking of metadata.
- This sequence will be different for different sources, e.g., non-periodic broadband.

Synthesis



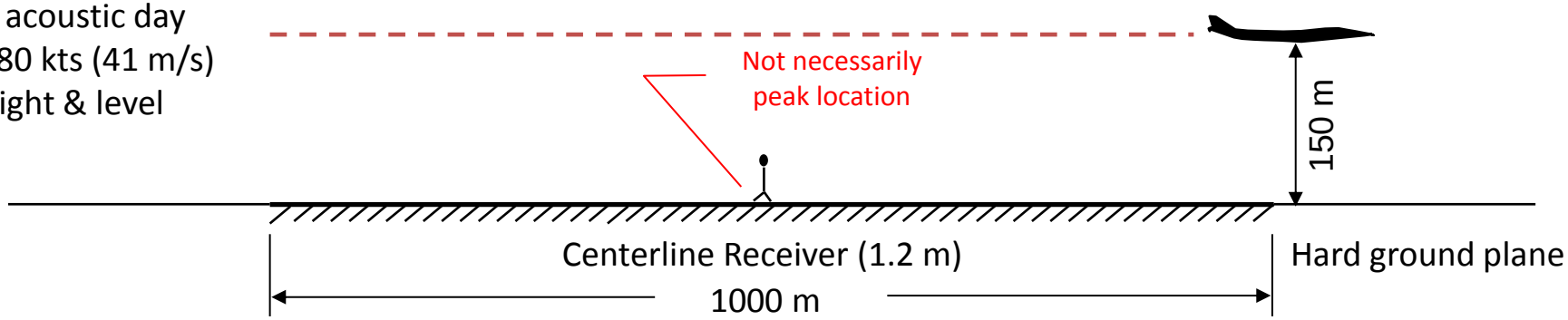
From a prediction of a single blade passage to a continuous, high resolution, audio stream.

Propagation



Auralization Results

Uniform atmosphere
Std. acoustic day
V = 80 kts (41 m/s)
Straight & level



Cases

Prop Type	# Props	# Blades	RPM	BPF (Hz)	Thrust (lbs)	Coherent/ Incoherent	Spread Spectrum* (Δf)	Min/Max BPF (Hz)
GA	1	3	2700	135	833	—	—	135
LEP	18	3	5866	293.3	47	Coherent	—	293.3
LEP	18	3	5866	293.3	47	Incoherent	10	208.3/378.3
LEP	18	3	5866	293.3	47	Incoherent	0.5	289.05/297.55

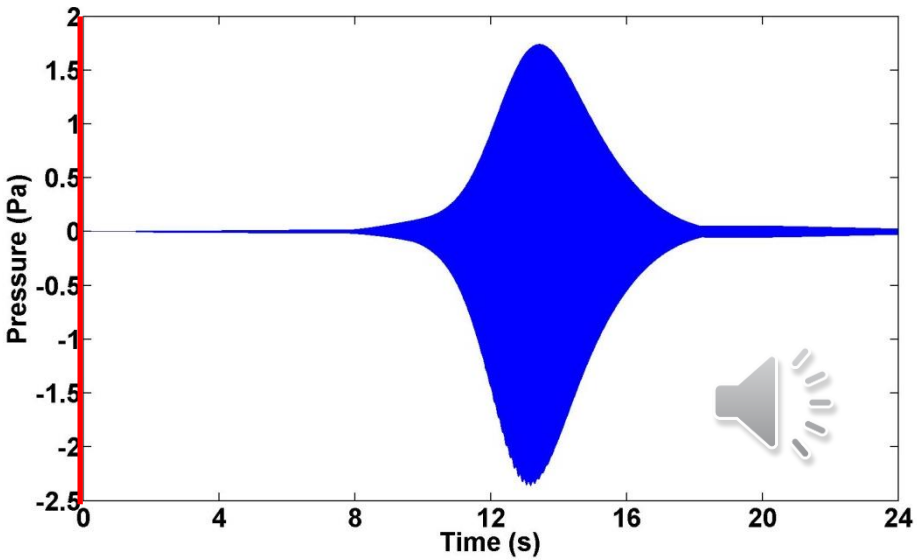
* Same source directivity used for all LEPs

General Aviation Prop

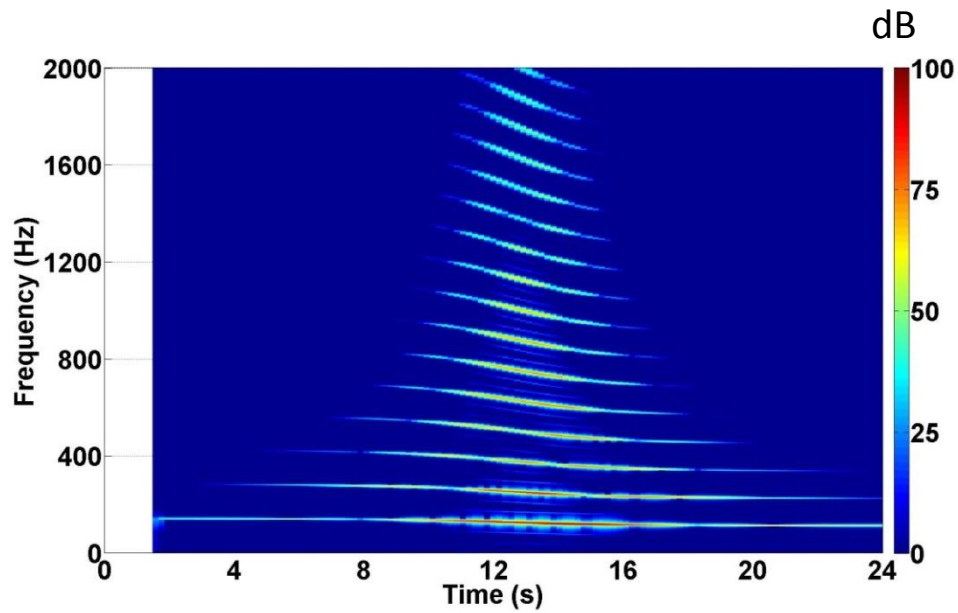
Average Power = 102.2 dB

Peak Level = 101.4 dB

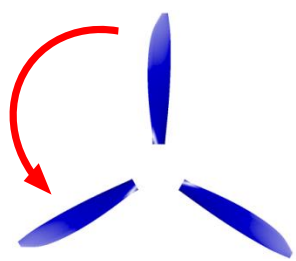
Time History



Spectrogram



135 Hz



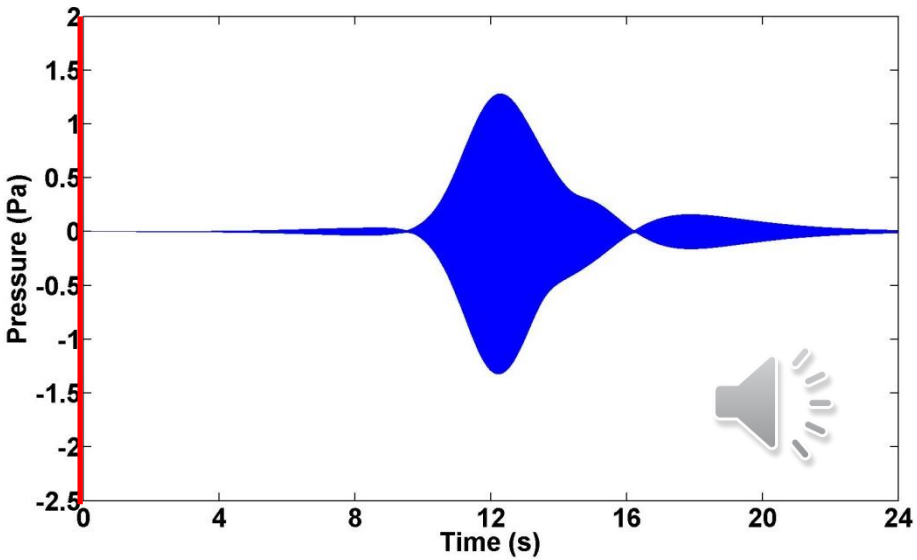
Maximum pressure on centerline

18 LE Props – Coherent DEP

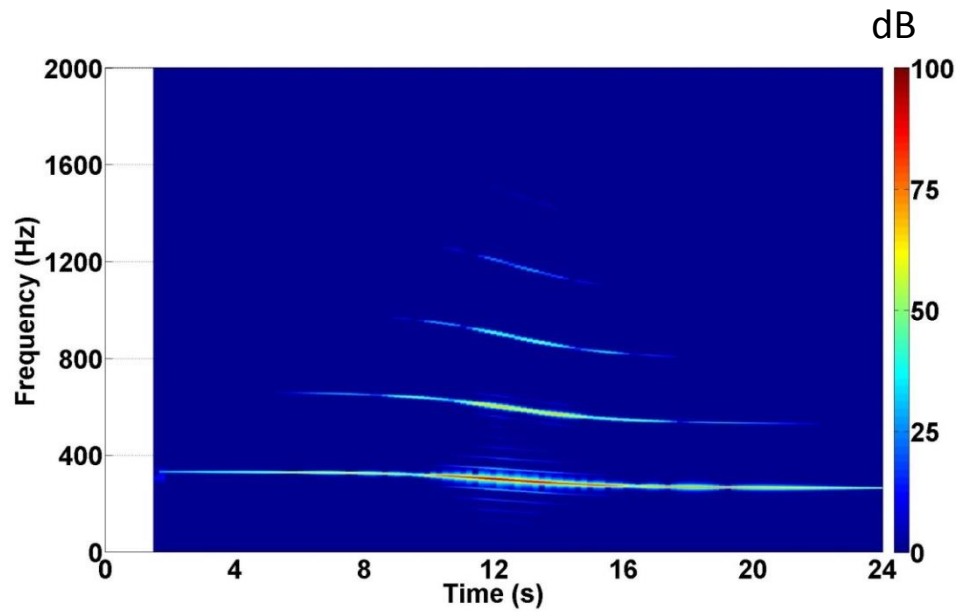
Average Power = 87.5 dB (-14.7 dB re: GA Prop)

Peak Level on Centerline= 96.4 dB (-5 dB re: GA Prop)

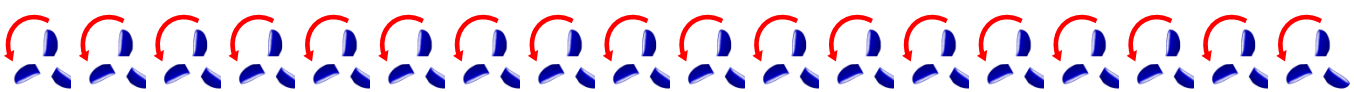
Time History



Spectrogram



All 293.3 Hz and in phase



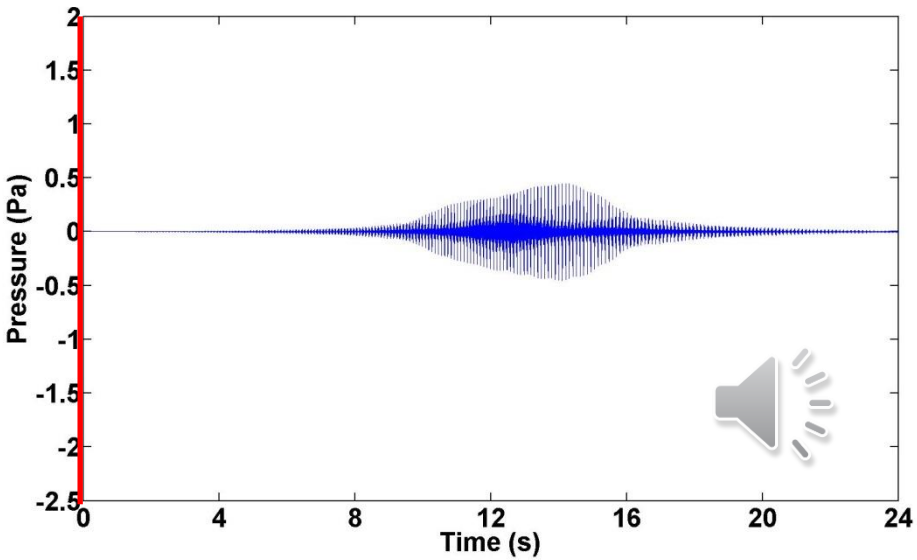
Maximum pressure on centerline

18 LE Props – Spread Spectrum DEP

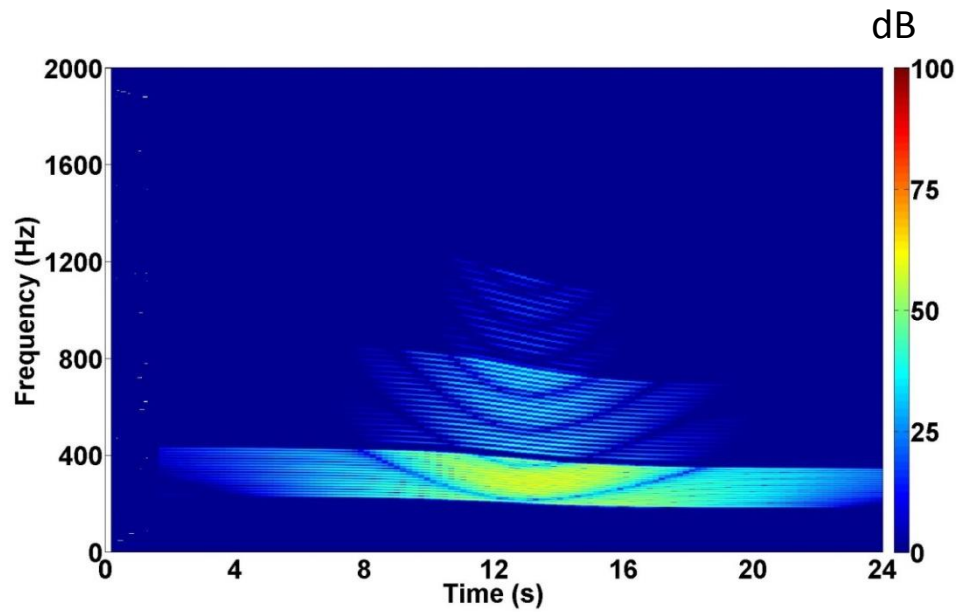
Average Power = 87.5 dB (-14.7 dB re: GA Prop)

Peak Level on Centerline= 90.1 dB (-11.3 dB re: GA Prop)

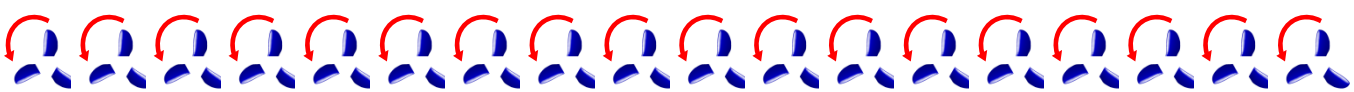
Time History



Spectrogram



Δf = 10 Hz



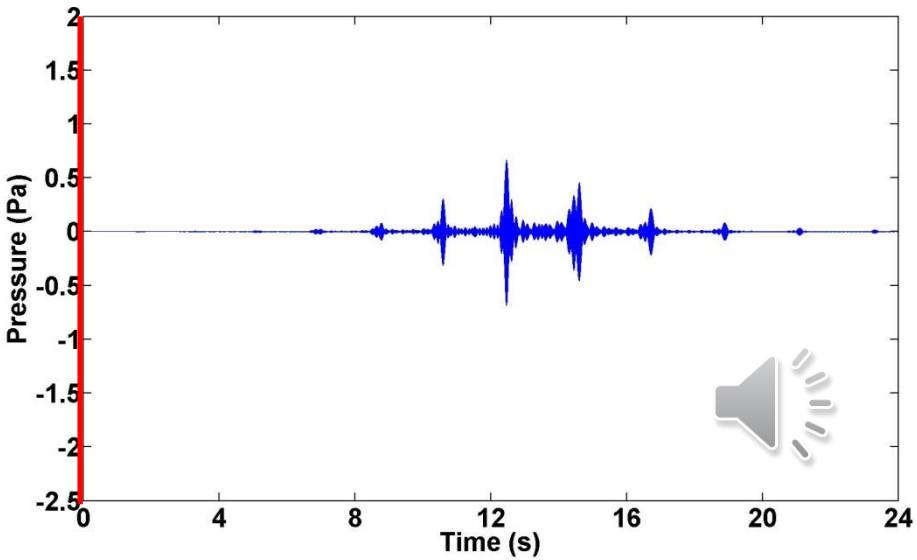
Maximum pressure not on centerline

18 LE Props – Spread Spectrum DEP

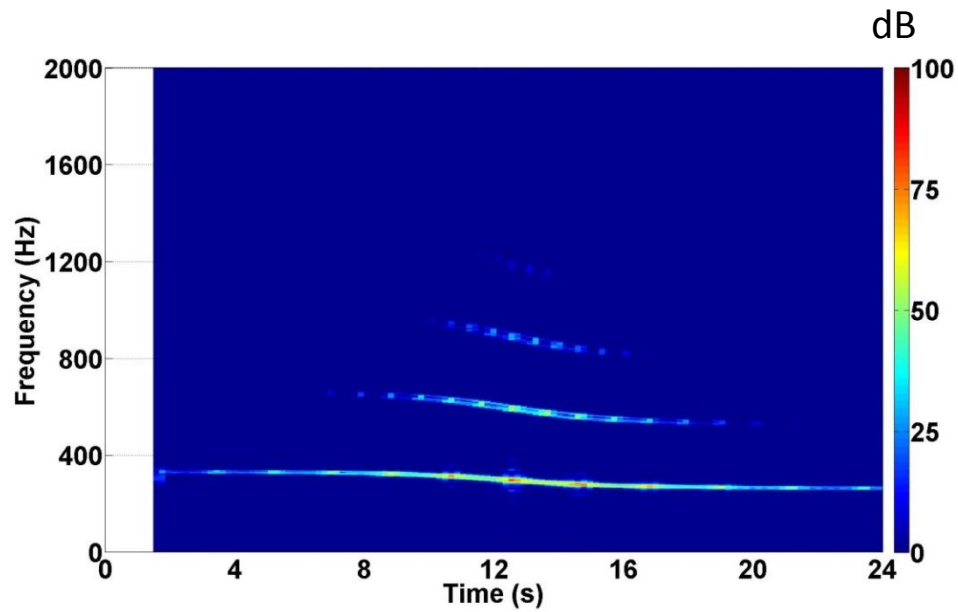
Average Power = 87.5 dB (-14.7 dB re: GA Prop)

Peak Level on Centerline = 90.7 dB (-10.7 dB re: GA Prop)

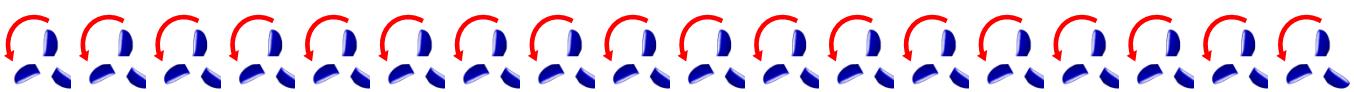
Time History



Spectrogram



Δf = 0.5 Hz



Maximum pressure not on centerline

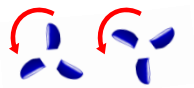
What Wasn't Modeled… Lots!

(We are just beginning)

- Wing tip props
- Interaction effects (hydrodynamics)
  - Prop-to-prop
  - Prop-to-structure
- Unsteady blade loading
  - For example, blade angle of attack
- Broadband propeller noise
- Motor Noise

Future Work

- Other DEP configurations
  - Spread phase (coherent)



  - Counter-rotating props (coherent or incoherent)

- Modeling
  - Improve source noise model fidelity
  - Continue development of auralization framework & Quick Look
  - Validate modeling

- Integration
  - How tightly can we control the motors?

- Perceptual testing
  - What is an appropriate annoyance metric?