

# Aural Effects of Distributed Propulsion

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Enabling New Flight Concepts through Novel Propulsion and Energy Architectures

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# Motivation

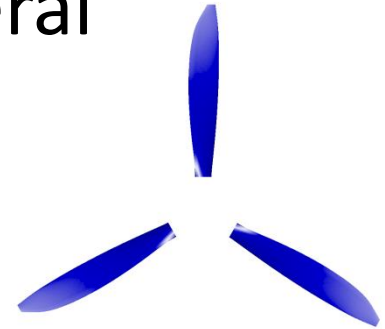
- Large potential noise reduction with Distributed Electric Propulsion (DEP) aircraft
- Use human perception of noise to influence early design process
  - Determine suitable metrics which correlate well with annoyance and/or detection for this unique noise source

# 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

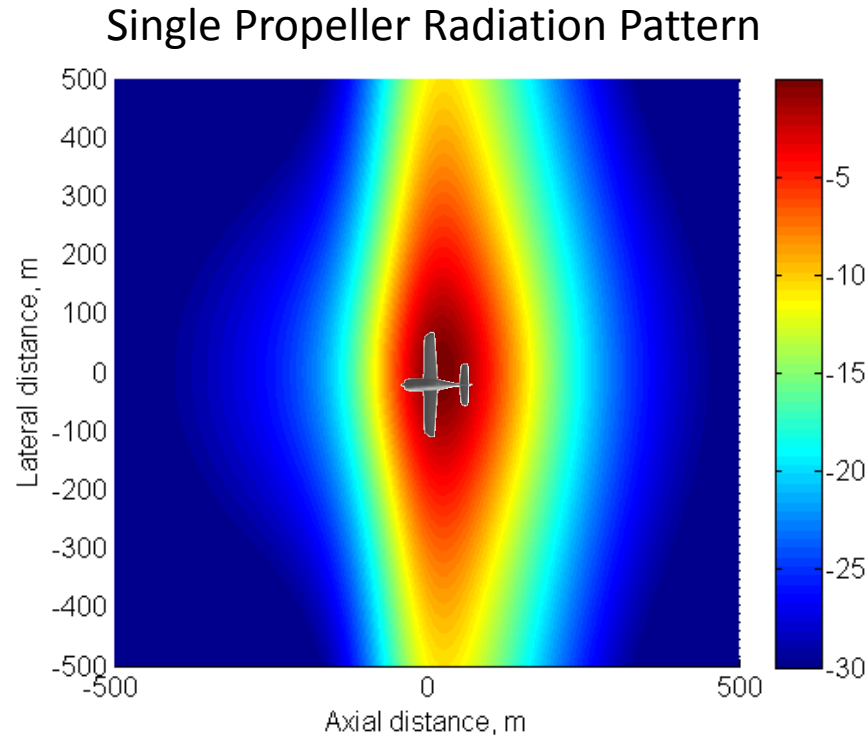
# Quick Look Test Cases

- 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         |

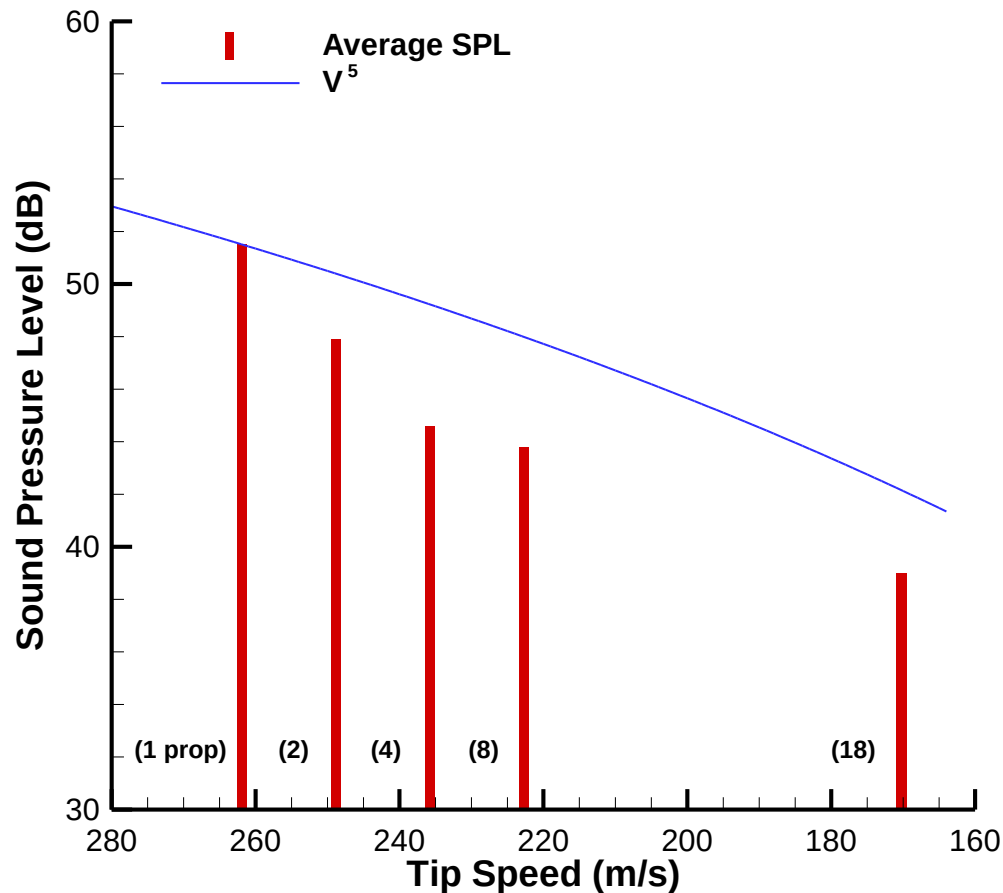
# Context of Analysis



- 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)<br>(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.

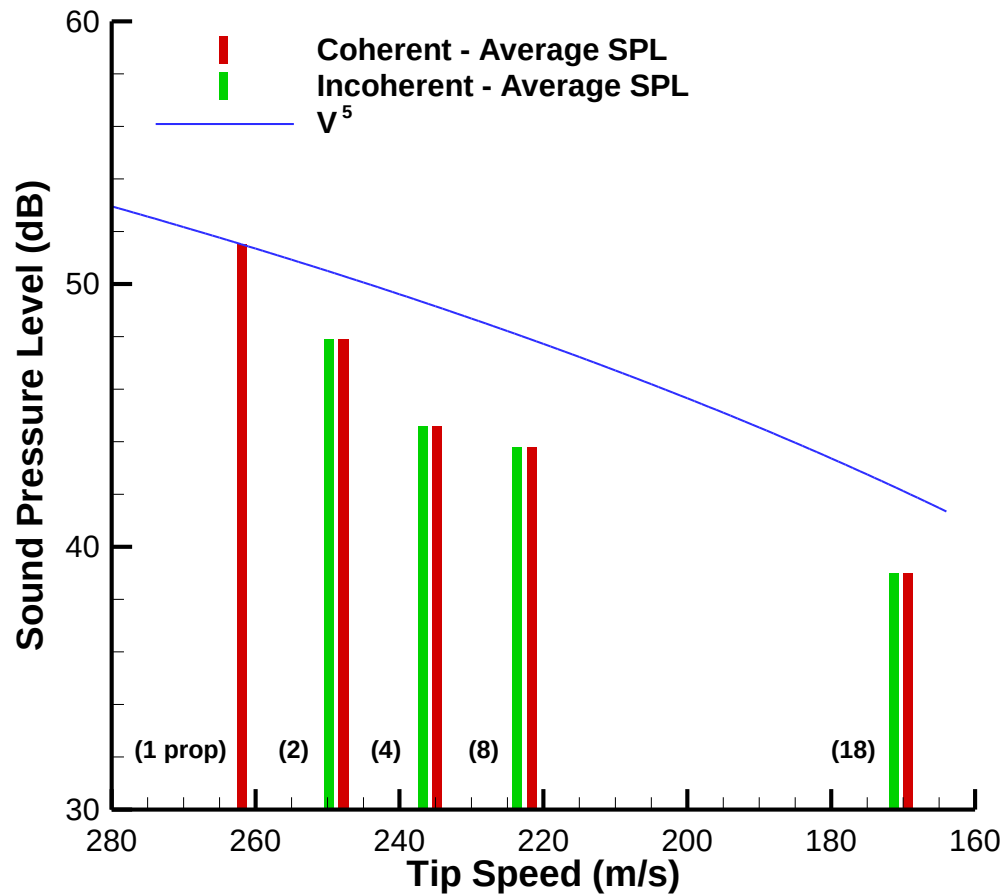
- Say we have two noise sources  $S_1$  and  $S_2$  emitting sound.
- At some point, the sound pressure from the sources is A and B respectively.
- The total sound power at this point is

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

Only coherent sources will include cross terms

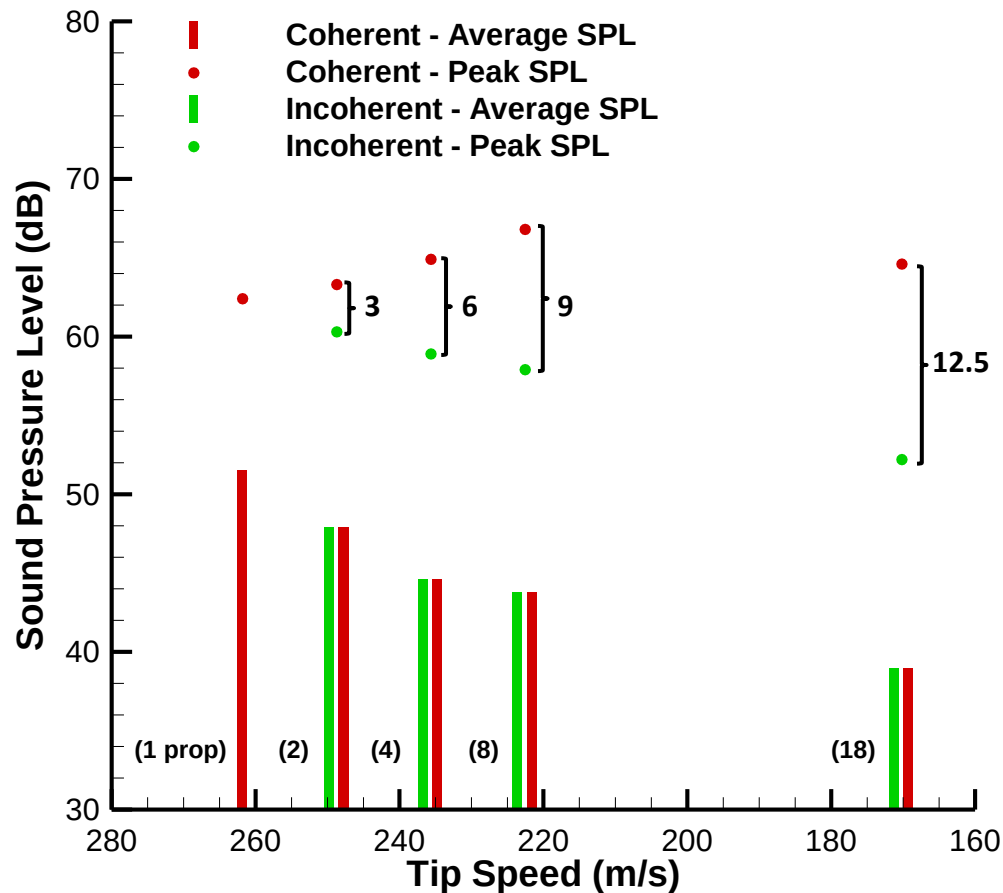
- If  $A=B=1$  and A and B are coherent, the total power would be 4, a 6 dB increase
  - Coherent power increases as  $10\log_{10}(N^2)$ .
- If A is not coherent with B, the total power will be 2, a 3 dB increase.
  - Incoherent power increases as  $10\log_{10}(N)$ .
- Ideally, the peak noise power reduction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

# Effect of Spread Spectrum



Spread spectrum has no effect on average SPL

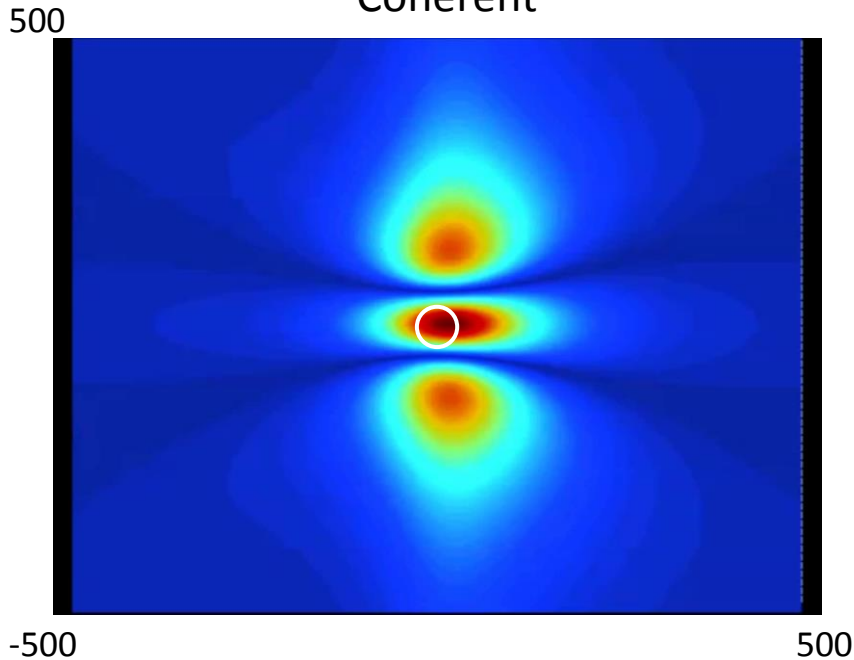
# Effect of Spread Spectrum



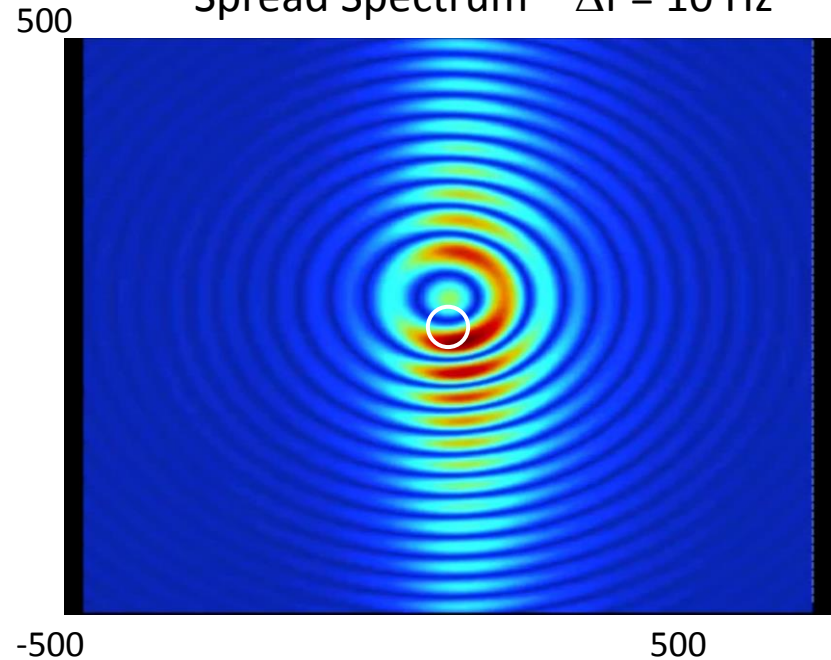
- Spread spectrum has theoretical peak SPL reduction of  $-10\log_{10}(N)$
- Average SPL reduction due to tip speed does not add to peak SPL reduction due to spread spectrum

# 2 Sources – Quick Look

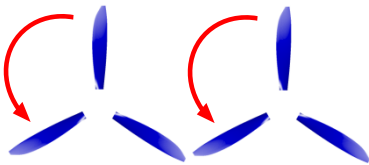
Coherent



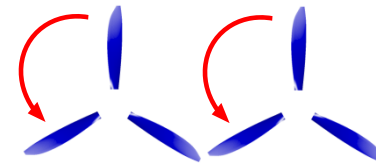
Spread Spectrum –  $\Delta f = 10$  Hz



Both at 125 Hz and in phase



120 Hz      130 Hz

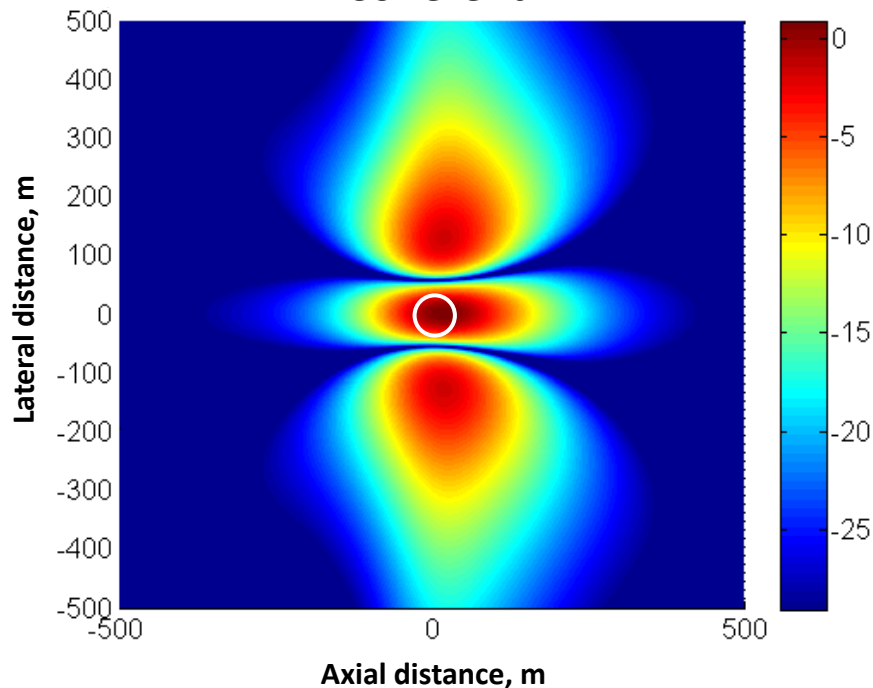


Stationary source, pure tone, altitude=150 m

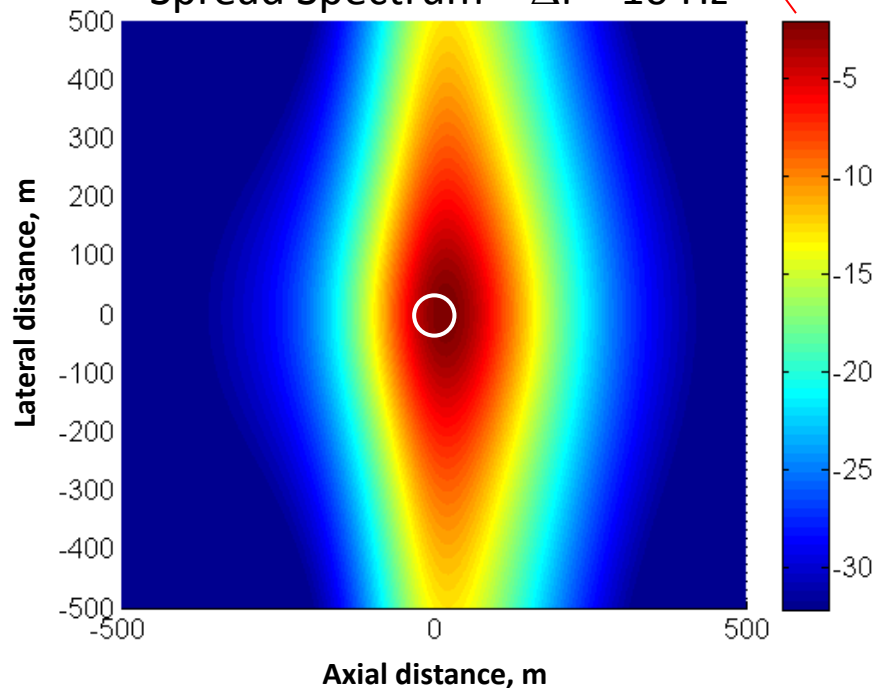
# Time Averaged Radiation Patterns from Quick Look – 2 Sources

Peak power  
down 3dB

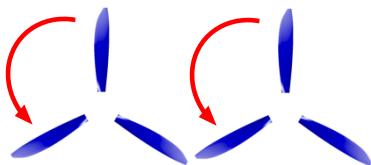
Coherent



Spread Spectrum –  $\Delta f = 10$  Hz

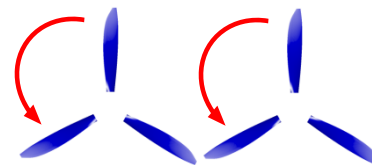


Both at 125 Hz and in phase



Same average  
radiated power

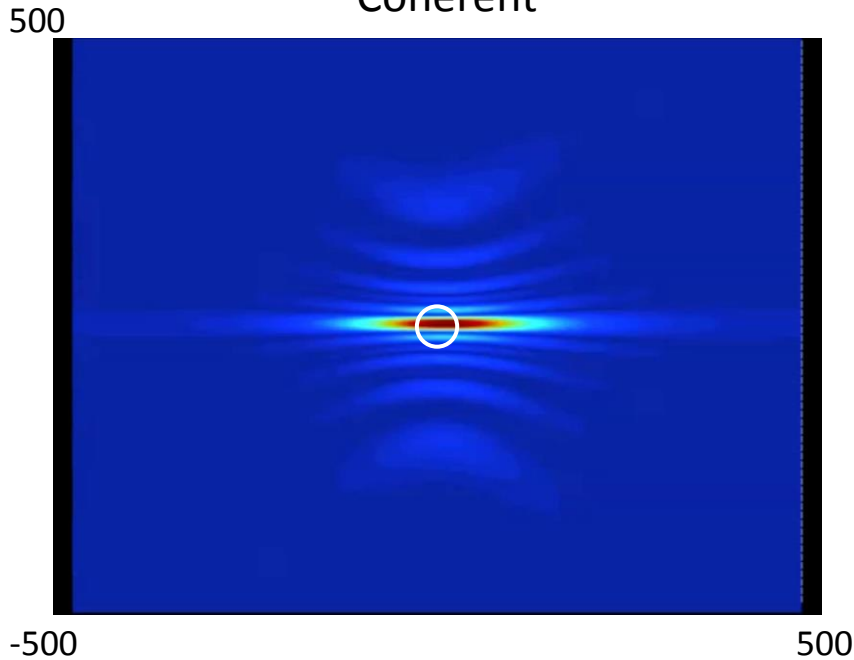
120 Hz      130 Hz



Stationary source, pure tone, altitude=150 m

# 18 sources – Quick Look

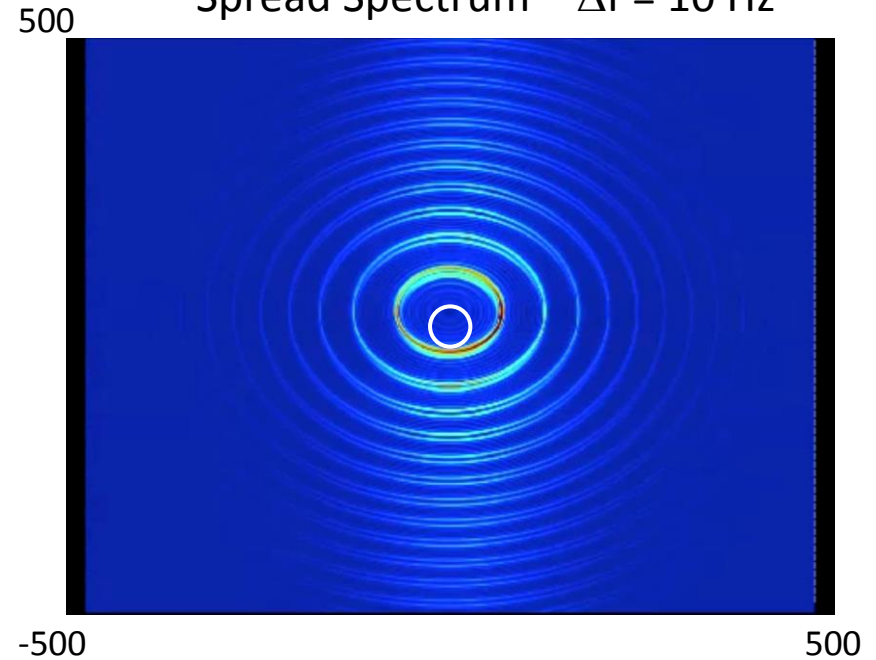
Coherent



All at 325 Hz and in phase



Spread Spectrum –  $\Delta f = 10$  Hz



240  
Hz

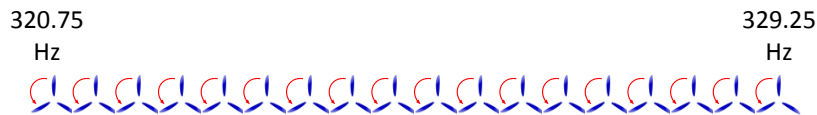
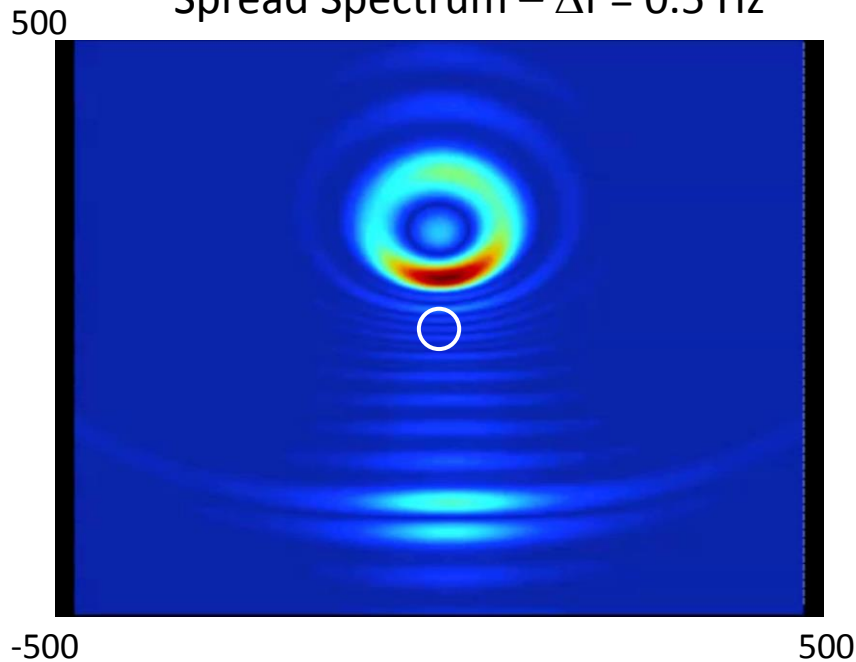


410  
Hz

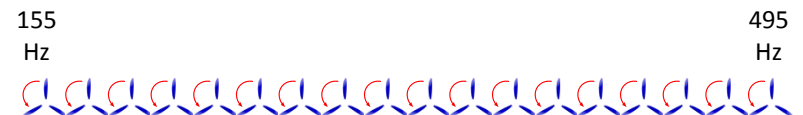
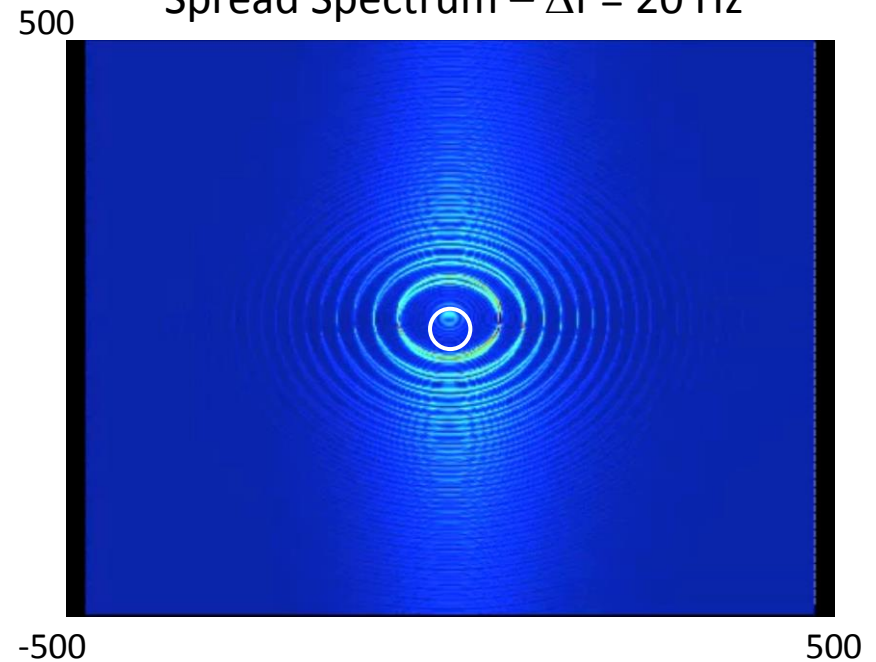
Stationary source, pure tone, altitude=150 m

# 18 Sources – Quick Look

Spread Spectrum –  $\Delta f = 0.5$  Hz



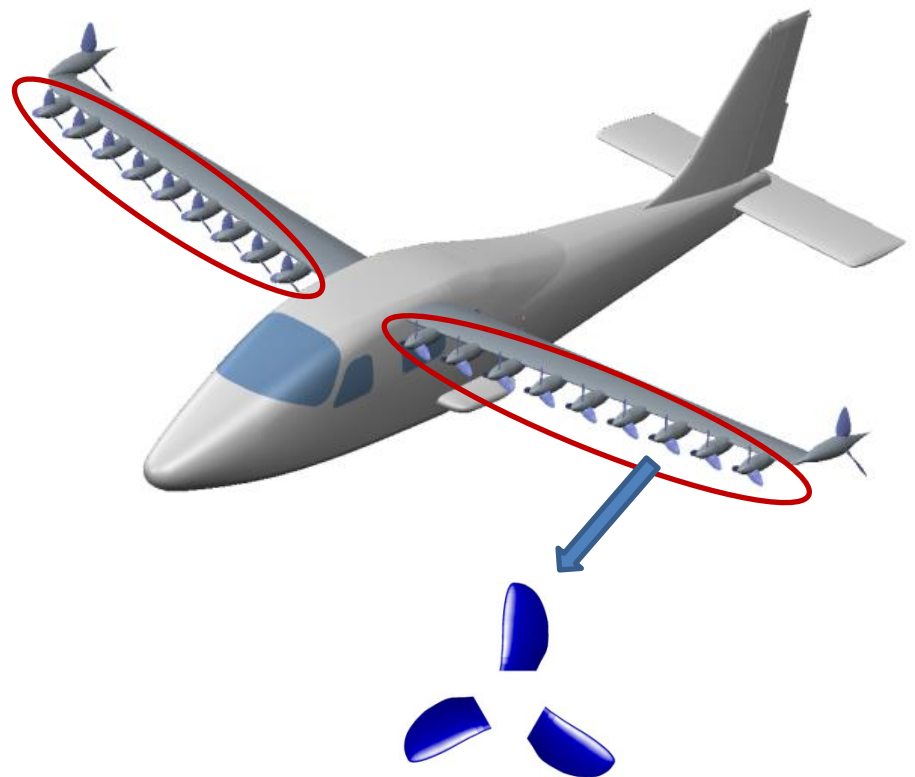
Spread Spectrum –  $\Delta f = 20$  Hz



Stationary source, pure tone, altitude=150 m

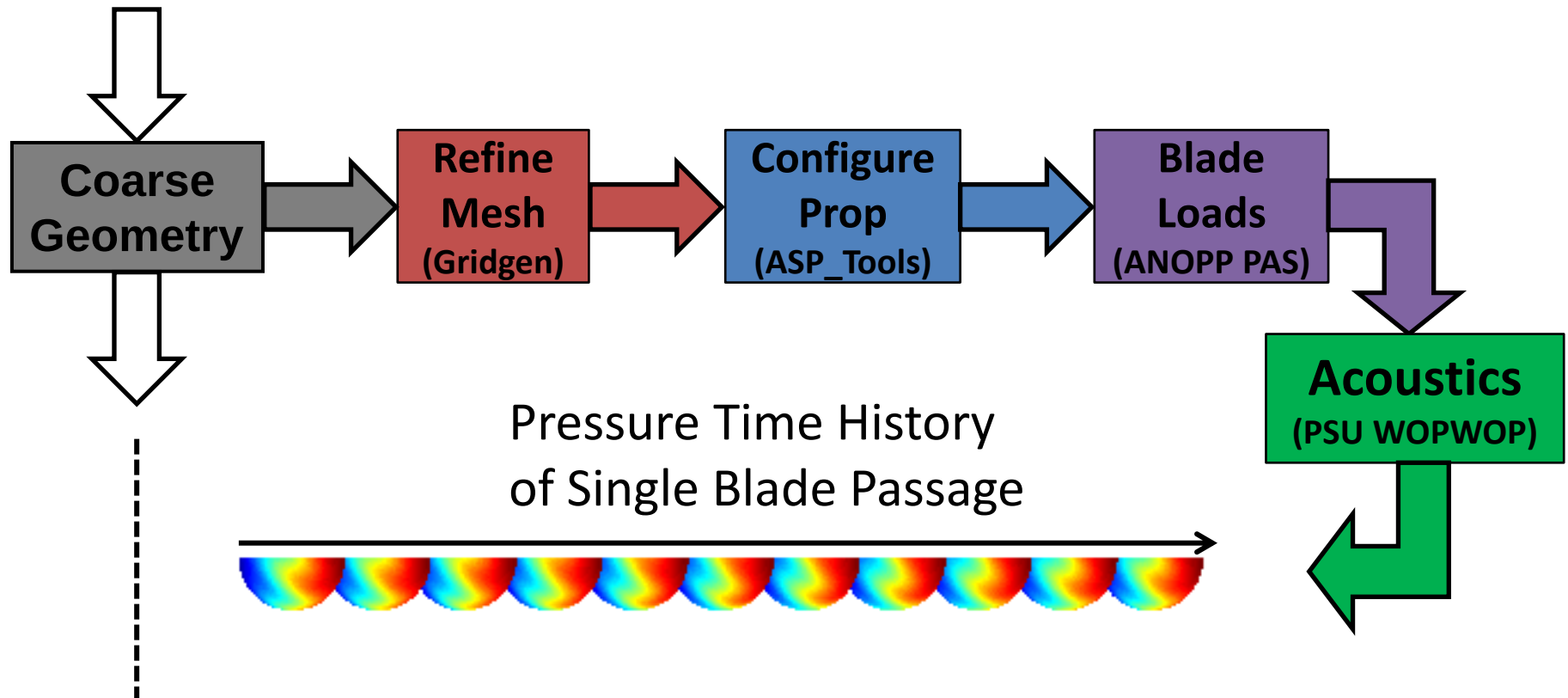
# Auralization of DEP Configuration

- 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



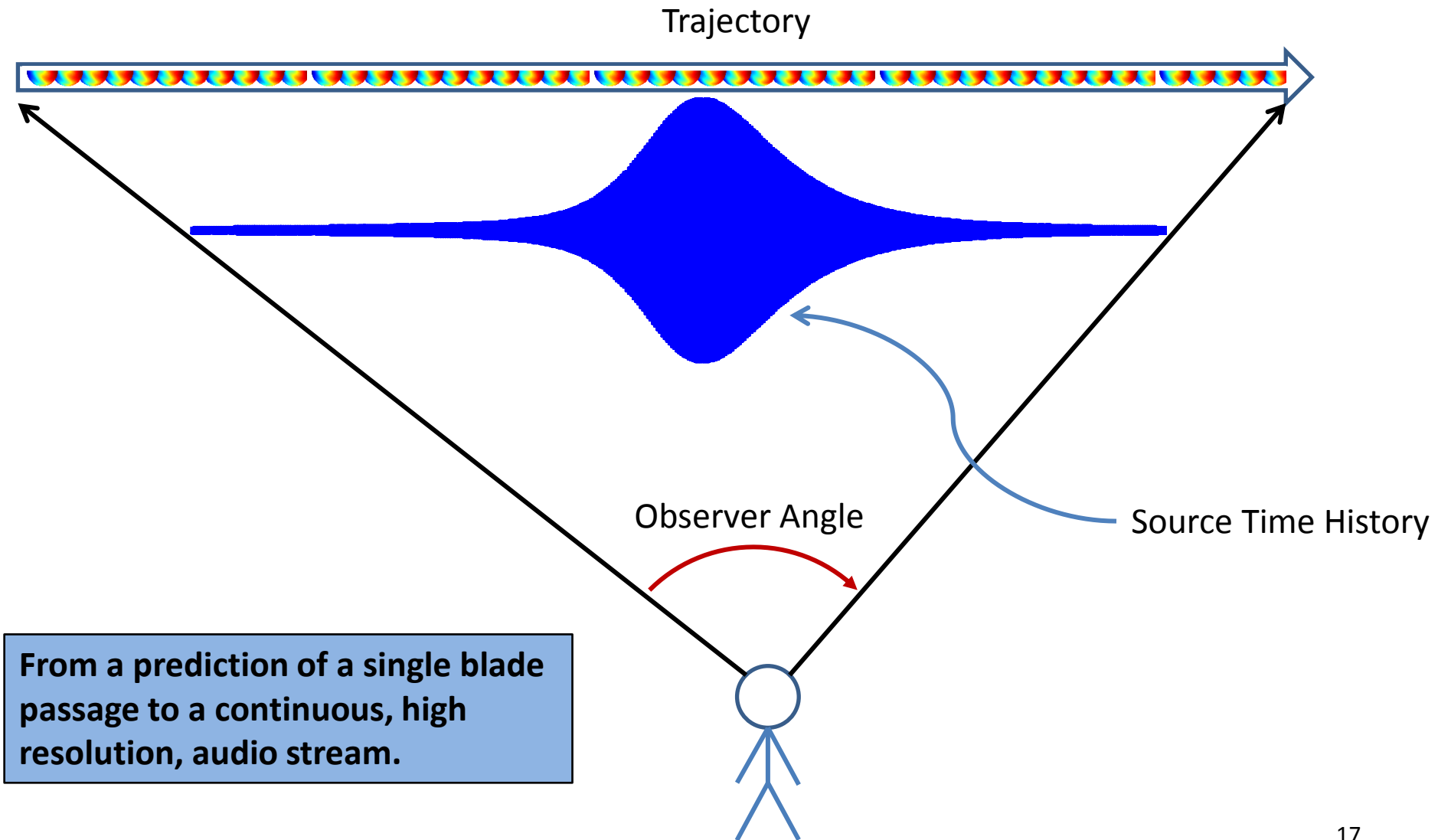
# Propeller Source Noise Definition Process

## Design Loop

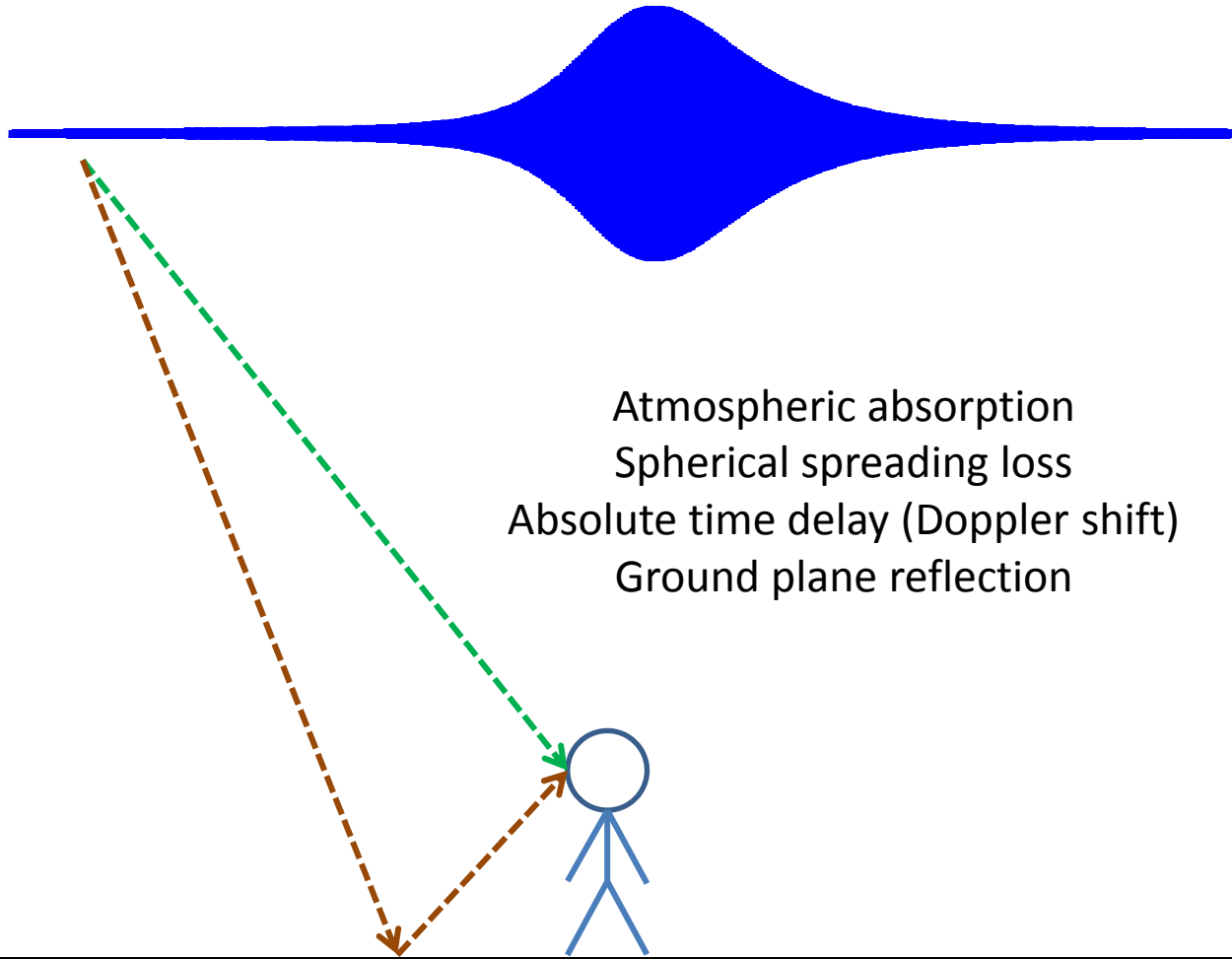


- Many steps from coarse prop geometry to sound pressure prediction.
- Each step now requires format translation and manual tracking of metadata.
- This sequence will be different for different sources, e.g., non-periodic broadband. <sup>16</sup>

# Synthesis

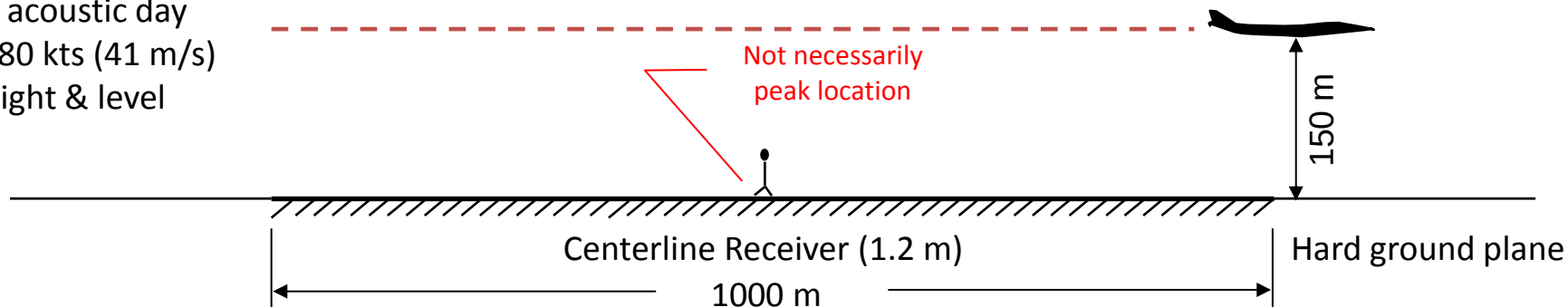


# Propagation



# 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* ( $\Delta f$ ) | 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    |

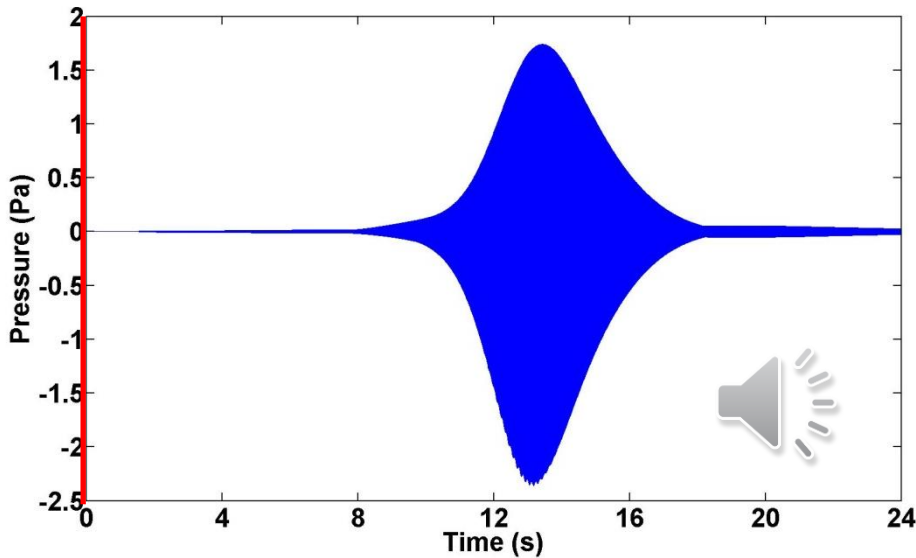
\* Same source directivity used for all LEPs

# General Aviation Prop

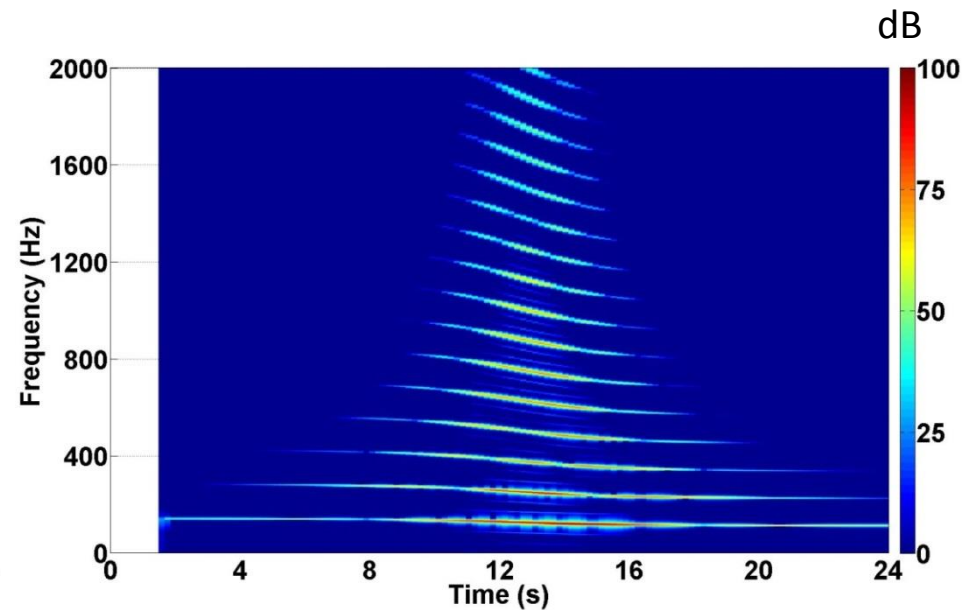
Average Source Power = 101.8 dB

Peak Level at Centerline Receiver = 101.4 dB

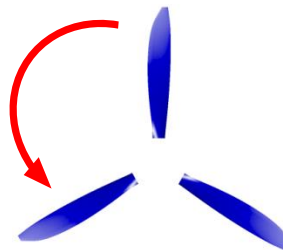
Time History



Spectrogram



135 Hz



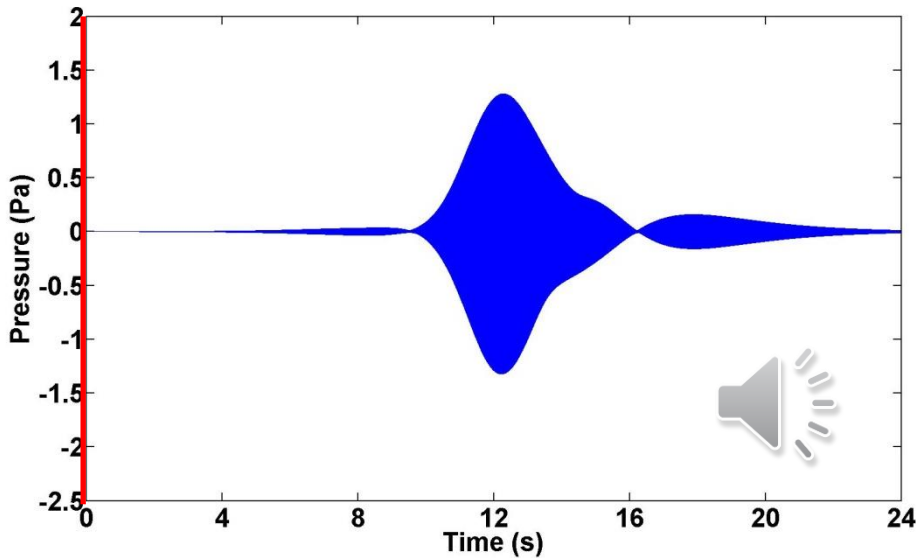
Maximum pressure on centerline

# 18 LE Props – Coherent DEP

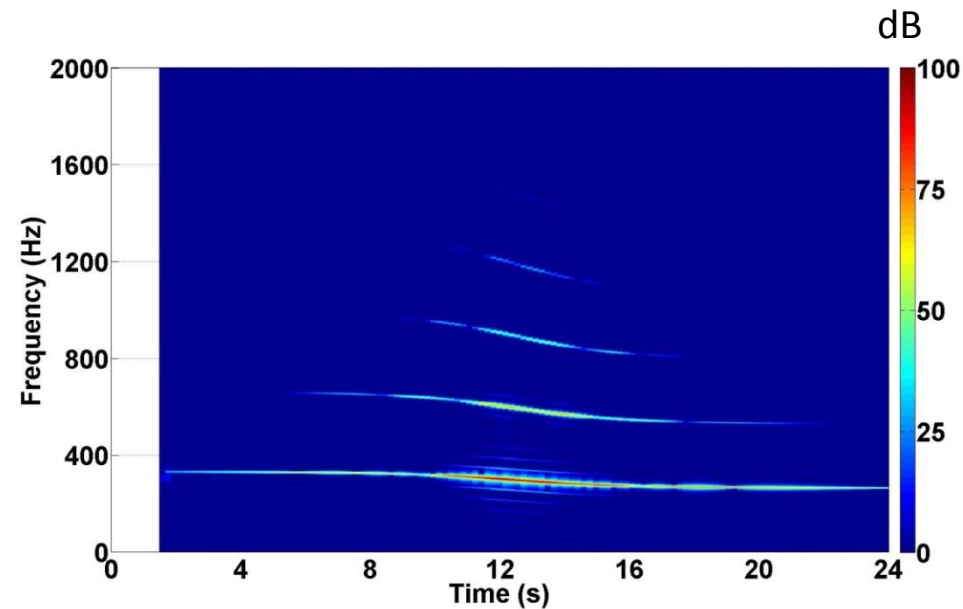
Average Source Power = 89.0 dB (-12.8 dB re: GA Prop)

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

Time History



Spectrogram



All 293.3 Hz and in phase



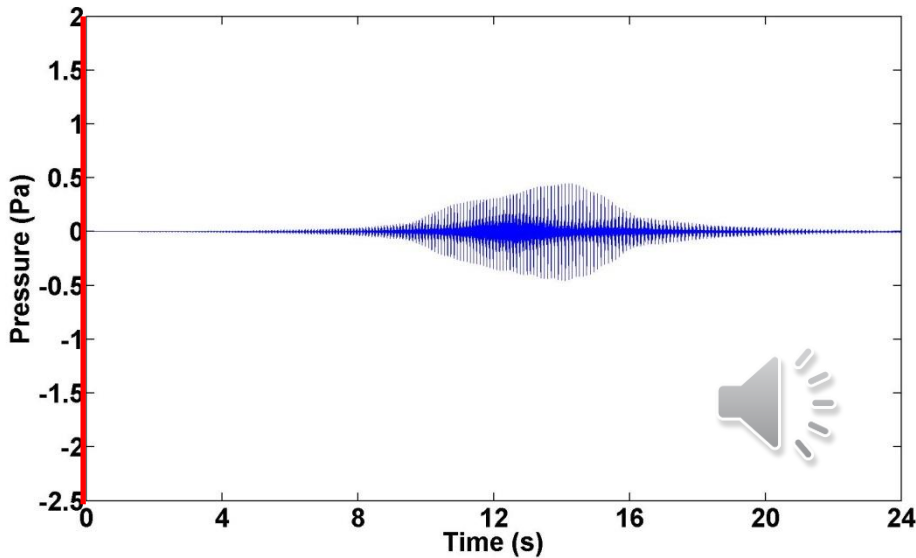
Maximum pressure on centerline

# 18 LE Props – Spread Spectrum DEP

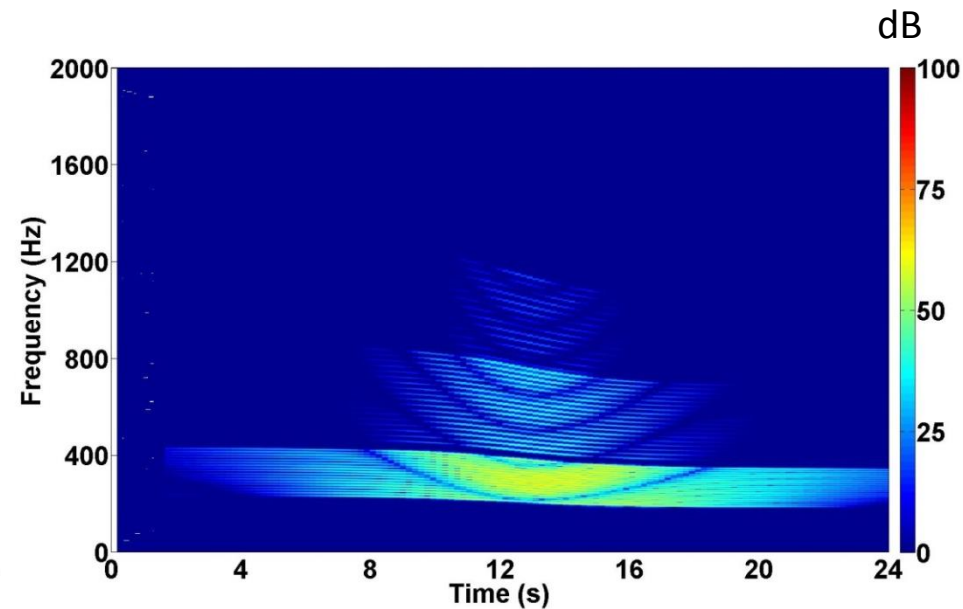
Average Source Power = 89.0 dB (-12.8 dB re: GA Prop)

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

Time History



Spectrogram



$\Delta f = 10 \text{ Hz}$



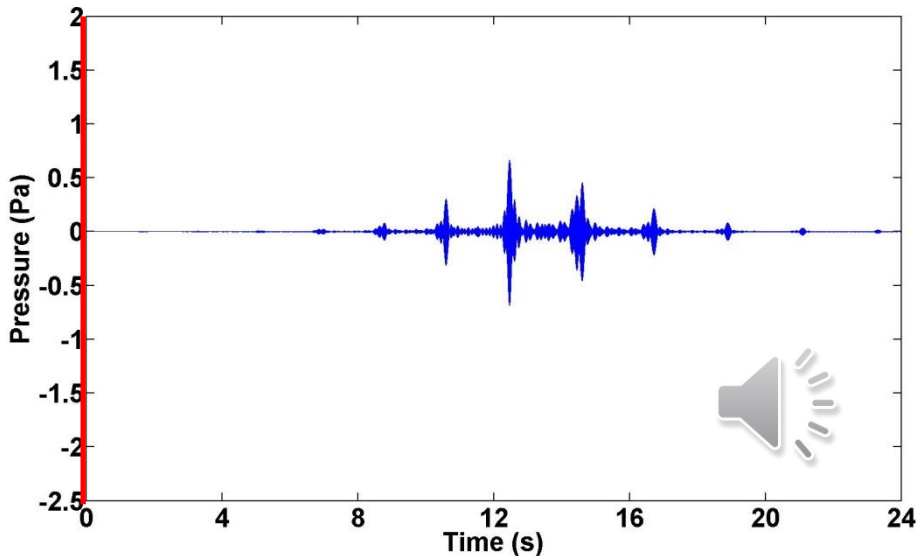
Maximum pressure not on centerline

# 18 LE Props – Spread Spectrum DEP

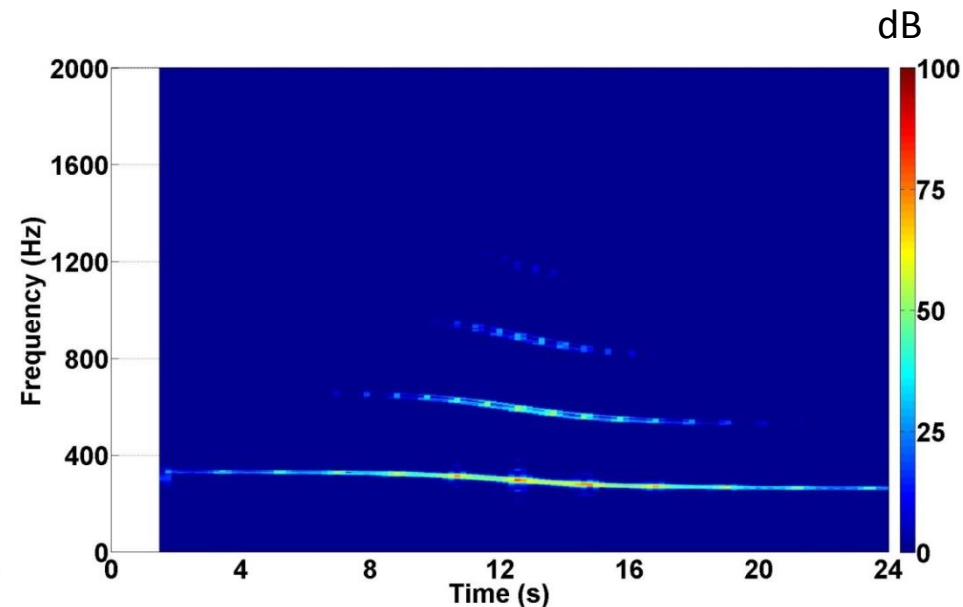
Average Source Power = 89.0 dB (-12.8 dB re: GA Prop)

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

Time History



Spectrogram



$\Delta f = 0.5 \text{ Hz}$



Maximum pressure not on centerline

# What Wasn't Modeled... Lots!

(We are just beginning)

- Wing tip props
- Interaction/installation effects
  - 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?