Measuring flow speed in a long-wavelength acoustic flowmeter

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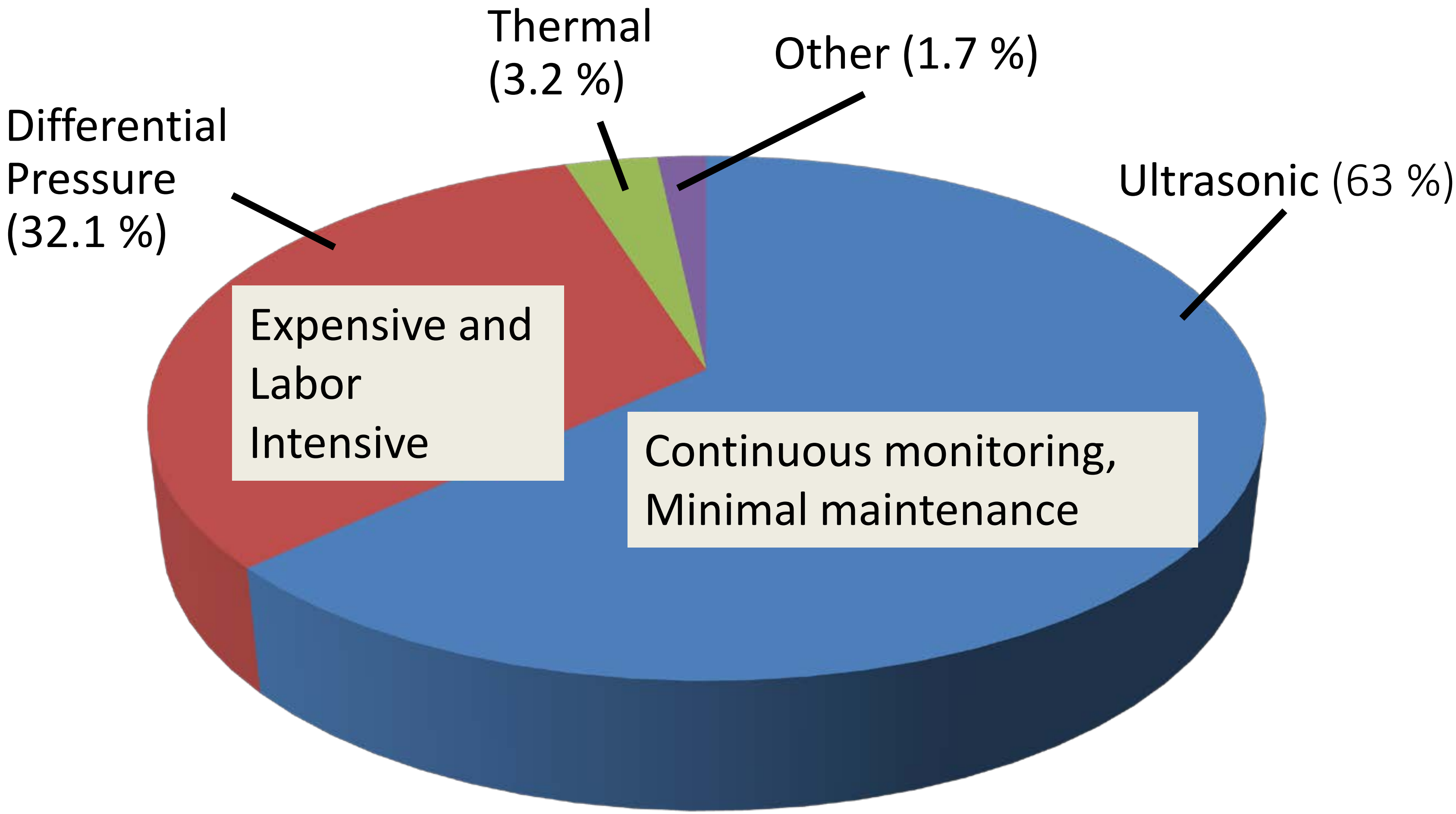
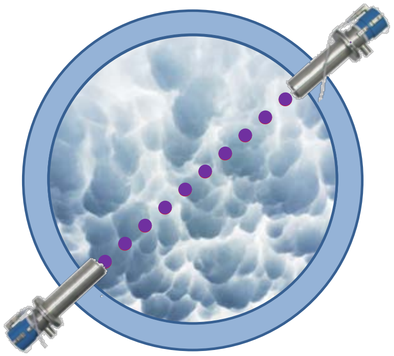
Technologies for monitoring flow



Ultrasonic meters sample a small portion of the flow field



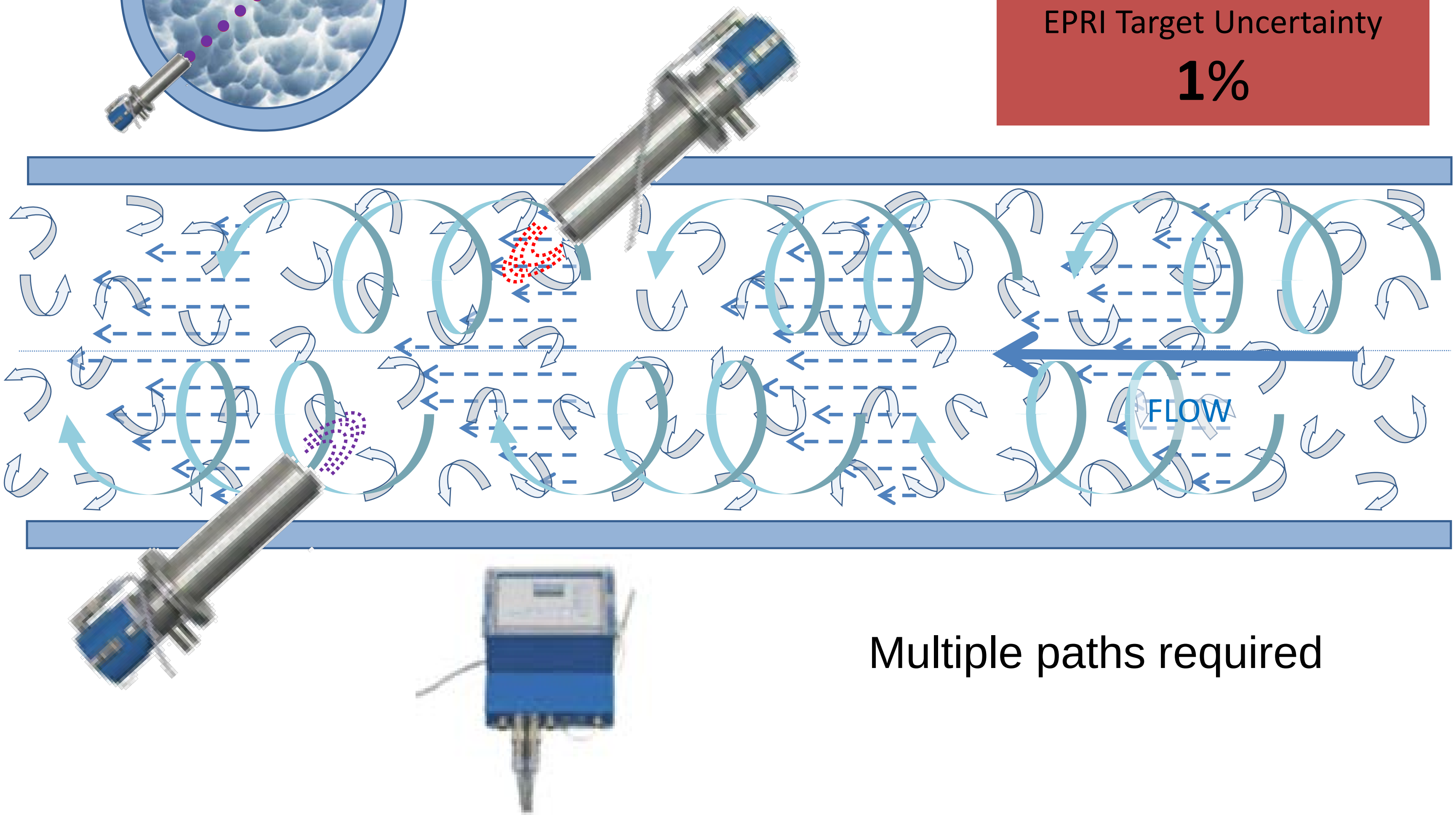
Estimated Uncertainty

5-20%

EPRI Target Uncertainty

1%

Open
End

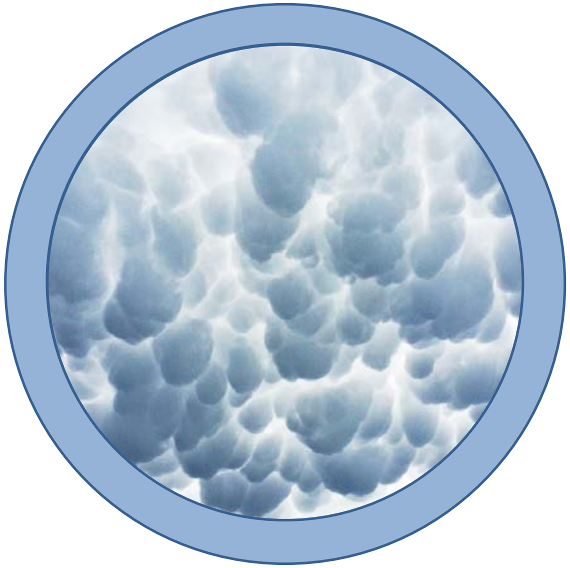


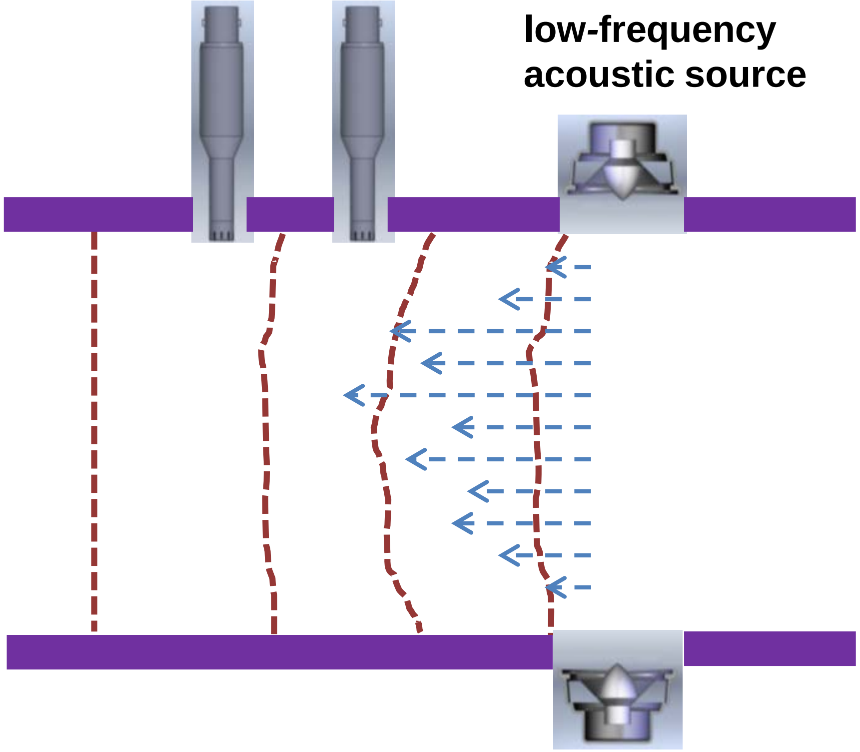
Multiple paths required

A long wavelength acoustic flowmeter (LWAF) measures flow with low frequency sound.

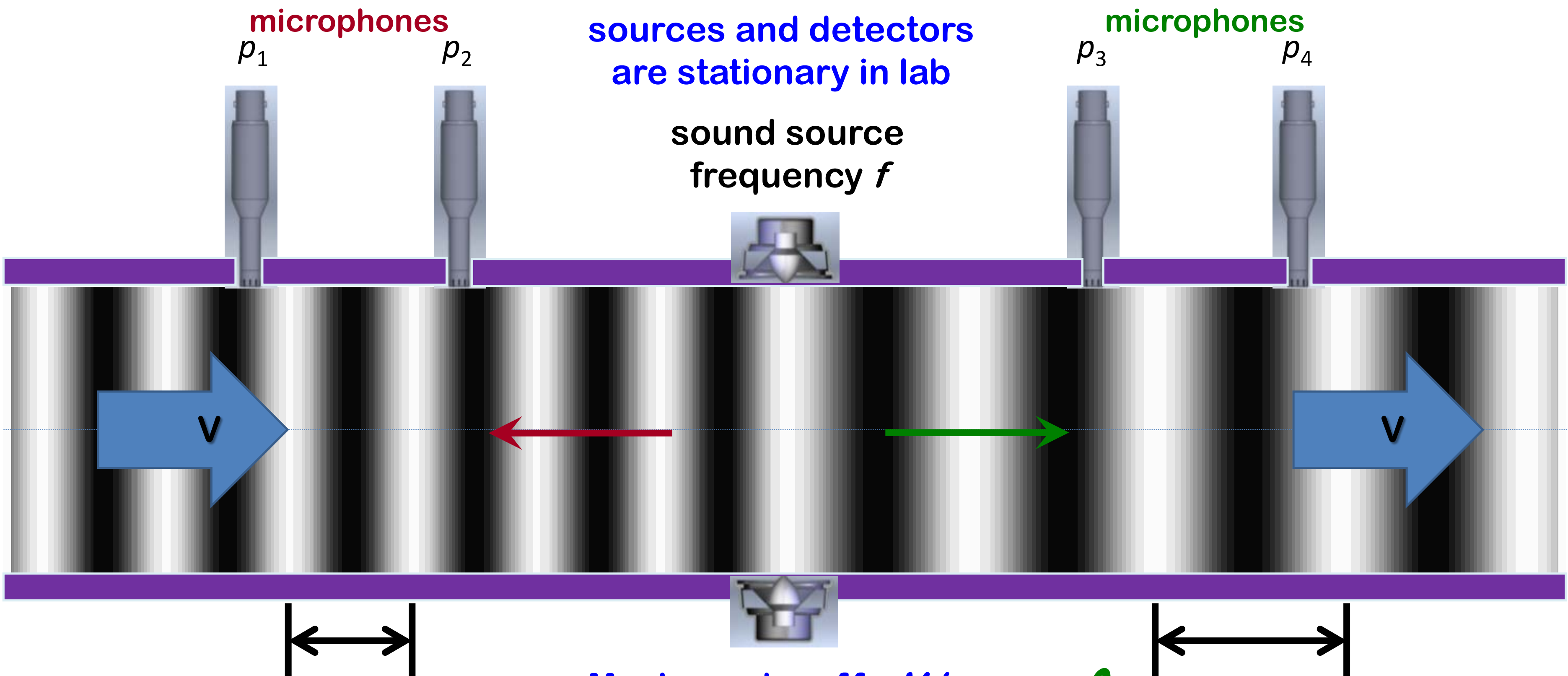
Plane wave propagation if $\lambda > 1.7 \times$ diameter

Plane wave averages over cross-section





Sound propagation in flow



$\lambda_{\text{left}} = (c - V)/f$

Mach number $M = V/c$

λ = wavelength

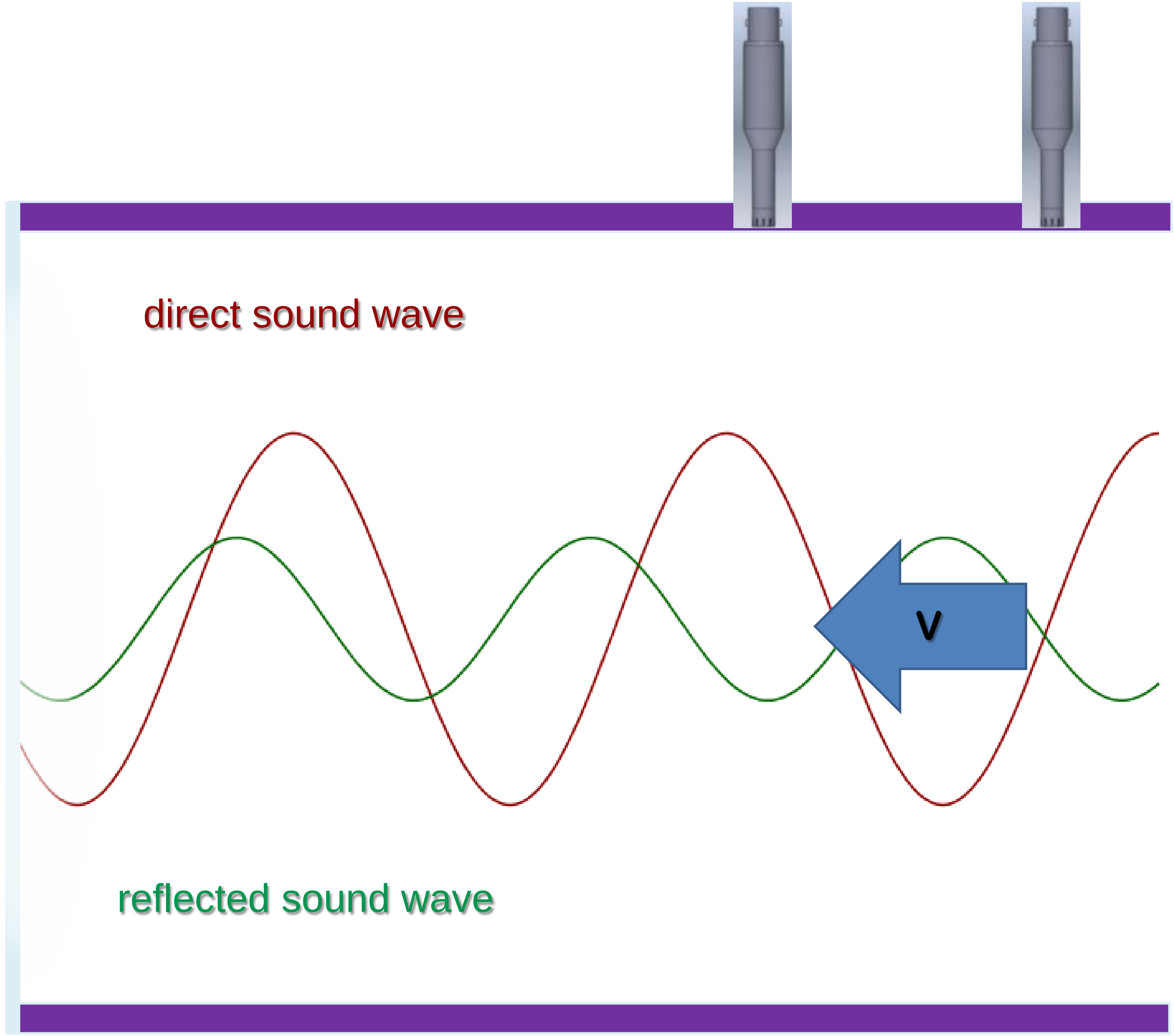
$\lambda_{\text{right}} = (c + V)/f$

$\lambda_{\text{left}} = (1 - M)\,\lambda_0 < \lambda_{\text{right}} = (1 + M)\,\lambda_0$

$$c = \tfrac{1}{2}\left(\lambda_{\text{right}} + \lambda_{\text{left}}\right) f \quad \text{and} \quad V = \tfrac{1}{2}\left(\lambda_{\text{right}} - \lambda_{\text{left}}\right) f$$

Partial standing waves in a duct with flow

$k_0 L = 18.2, \qquad M = 0.1$



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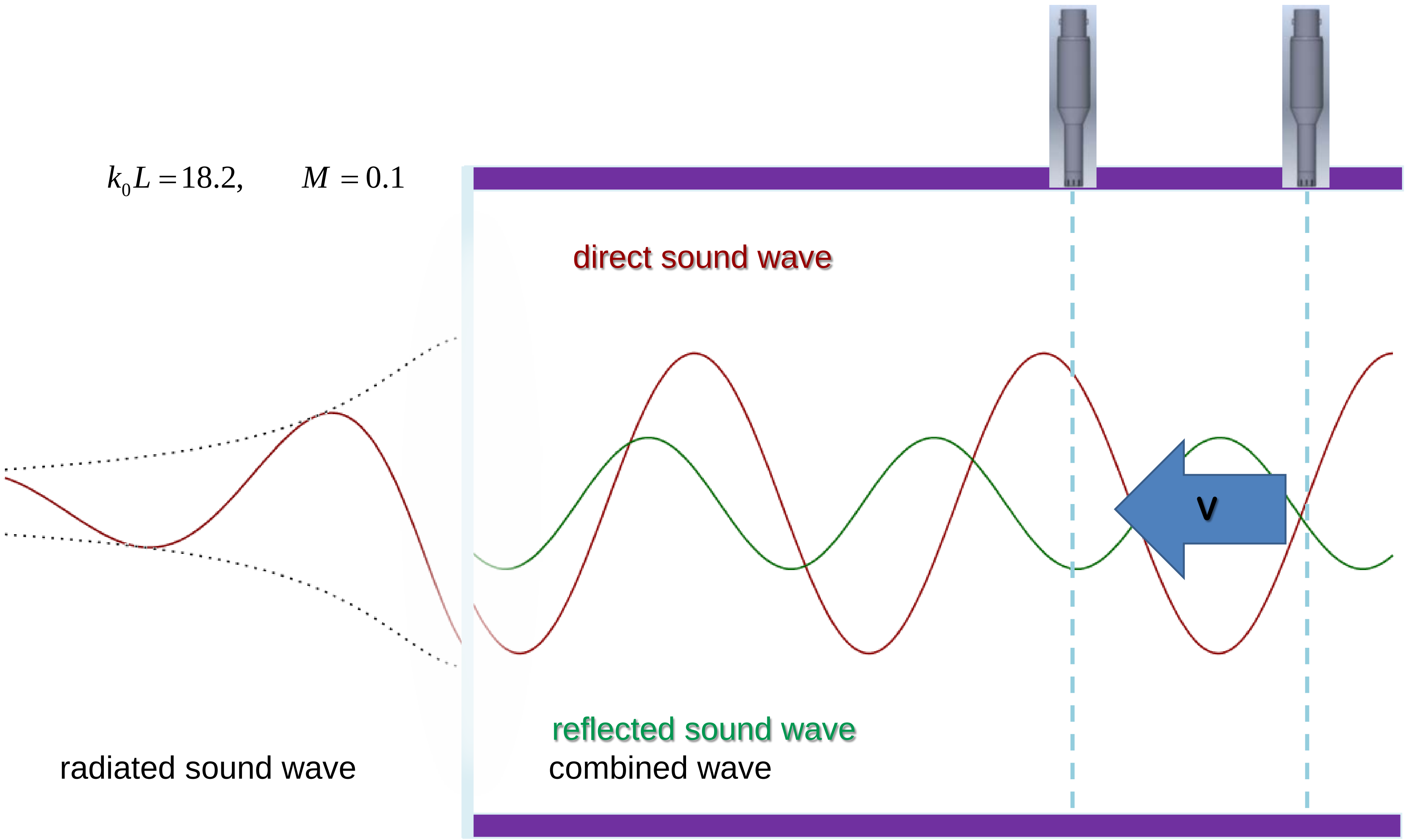
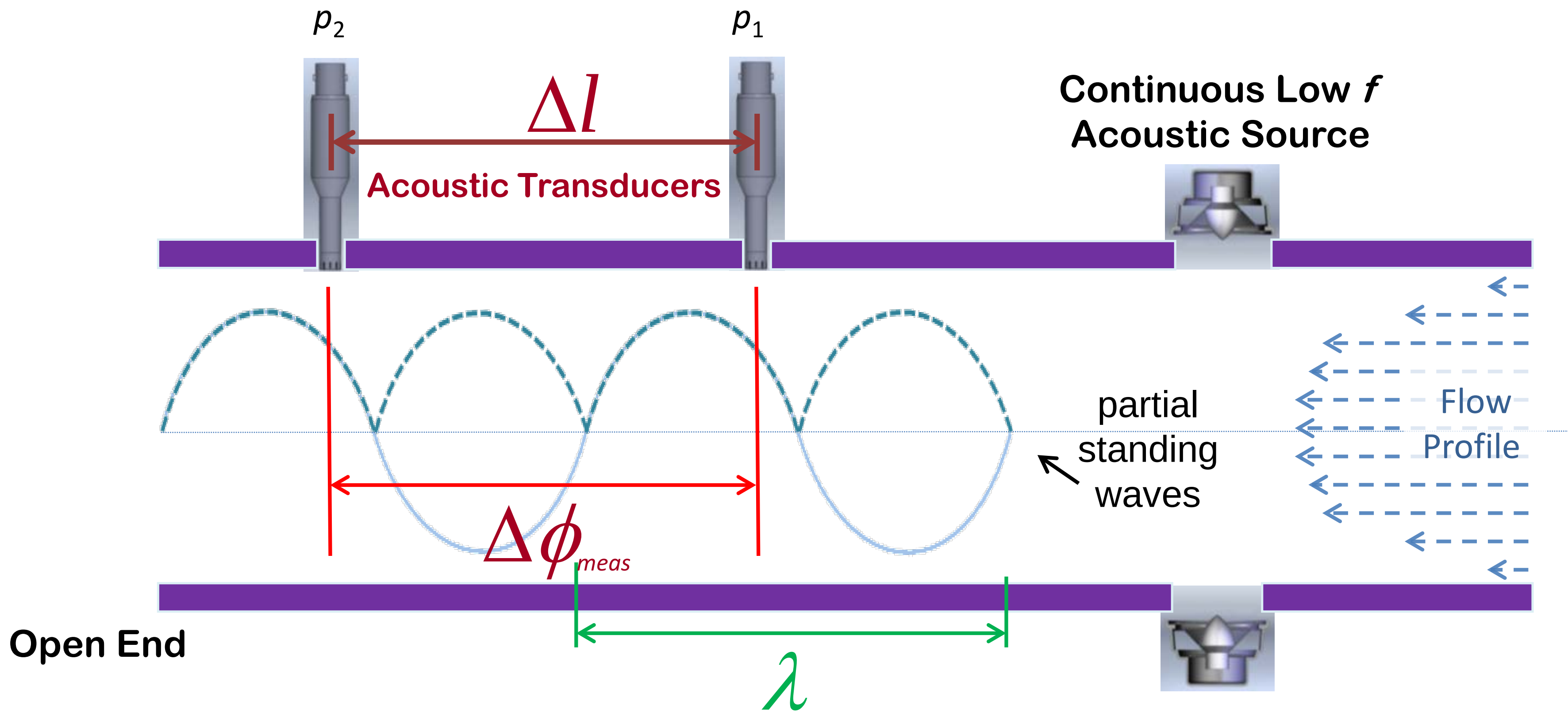


Acoustic measurements of flow



$p_2/p_1 = | p_2/p_1 | e^{i\Delta\phi}$

λ - wavelength is proportional to the speed of sound.

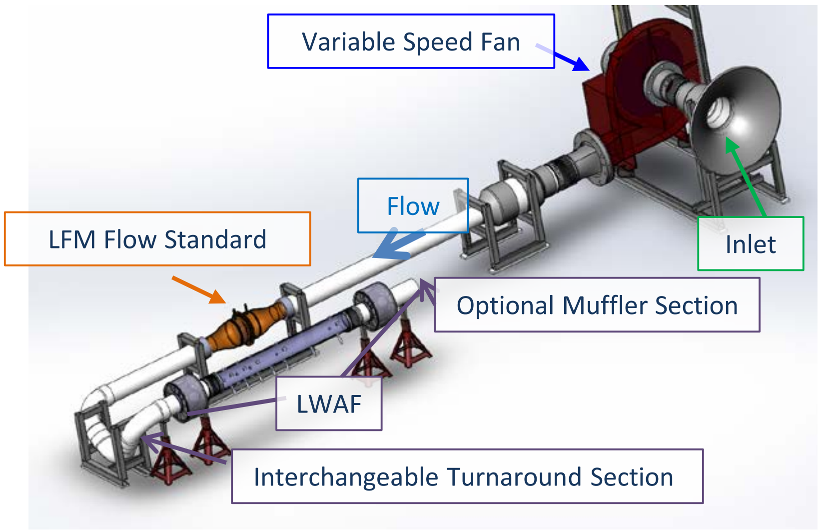
$\Delta\phi_{meas}$ - phase difference changes inversely with flow.

$$c_0 = 2 f_n \Delta l / n$$

$$c_0 + V = 2\pi f_n \Delta l / \Delta\phi_n$$

LWAF with active sound generation: performance summary

Previously, we assessed the performance and scalability of the NIST 1/100th scale (10 cm diameter) LWAF facility using an active sound source to generate long wavelength sound (frequency < 2 kHz)



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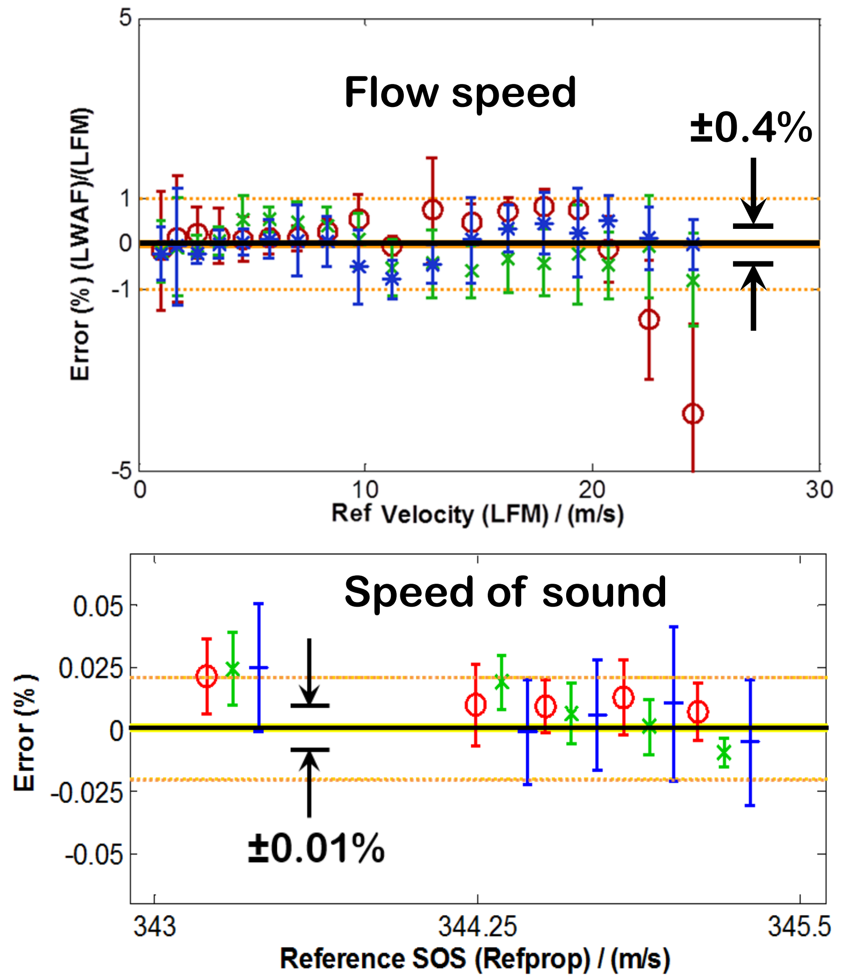

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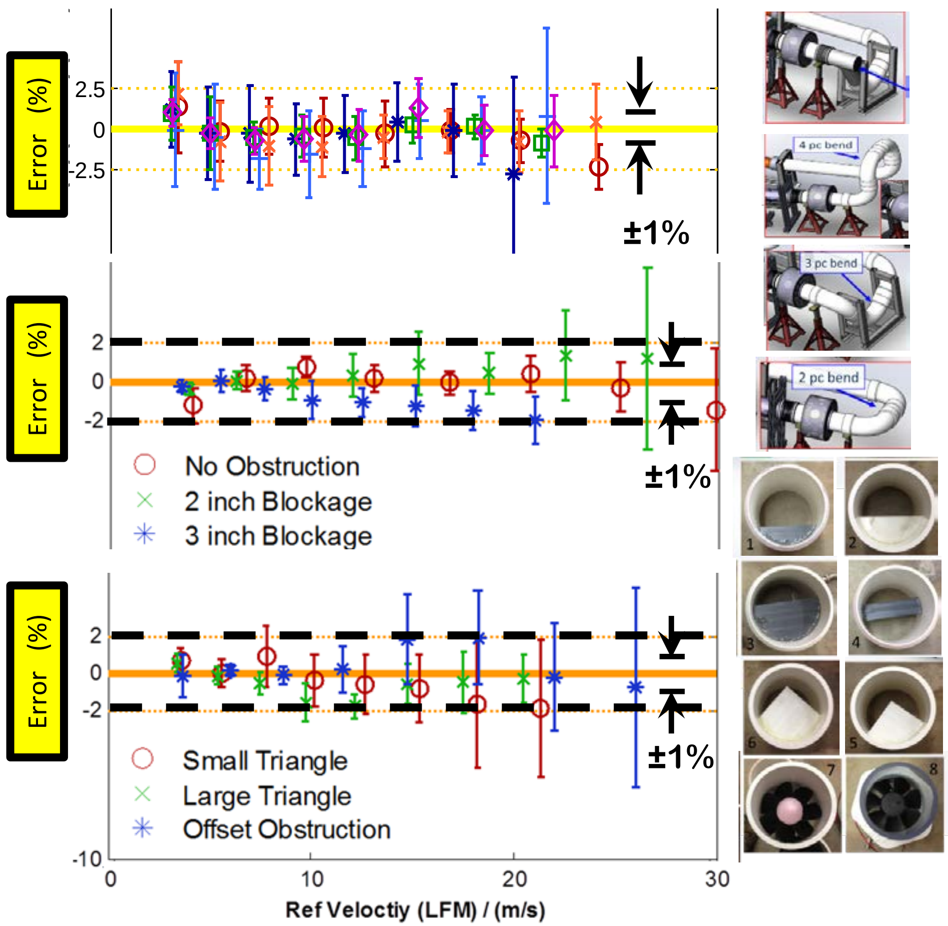

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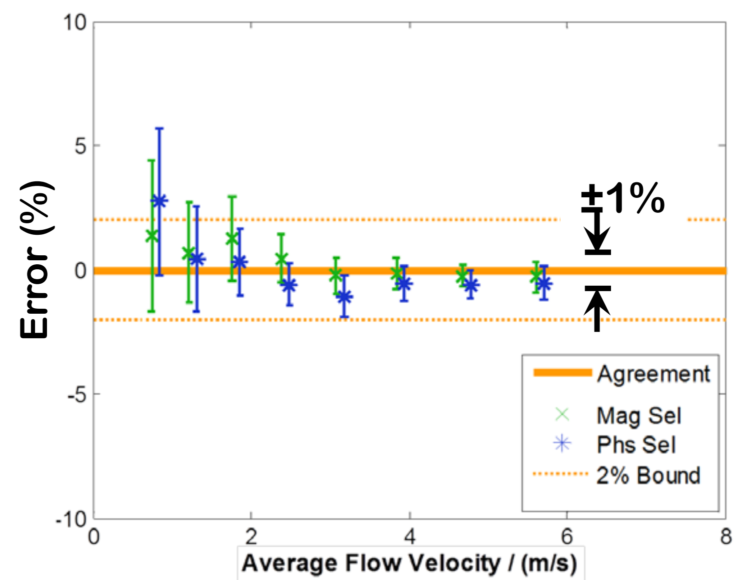

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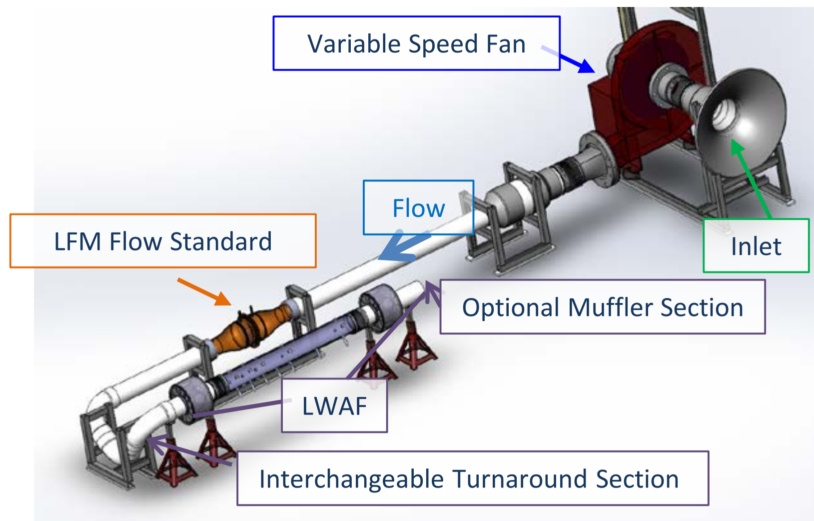


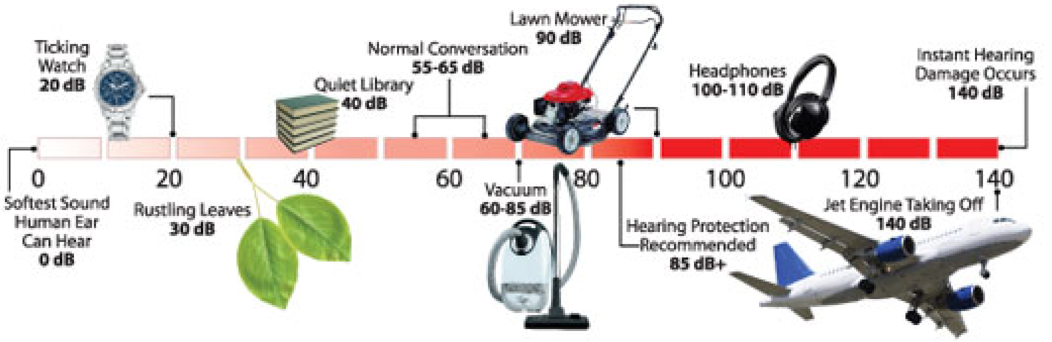
It works!!!...

But... generating sound in a smokestack is impractical...

Sound generation in a smokestack

The volume of a typical smokestack is 10^6x larger than the NIST 1/100th scale LWAF

- to achieve the same signal-to-noise ratio we need to generate 10^6x higher sound pressure
- $20 \log(10^6) = 120$ dB higher SPL
- smokestacks are noisy environments
- required sound level ~160 - 180 dB SPL! (that's loud)



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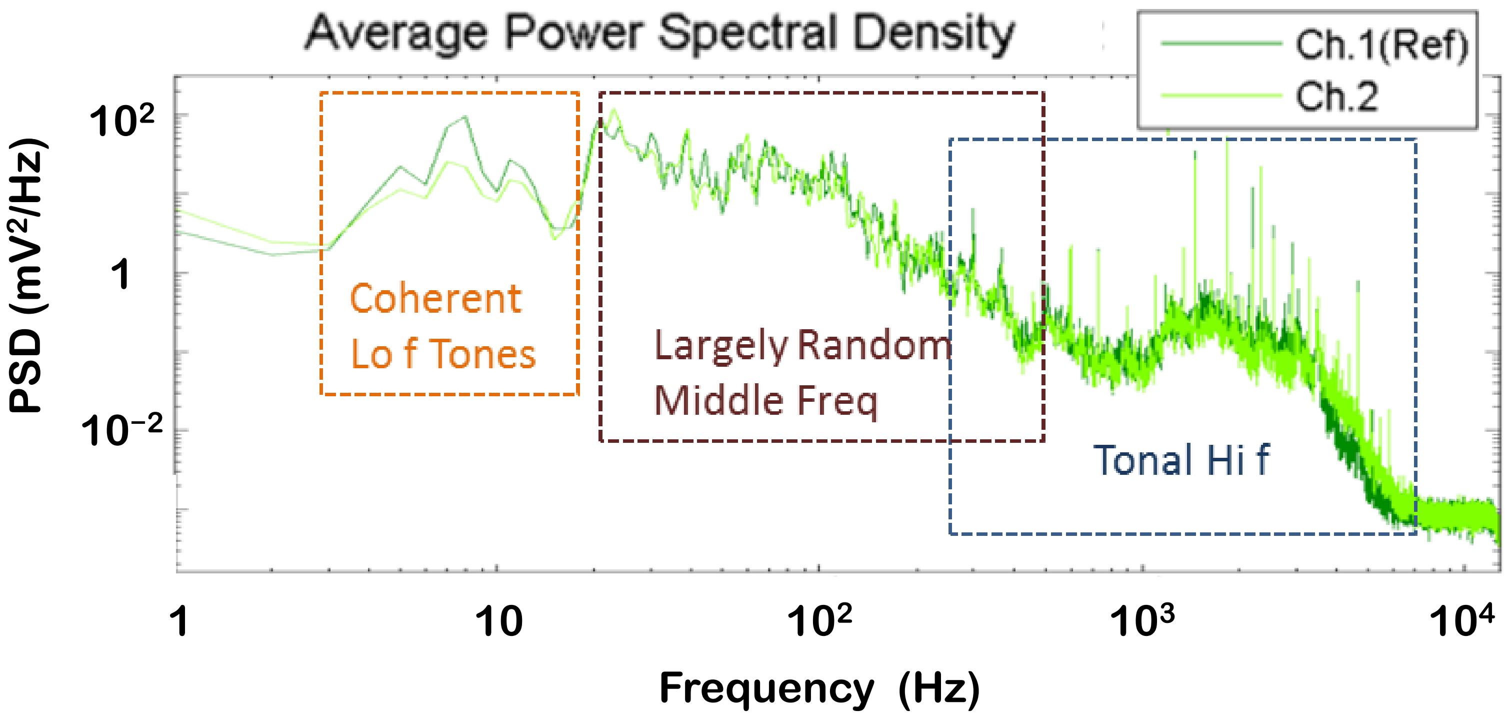
What is an alternative?

Acoustical noise in a power plant smokestack

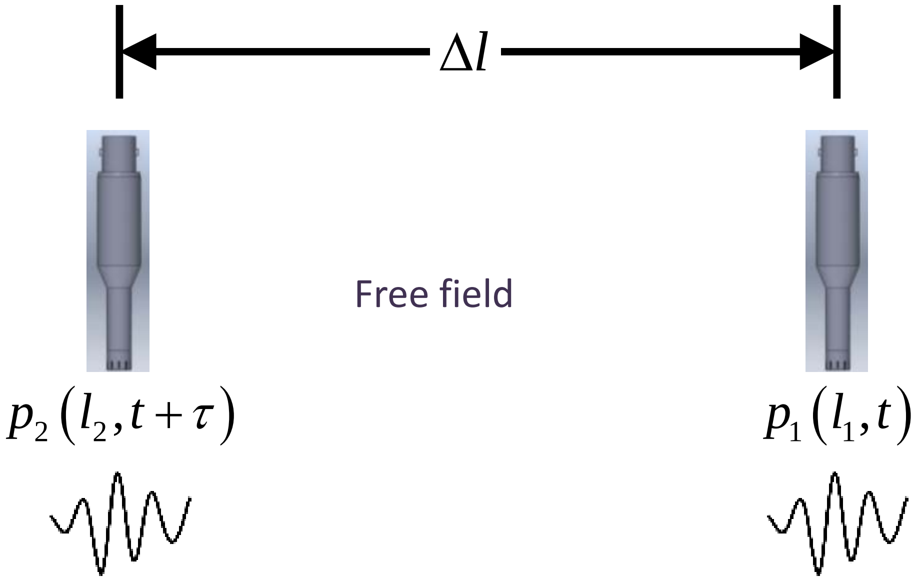
Measurements at Mirant (GenOn) plant in Dickerson, MD

Smokestack diameter ≈ 10 m
Plane wave sound for frequency < 20 Hz



Noise caused by blowers or turbulent flow.
Passive approach: correlate existing noise at particular frequencies

Velocity and pressure fluctuations due to flow instabilities generate acoustic noise

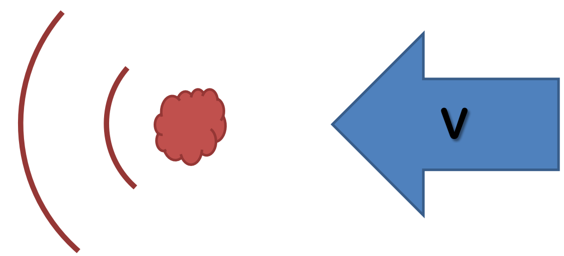


<u>fluctuations</u>

hydrodynamic $\tilde{p}_h \sim \rho \tilde{v}^2$

acoustic $\tilde{p}_a \sim \tilde{\rho} c^2 \sim \rho c \tilde{v}$

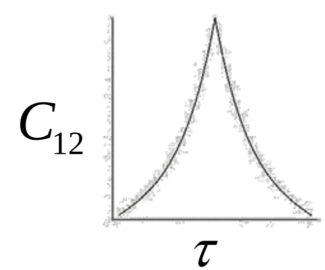
hydrodynamic energy is converted to acoustic energy



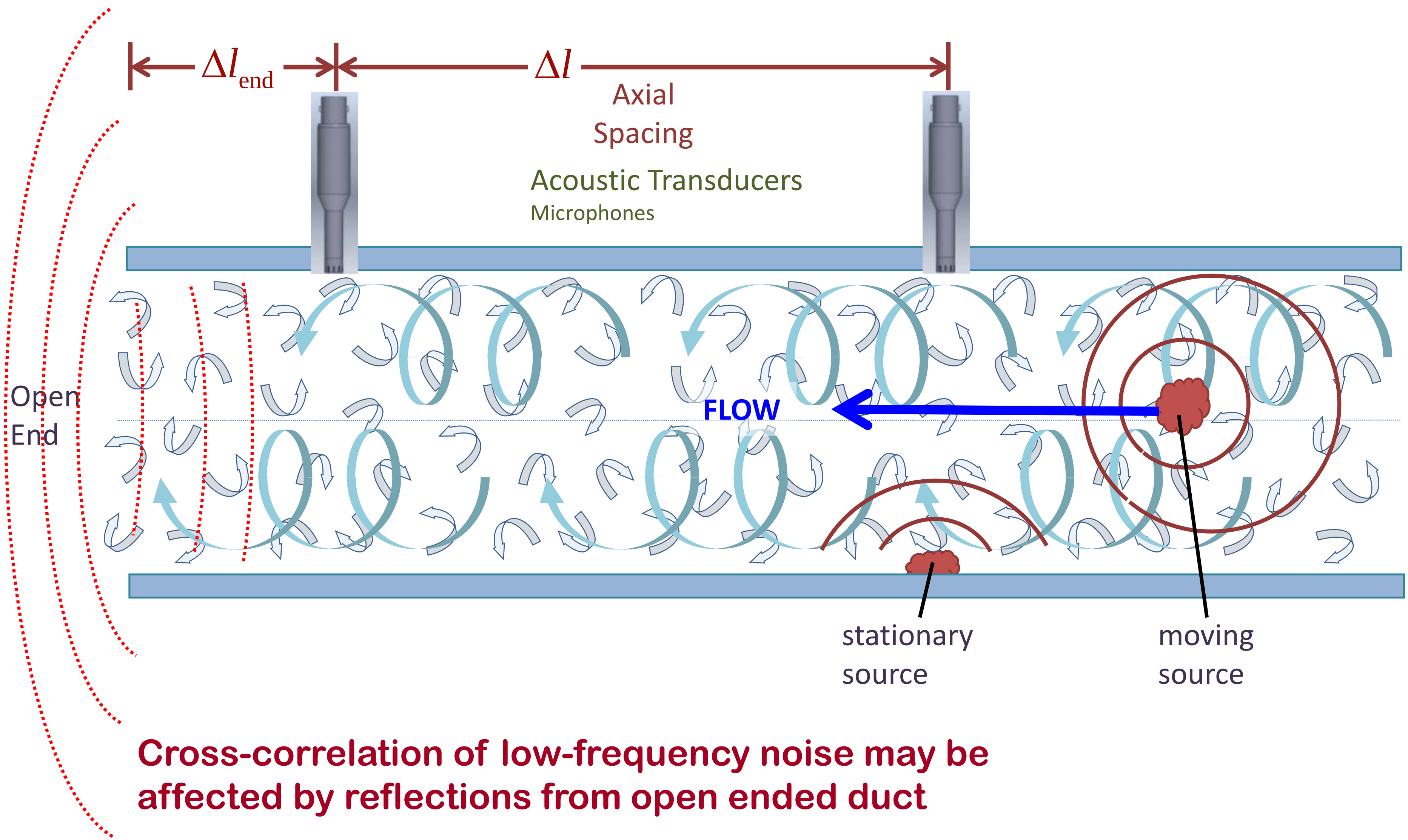
Cross-correlation of acoustic pressures

$$C_{12}(\tau) = \int_{-\infty}^{\infty} p_1(l_1, t)\, p_2(l_2, t+\tau)\, dt$$

$$\max C_{12} \text{ at } \tau_{\max} \Rightarrow \frac{\Delta l}{\tau_{\max}} \approx c + V$$

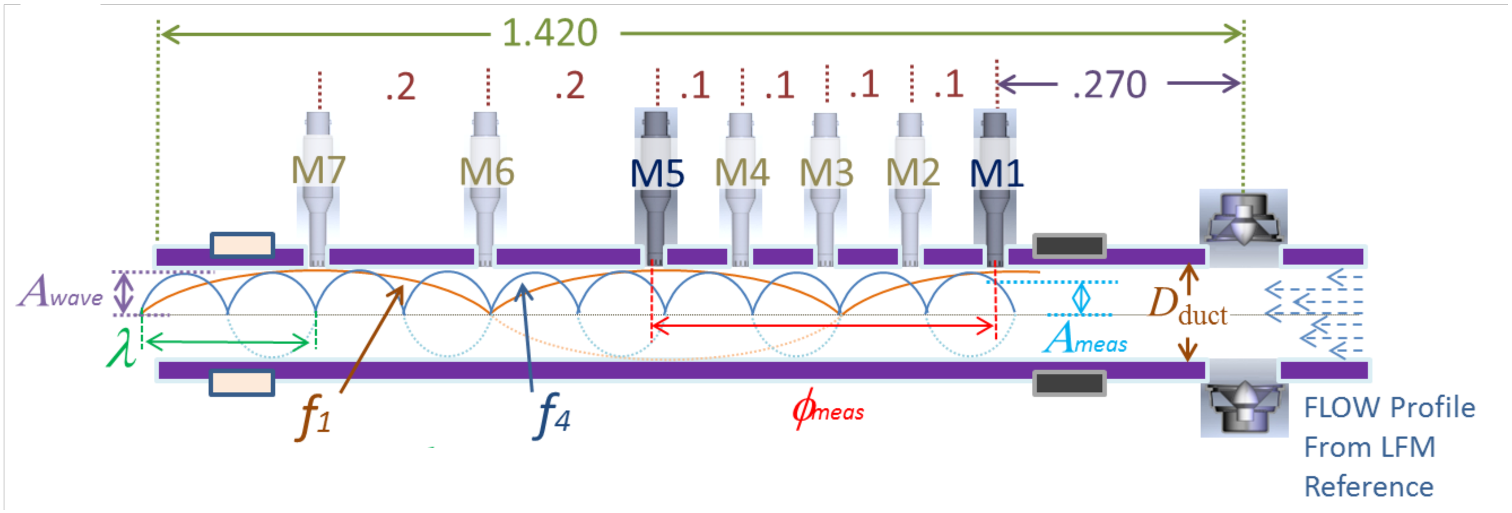


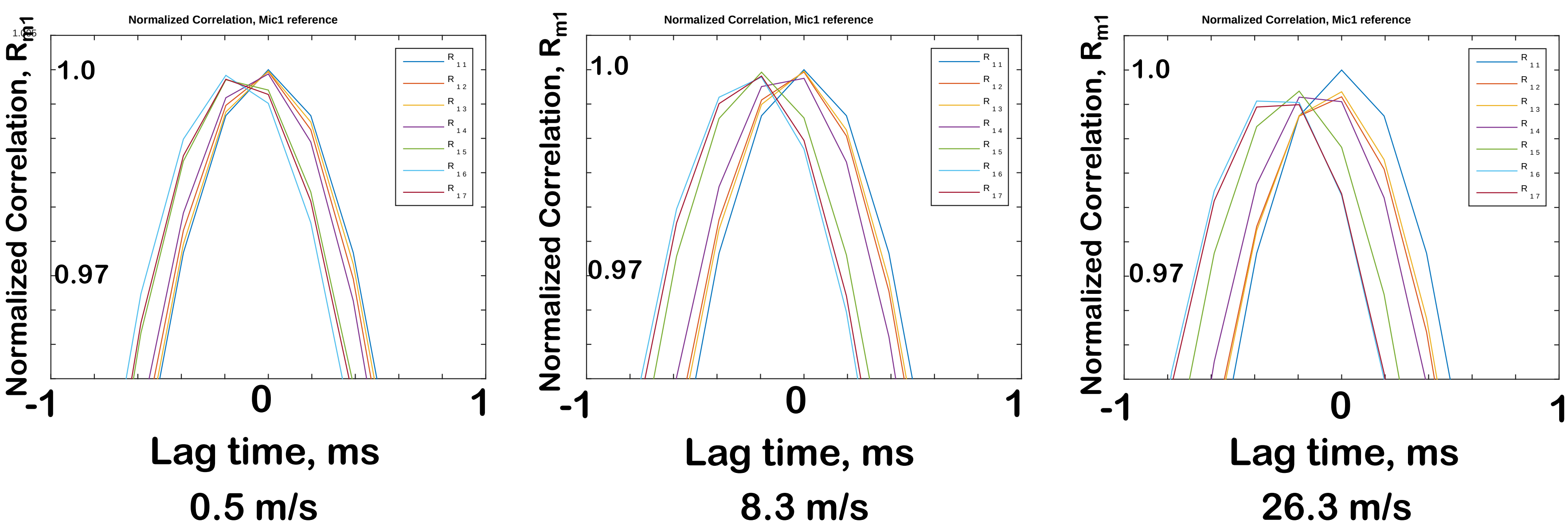
Acoustic noise generated by flow confined in a duct is complicated by reflections



Cross-correlation of low-frequency noise may be affected by reflections from open ended duct

Correlated noise in 1:100th scale LWAF



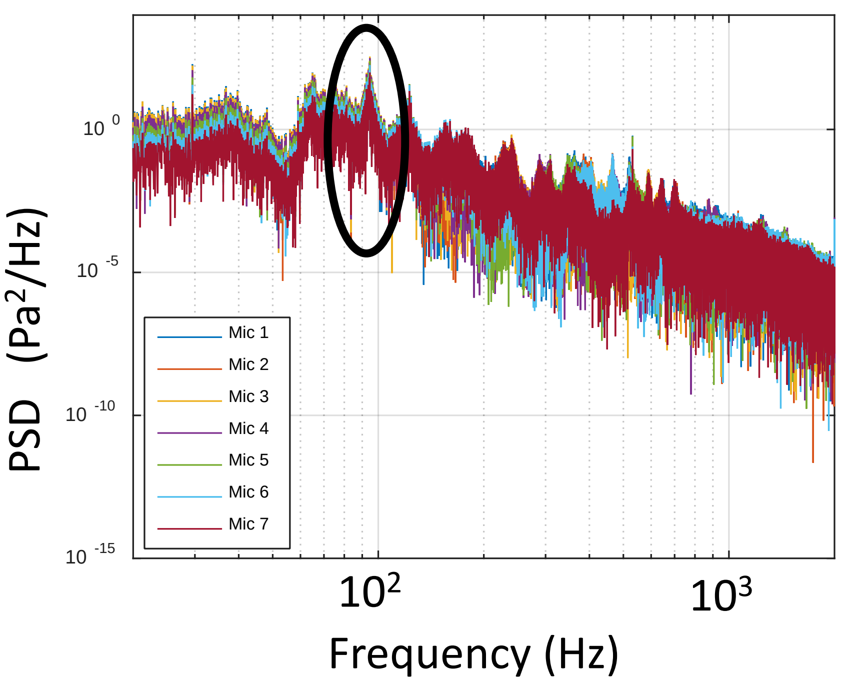


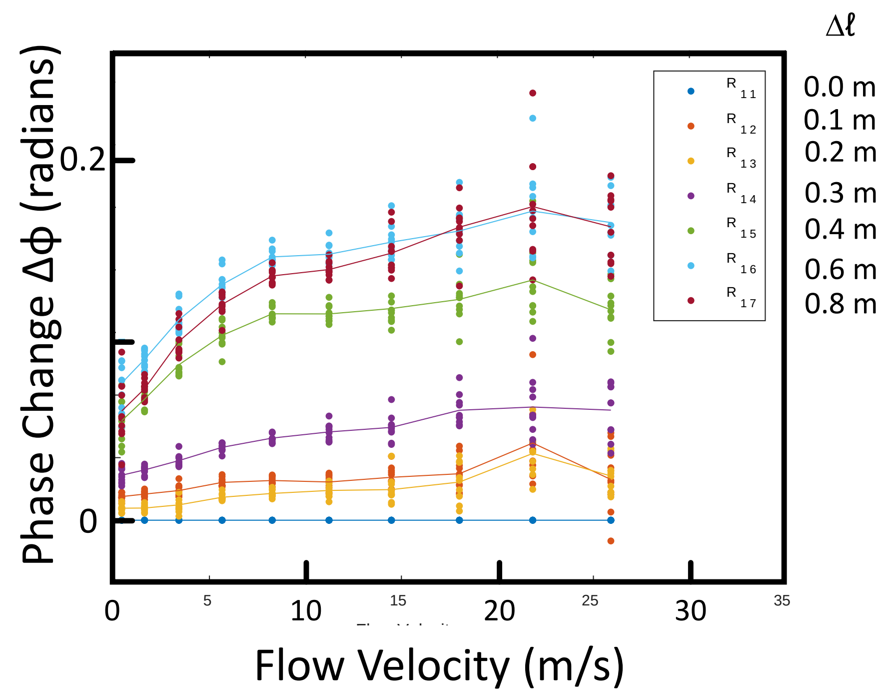
Correlated noise in 1:100th scale LWAF at 94 Hz

LWAF diameter ≈ 0.10 m
Plane wave sound for frequency < 2000 Hz

Preliminary measurements

Power Spectral Density





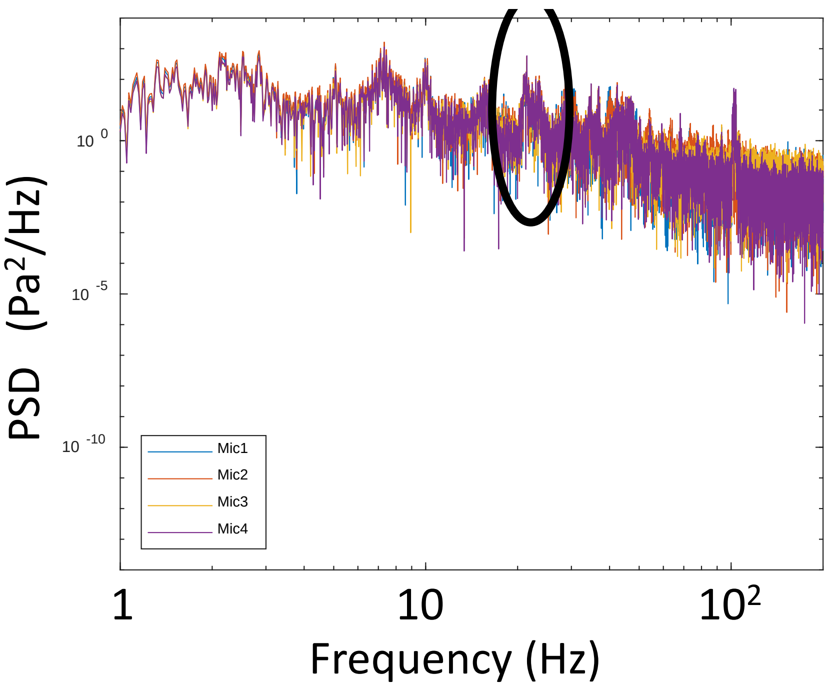
Filtered Correlations,
94 Hz Center Frequency , 1 Hz bandwidth

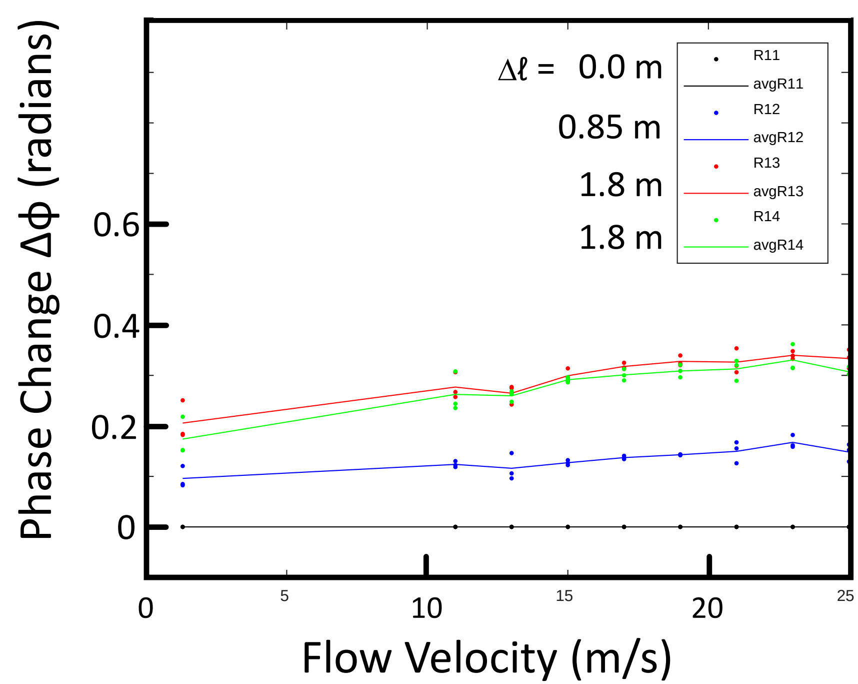
Correlations in 1:10th Scale Model Smokestack Simulator

SMSS diameter ≈ 1.2 m
Plane wave sound for frequency < 170 Hz

Preliminary measurements

Power Spectral Density





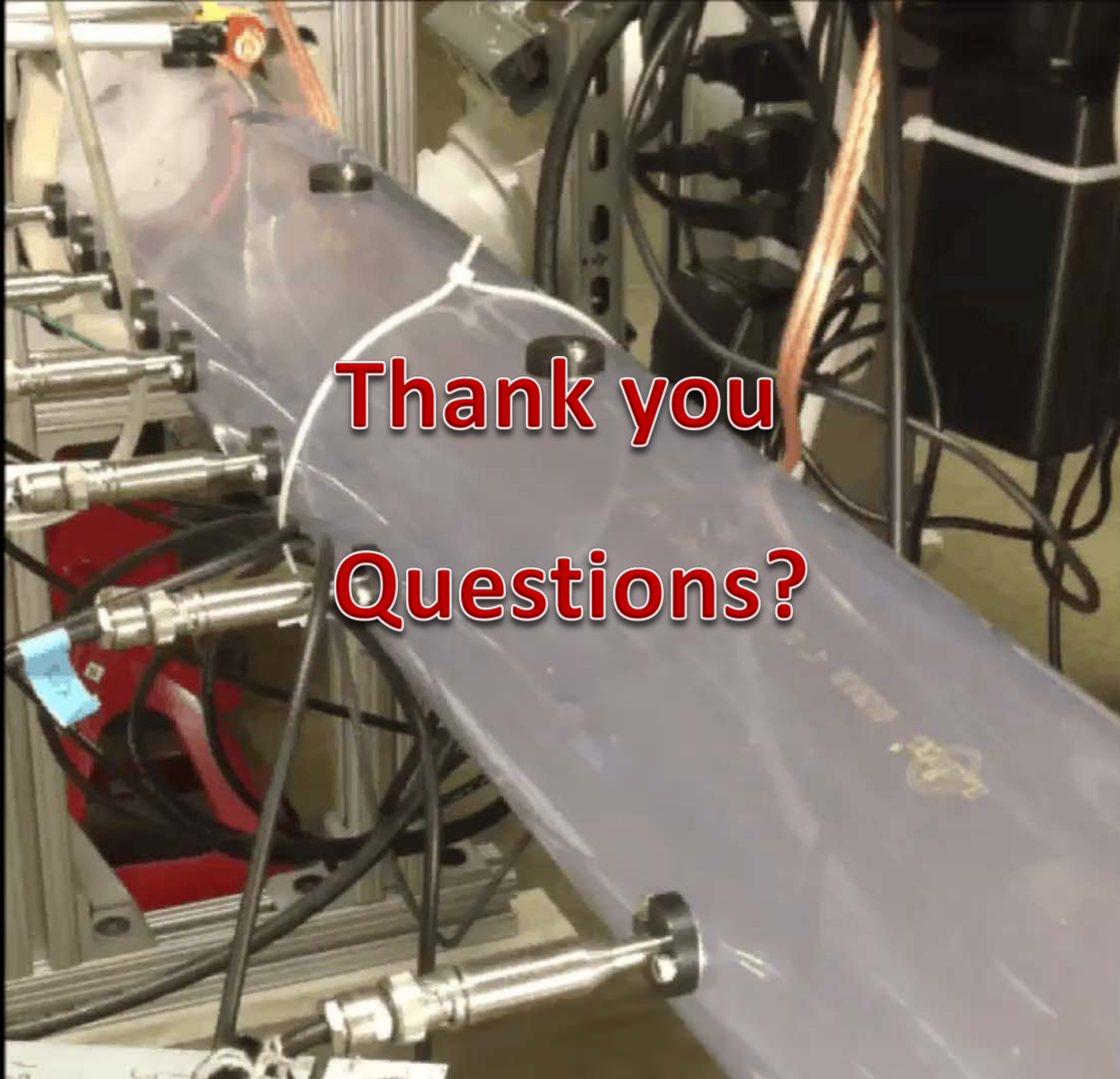
Filtered Correlations,
21 Hz Center Frequency , 1 Hz bandwidth

Summary and Future Work

- **Active Sound Generation:**
  - **Success measuring flow to $u(V) \leq 1\%$ for 1:100th scale test model**
- **Passive Sound Generation:**
  - **1:100th scale**
    - **Acoustic model predicts phase change as a function of velocity and frequency**
    - **Qualitative agreement with model**
  - **1:10th scale**
    - **Measured phase changes with respect to flow velocity**

Summary and Future Work

- Develop acoustic model for 1:10th SMSS
  - Theoretical model for correlations
  - Determine relation between flow velocity and measured phase change
  - Demonstrate measurement of *V*
  - Determine the uncertainty $u(V)$
    - Goal: $u(V) \leq 1\%$ relative to SMSS calibrated reference section


Thank you
Questions?