Is a long-wavelength acoustic flowmeter feasible for smokestacks?

Keith A. Gillis

Fluid Metrology Group
Sensor Science Division
National Institute of Standards and Technology

Measurement Challenges and Metrology for Monitoring CO_2 Emissions from Smokestacks
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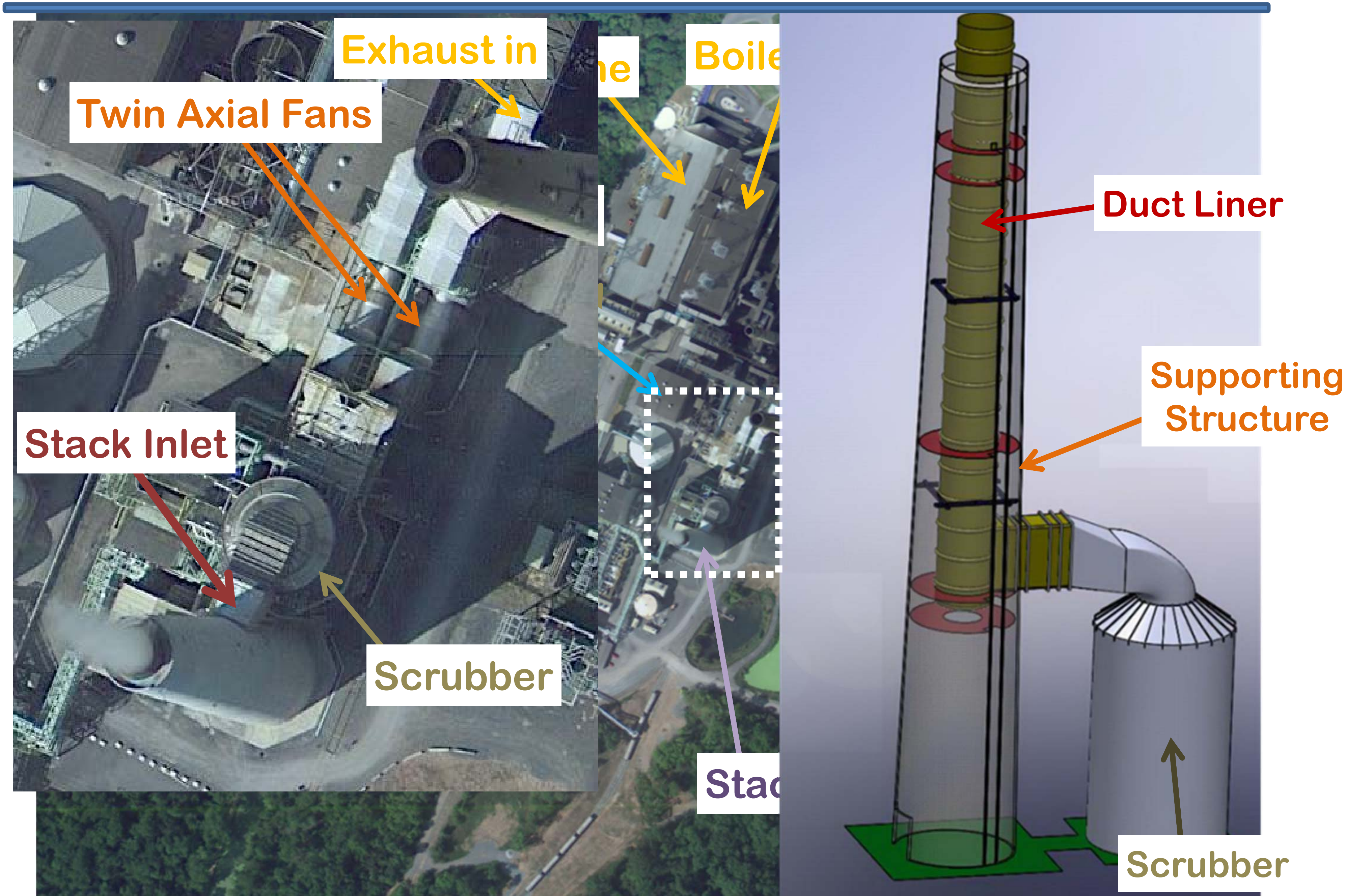
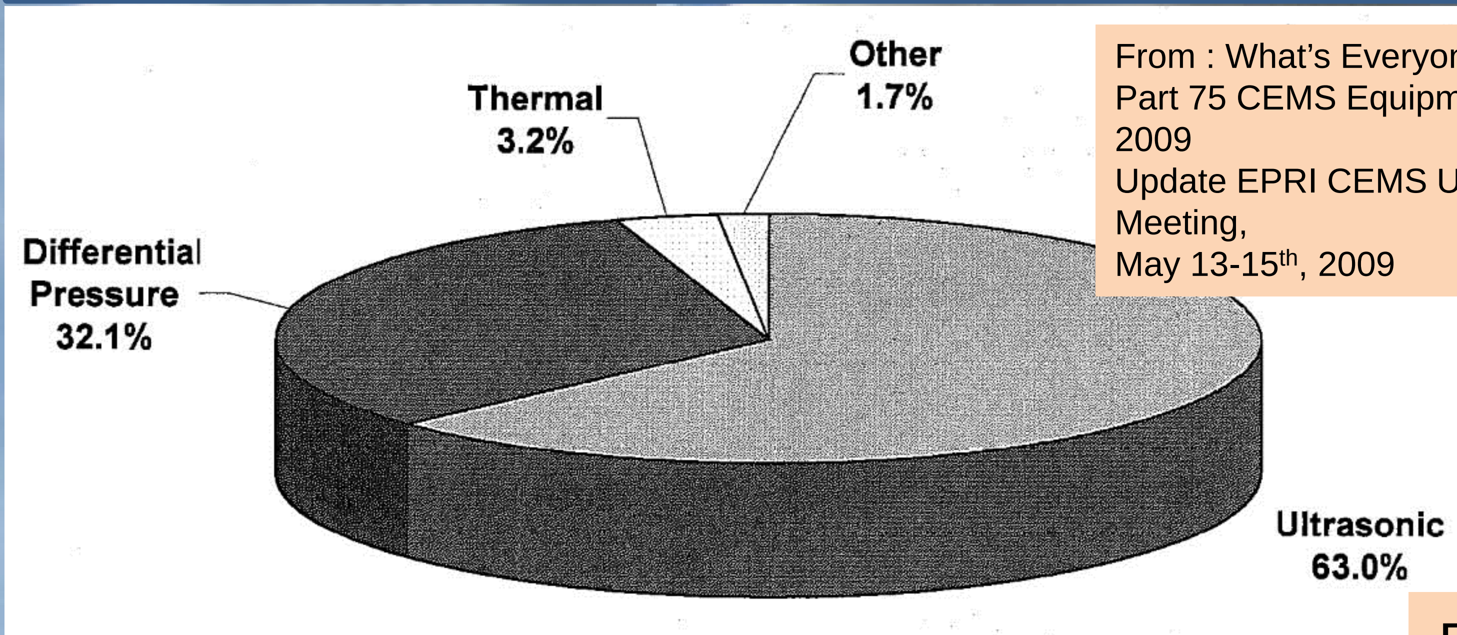
Collaborators

Lee Gorny
Aaron Johnson
Liang Zhang
John Wright
Mike Moldover

Anatomy of a nearby coal-burning power plant



Accurate measurement of flow is a challenge in this harsh environment



From : What's Everyone Using? Part 75 CEMS Equipment trends - 2009
Update EPRI CEMS Users Group Meeting,
May 13-15th, 2009

Estimated Uncertainty

5-20%

Reynold's number $>10^7$
Mach number < 0.1
Diameter 10 m
Height 130 m to 200 m
Temperature ~ 65 C
Humidity ~ 100 %
pH ~ 2

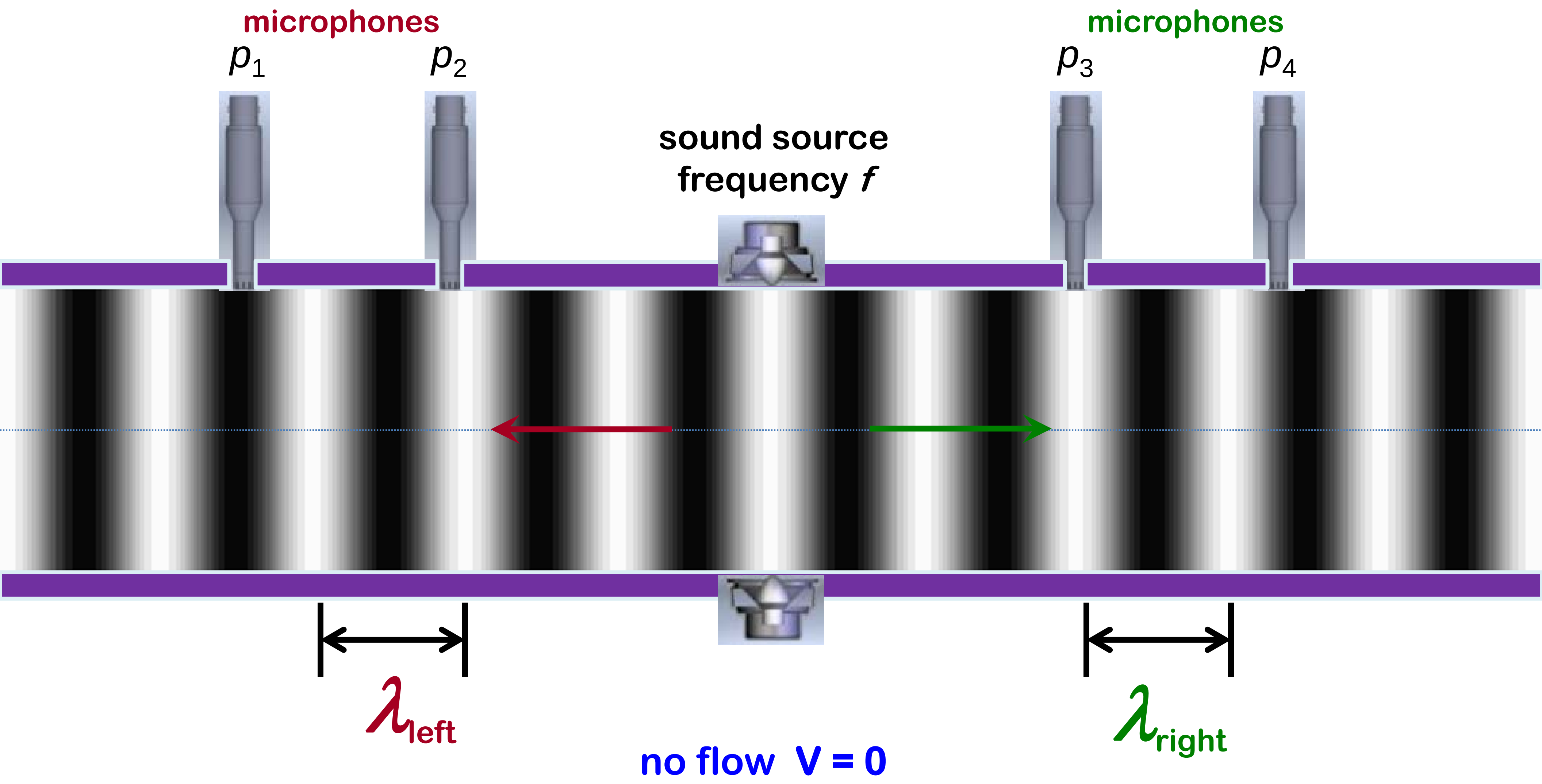
Measuring flow in a smokestack

Are there alternative methods to measure complicated flows in harsh environments?

Is acoustics a good hammer?

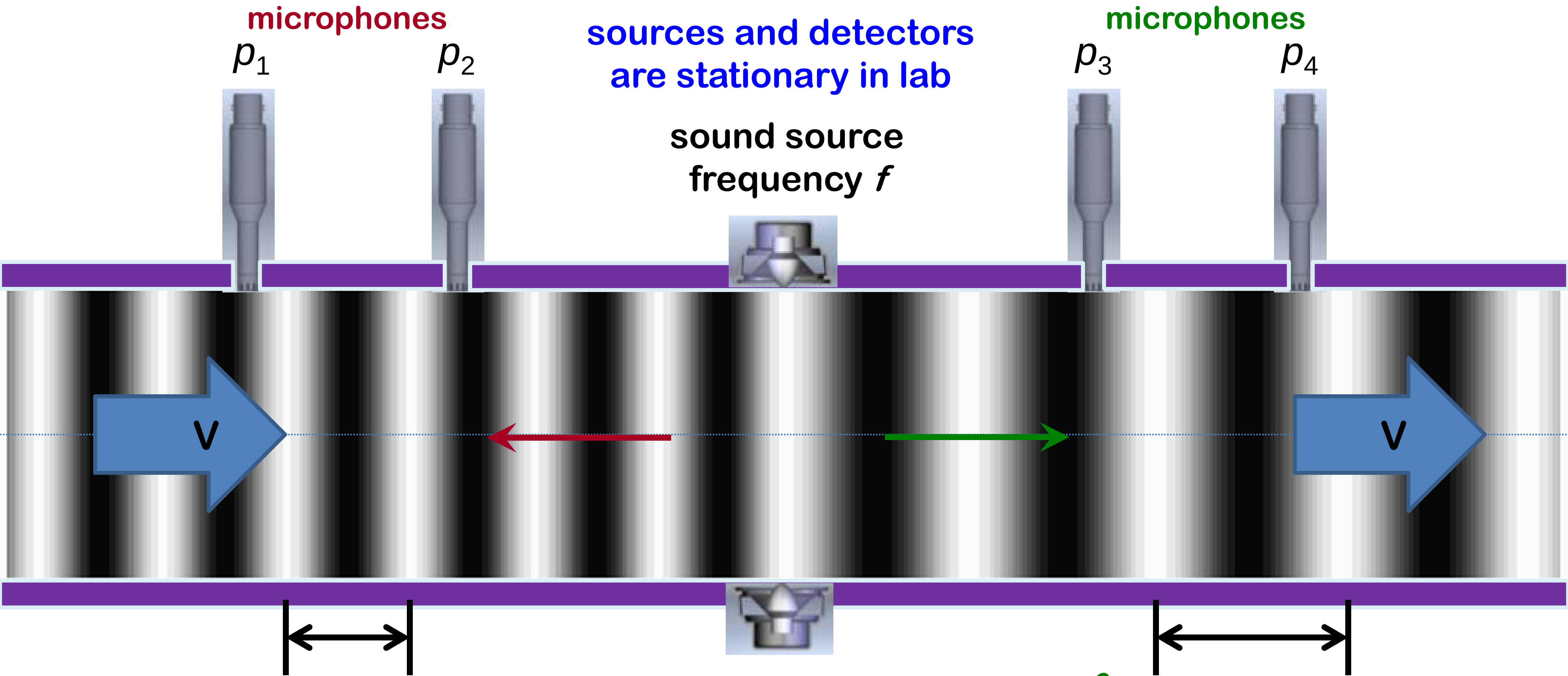
...even for large-scale flows?

Acoustics without flow



$$\lambda_{left} = \lambda_{right} = c\,/\,f = \lambda_0$$

Acoustics in flow



$\lambda_{\text{left}} = (c - V)/f$ Mach number $M = V/c$ $\lambda_{\text{right}} = (c + V)/f$

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

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

Measuring flow with sound

History of the Long-wavelength acoustic flowmeter (LWAF)

- plane wave propagation in a pipe is predicted to be insensitive to temperature and velocity profiles, including swirl and turbulence

[B. Robertson, "Effect of arbitrary temperature and flow profiles on the speed of sound in a pipe", *J. Acoust. Soc. Am.* **62**, pp. 813-818 (1977).]

- prototype LWAF is described and evaluated

[J.E. Potzick and B. Robertson "Long-wave acoustic flowmeter," *ISA Transactions* **22**, pp. 9-15 (1983); J. Potzick, "Performance evaluation of the NBS long-wave acoustic flowmeter," *Rev. Sci. Instrum.* **55**, 1173 (1984).]

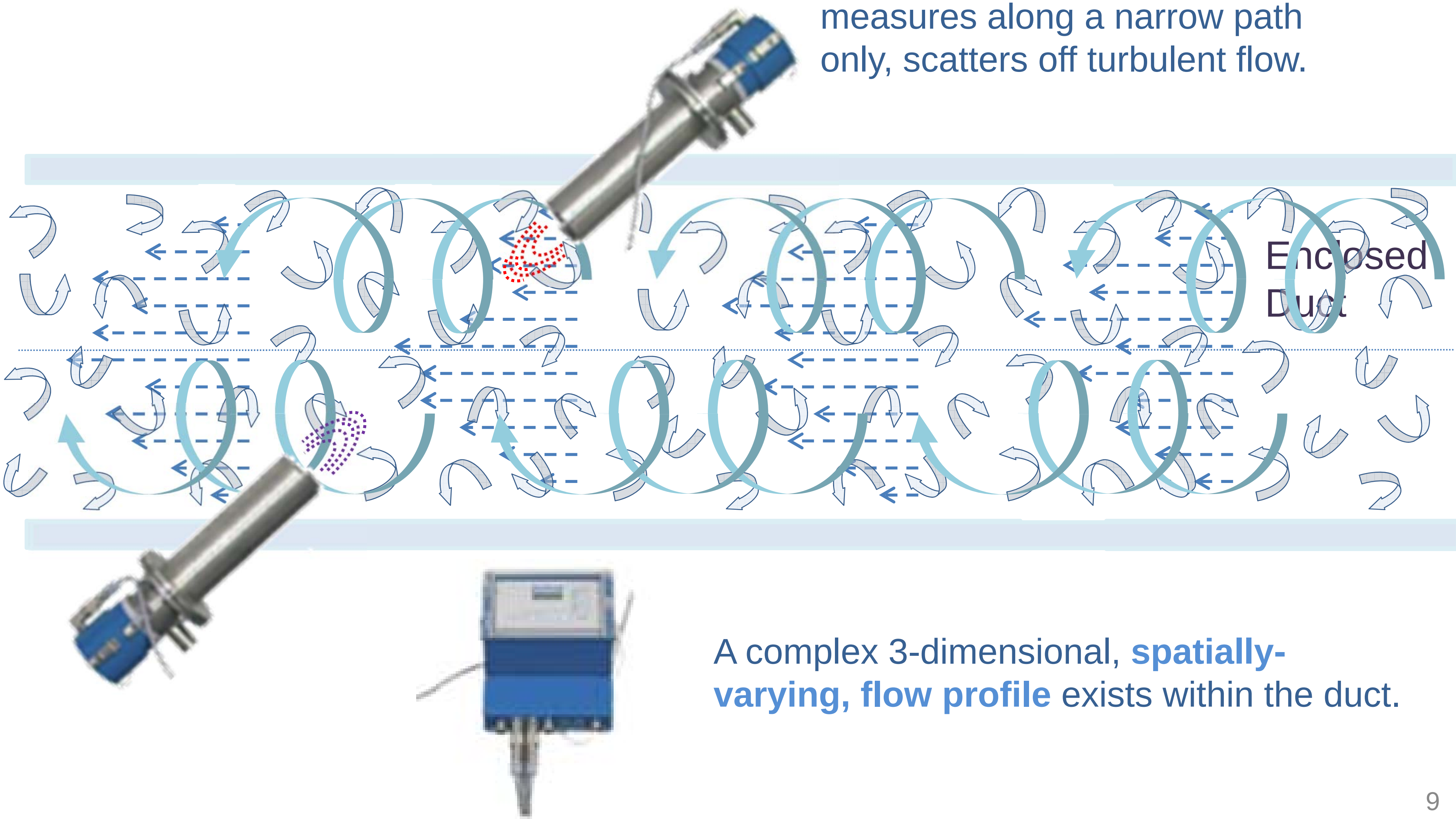
- NBS LWAF instrument is patented (May, 1984)

[Long wavelength acoustic flowmeter, US Patent 4,445,389]

- VTT in Finland develops a small commercial instrument (~2000)

A Long Wavelength Acoustic Flowmeter (LWAF) measures flow with low frequency sound.

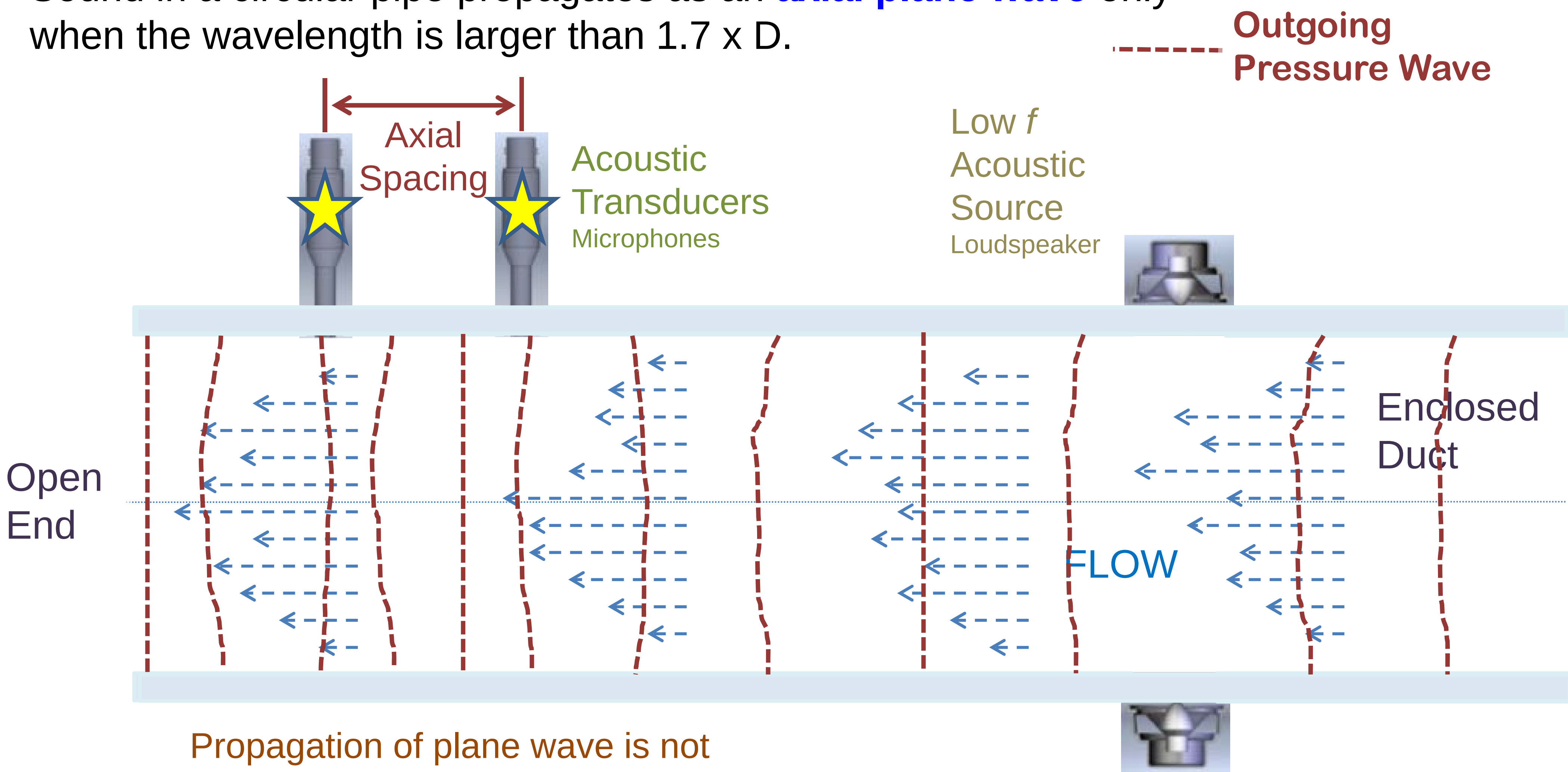
Conventional ultrasonic flow meter measures along a narrow path only, scatters off turbulent flow.



A complex 3-dimensional, **spatially-varying, flow profile** exists within the duct.

A Long Wavelength Acoustic Flowmeter (LWAF) measures flow with low frequency sound.

Sound in a circular pipe propagates as an **axial plane wave** only when the wavelength is larger than 1.7 x D.



Propagation of plane wave is not affected by complex flow to first order in *M*

Measuring flow with sound

Acoustic flow metering methods measure phase to determine the convective speed of sound ($c_0 + V$).

Flow velocities are < 10 % of the speed of sound for a power plant. Therefore, a measurement of flowrate with 1 % uncertainty, requires that the convective speed of sound must be measured to better than 0.1 %.

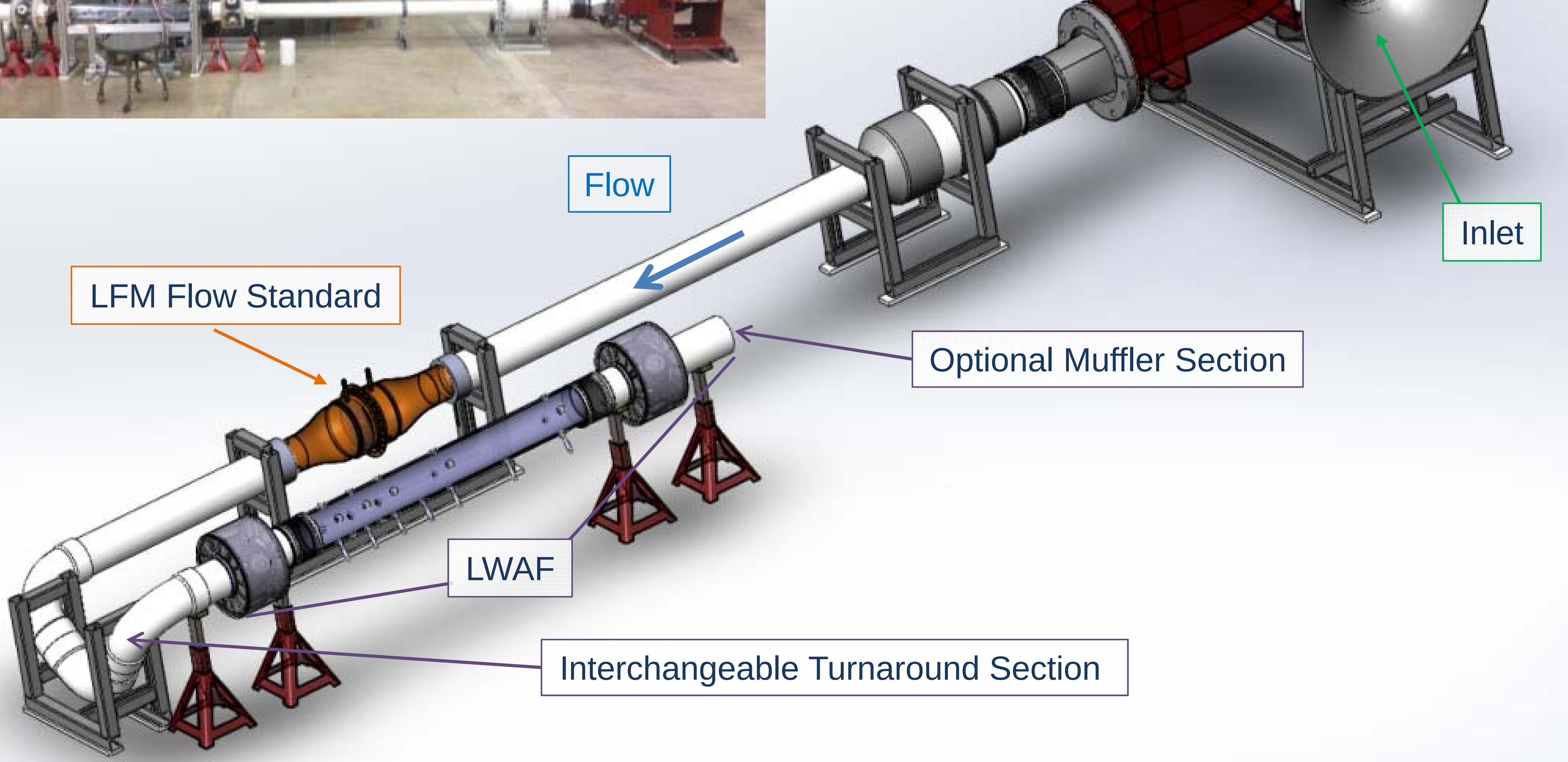
NIST's long-wavelength acoustic flowmeter

We constructed a 1/100th scale (10 cm diameter) laboratory flow facility to study the performance of LWAF. Target uncertainty is 1%.

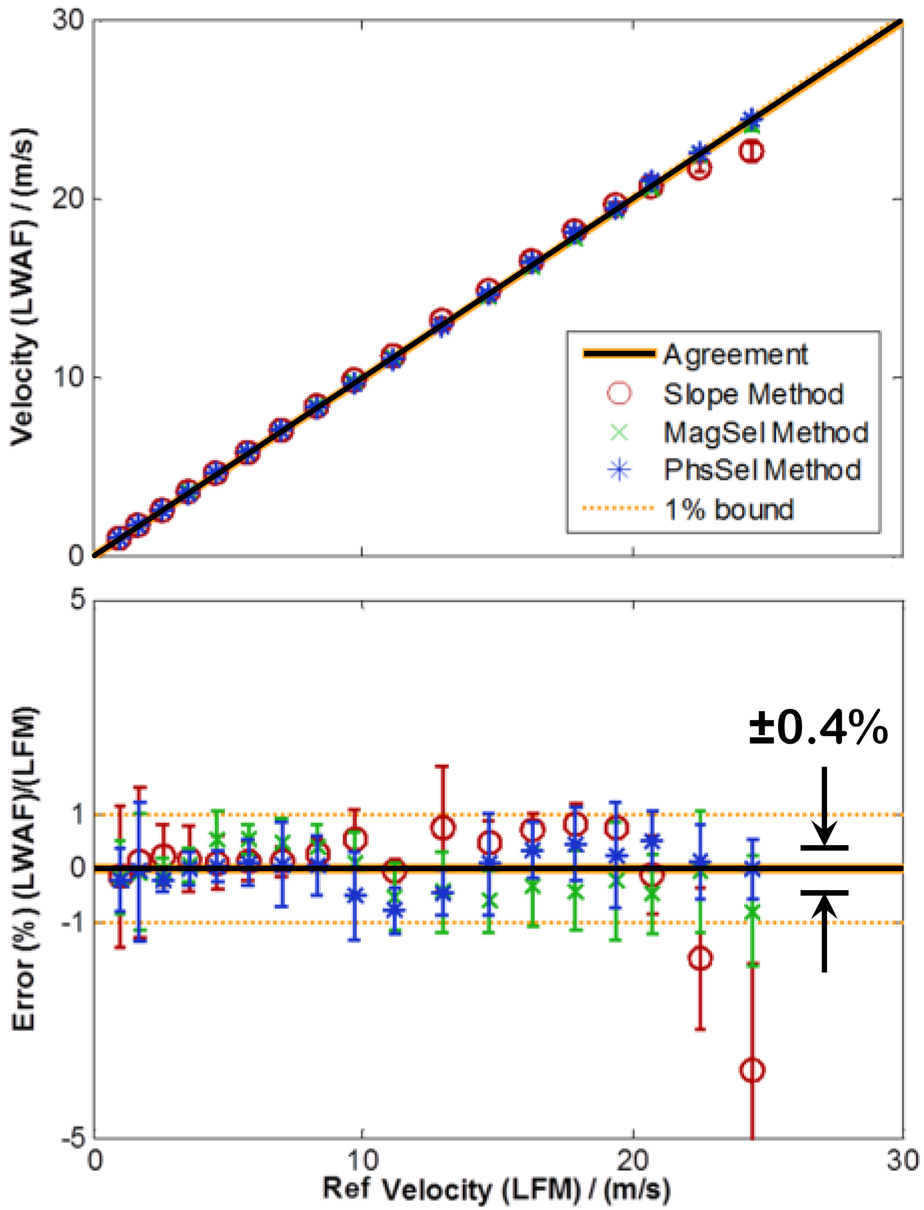
Our LWAF met target performance: (spoiler alert)

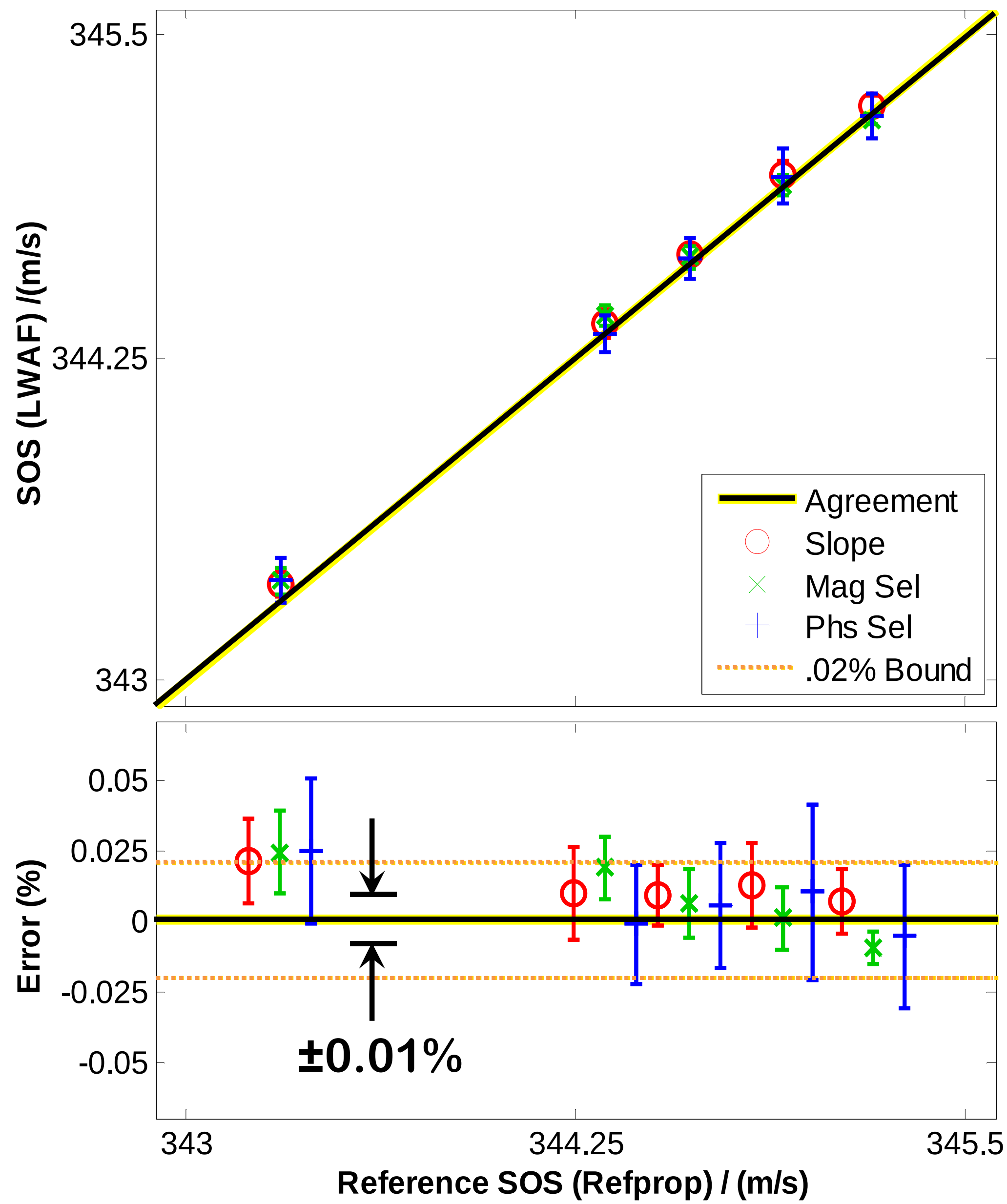
- in symmetric flows up to 25 m/s
- in distorted flows with swirl, vortices, and recirculation up to 25 m/s
- scaling to 1/50th (20 cm diameter) up to 6 m/s (limited by fan)
- preliminary measurements in humid air

Long-wavelength acoustic flowmeter test facility



LWAF measurements in undistorted flow

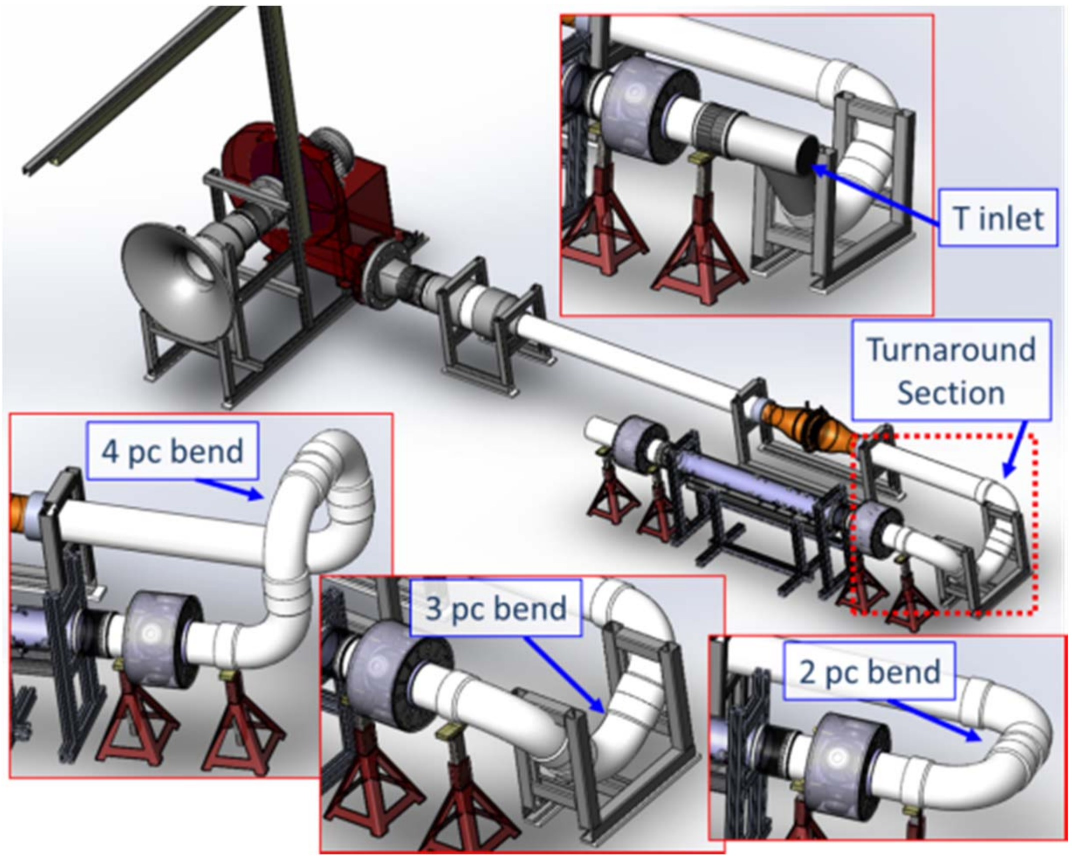


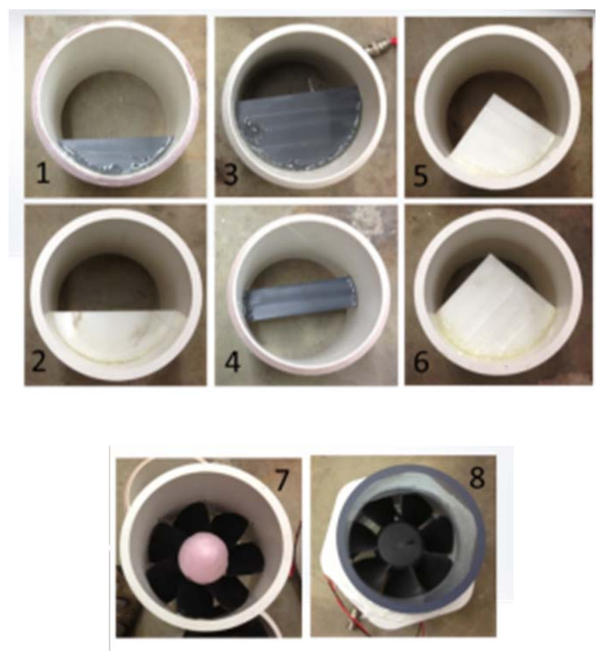


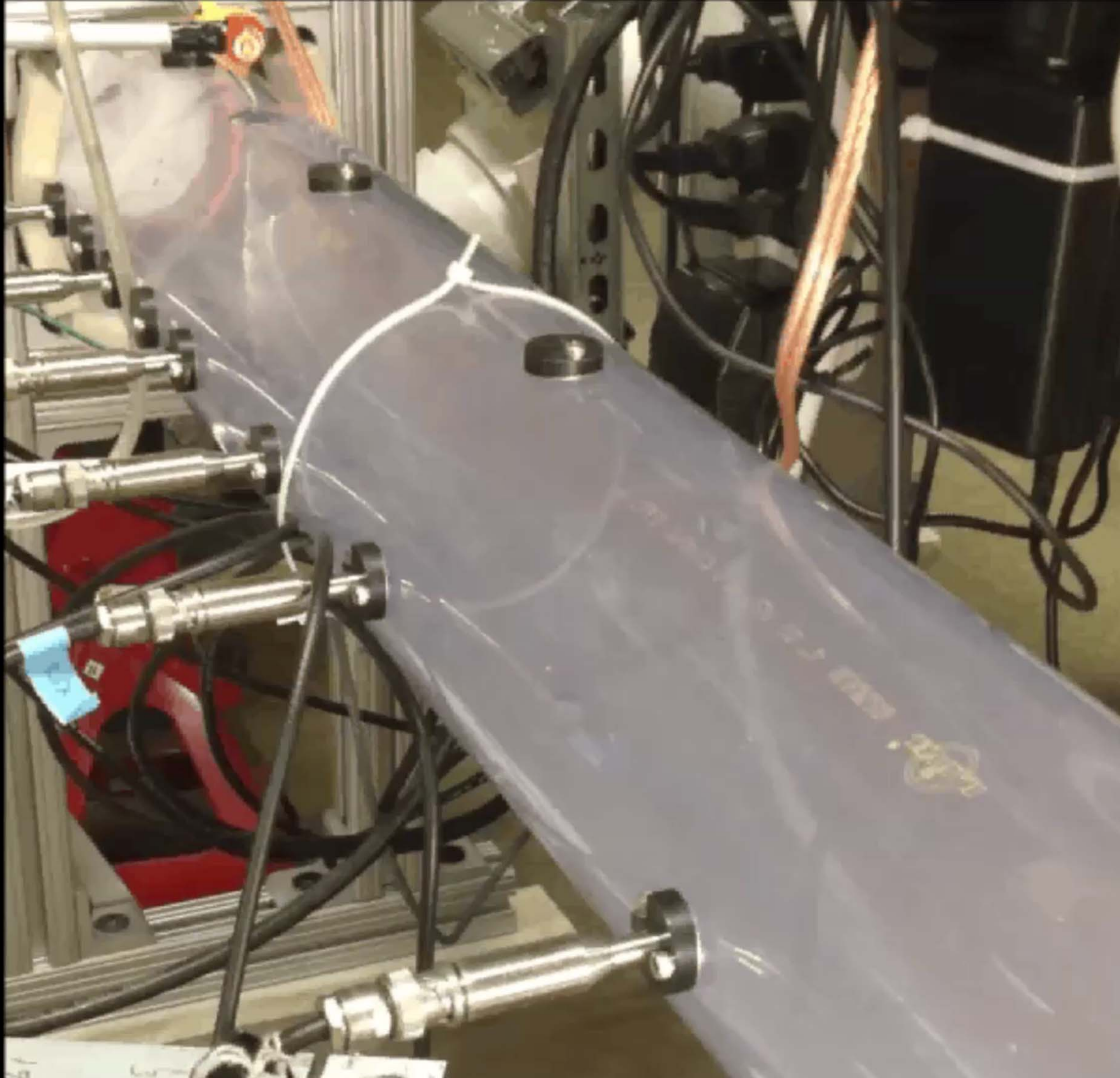
Measurements in distorted flow

Demonstrate accurate measurements with LWAF in distorted flow:

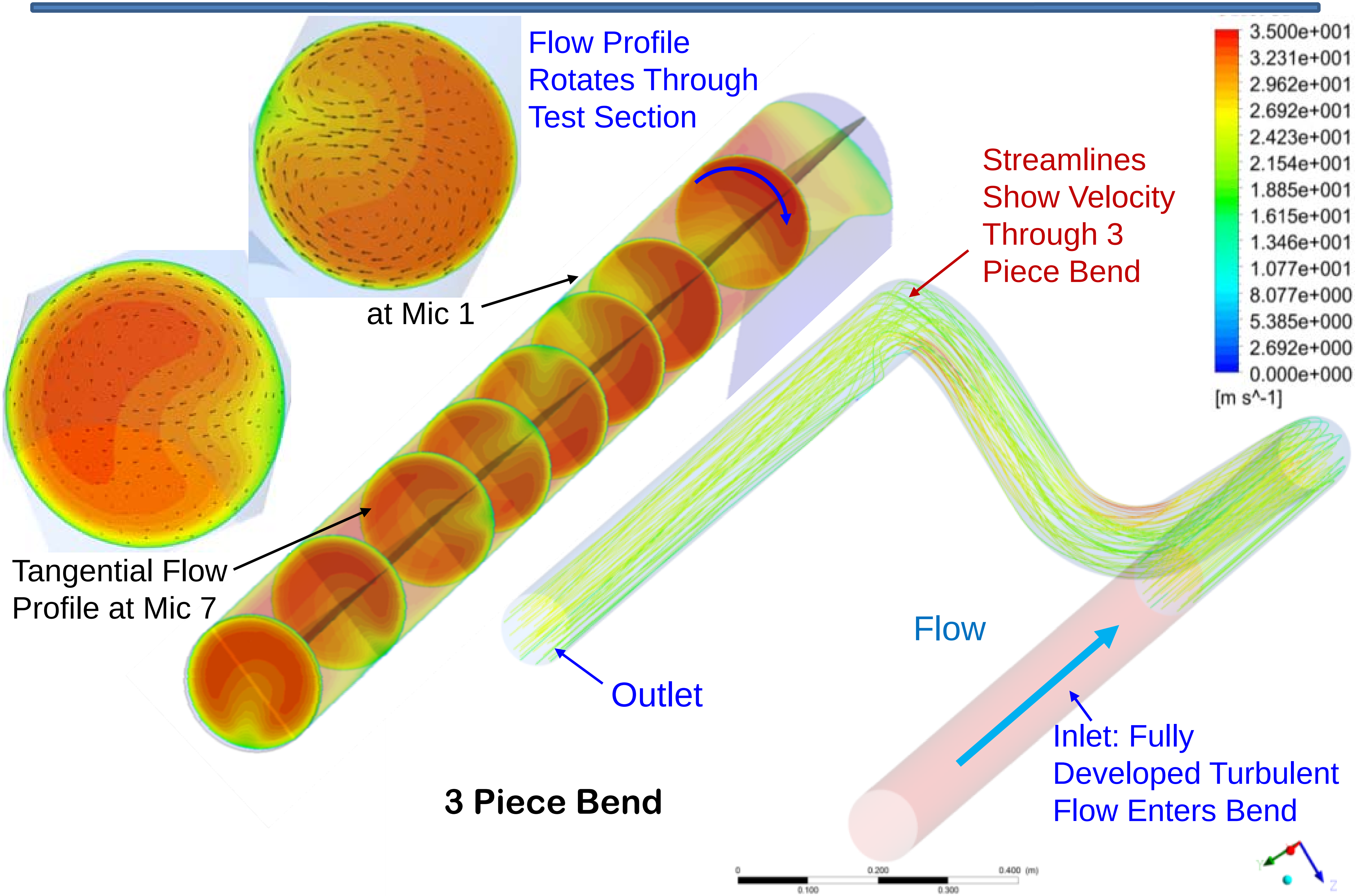
- **T section and bends in the pipe to generate swirl**
- **obstructions to generate asymmetric flow**





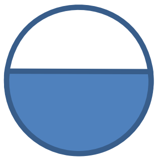


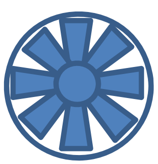
Use CFD to visualize distorted flows

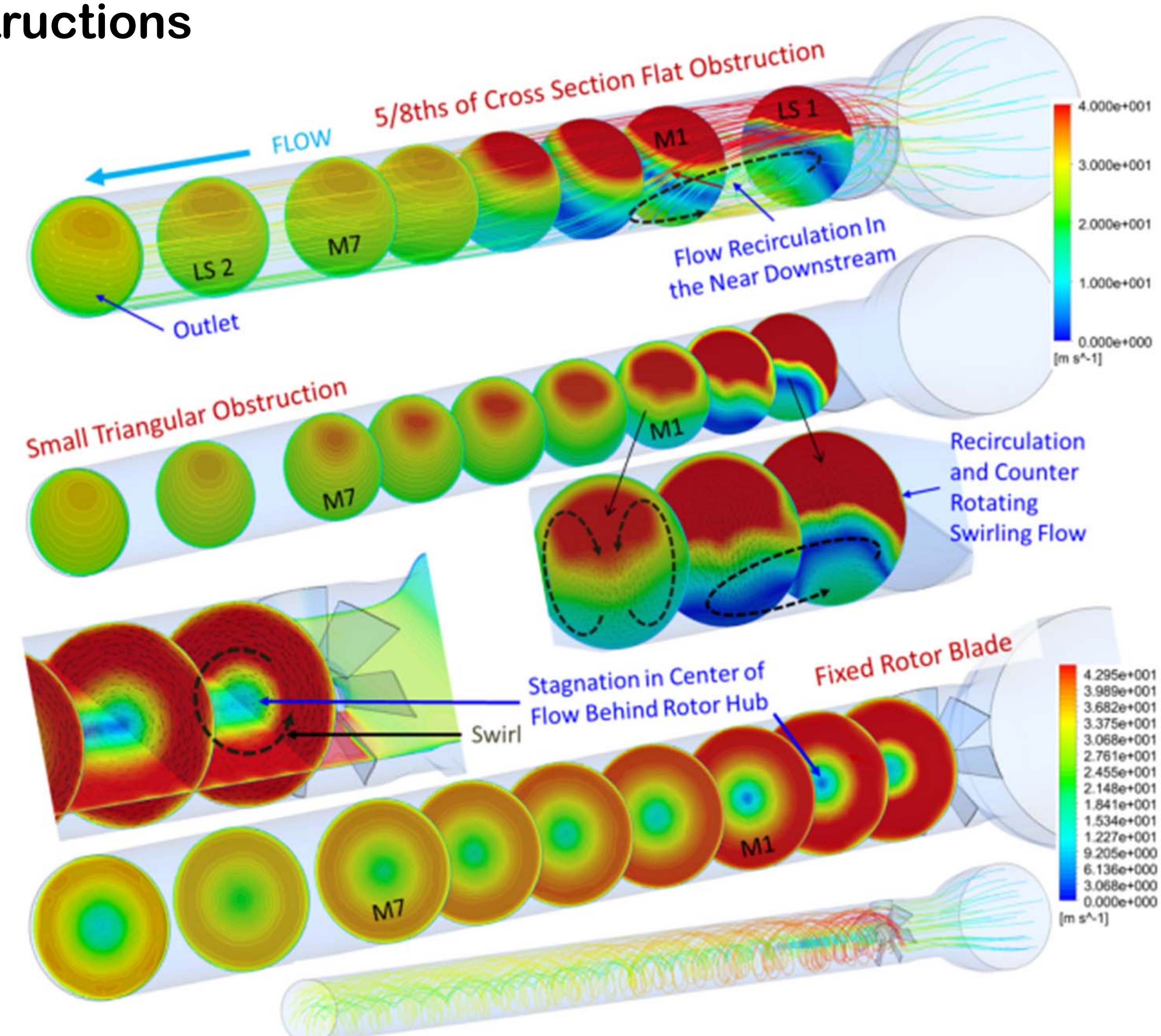


Use CFD to visualize distorted flows

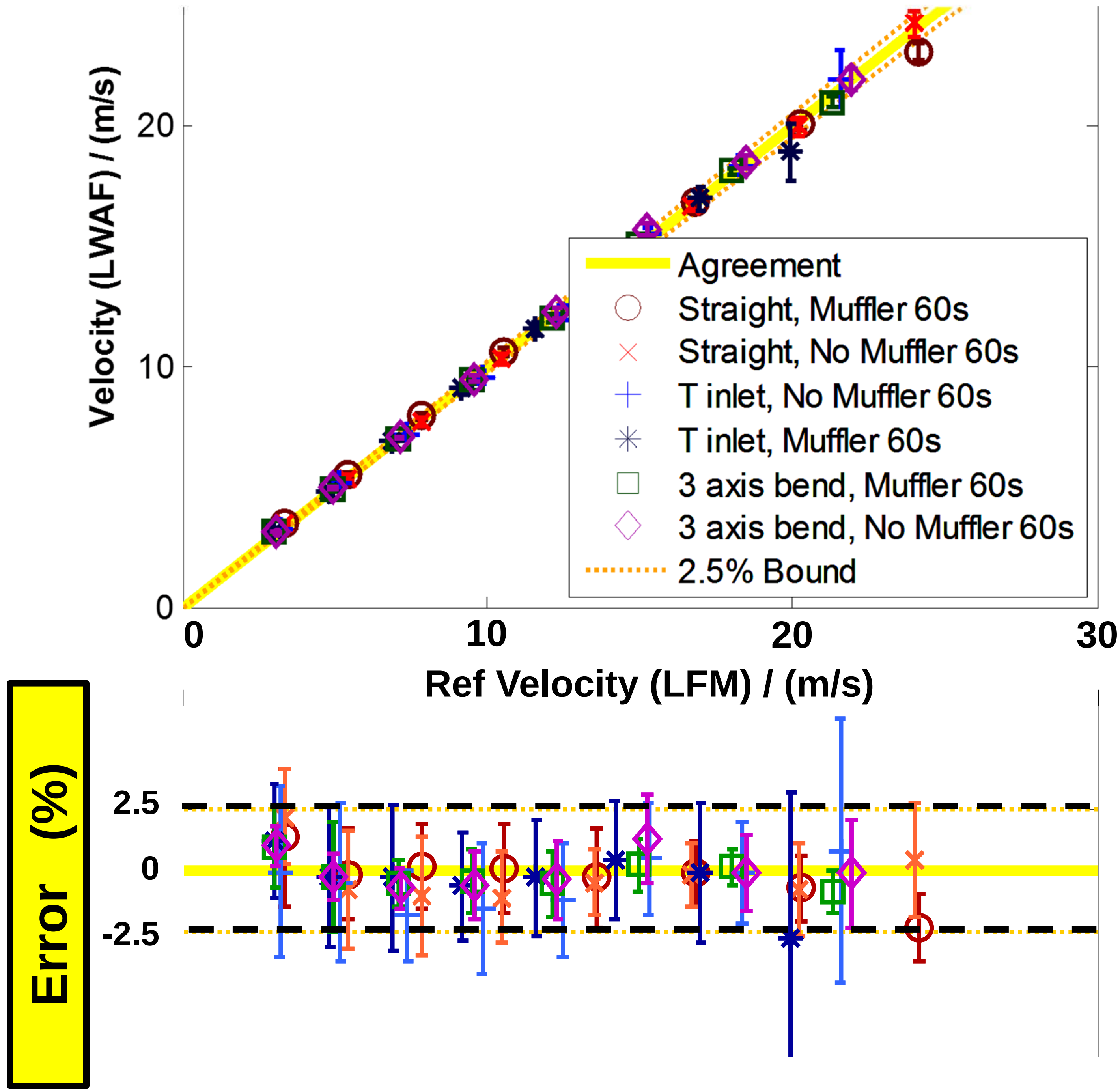
obstructions



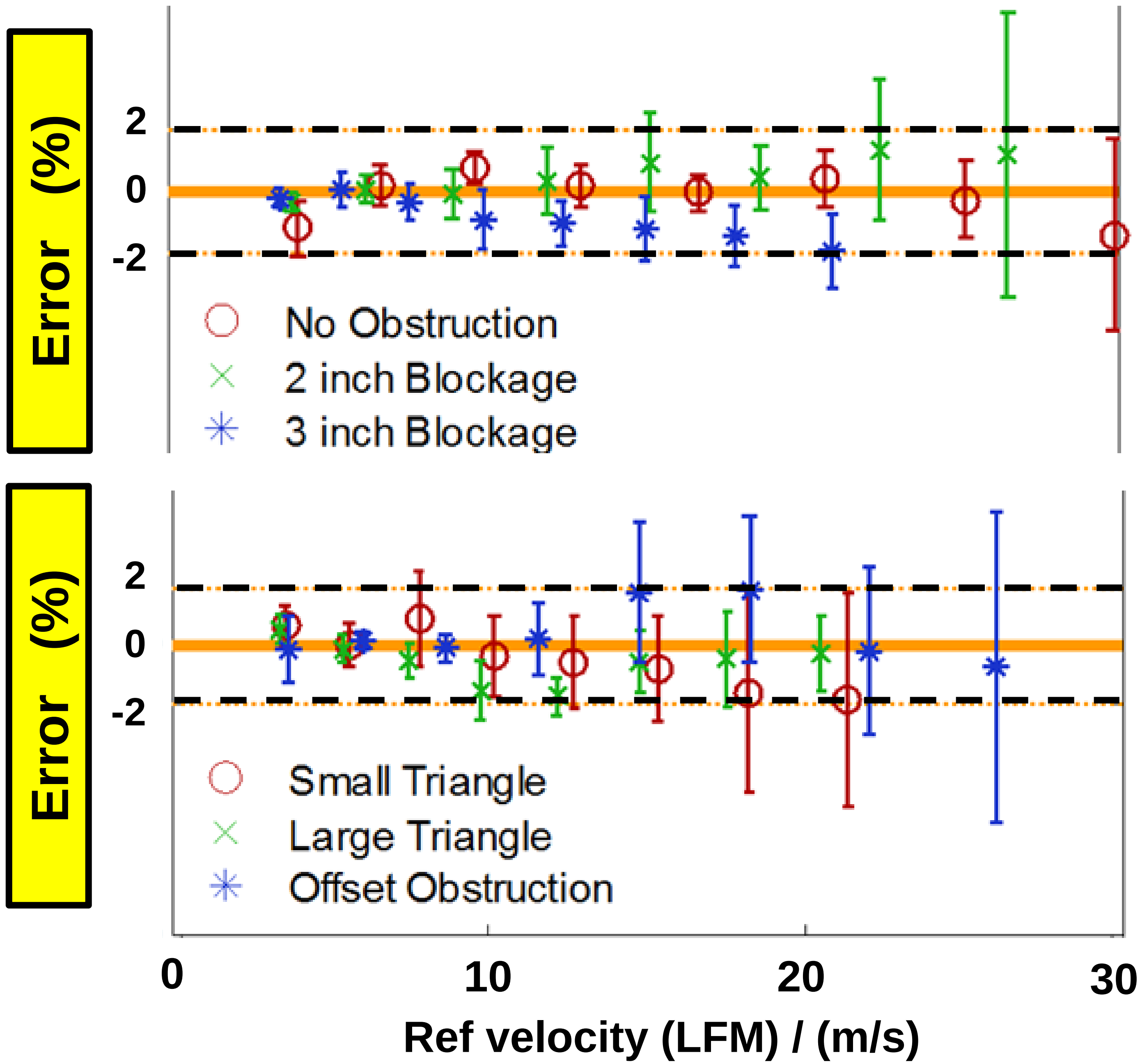




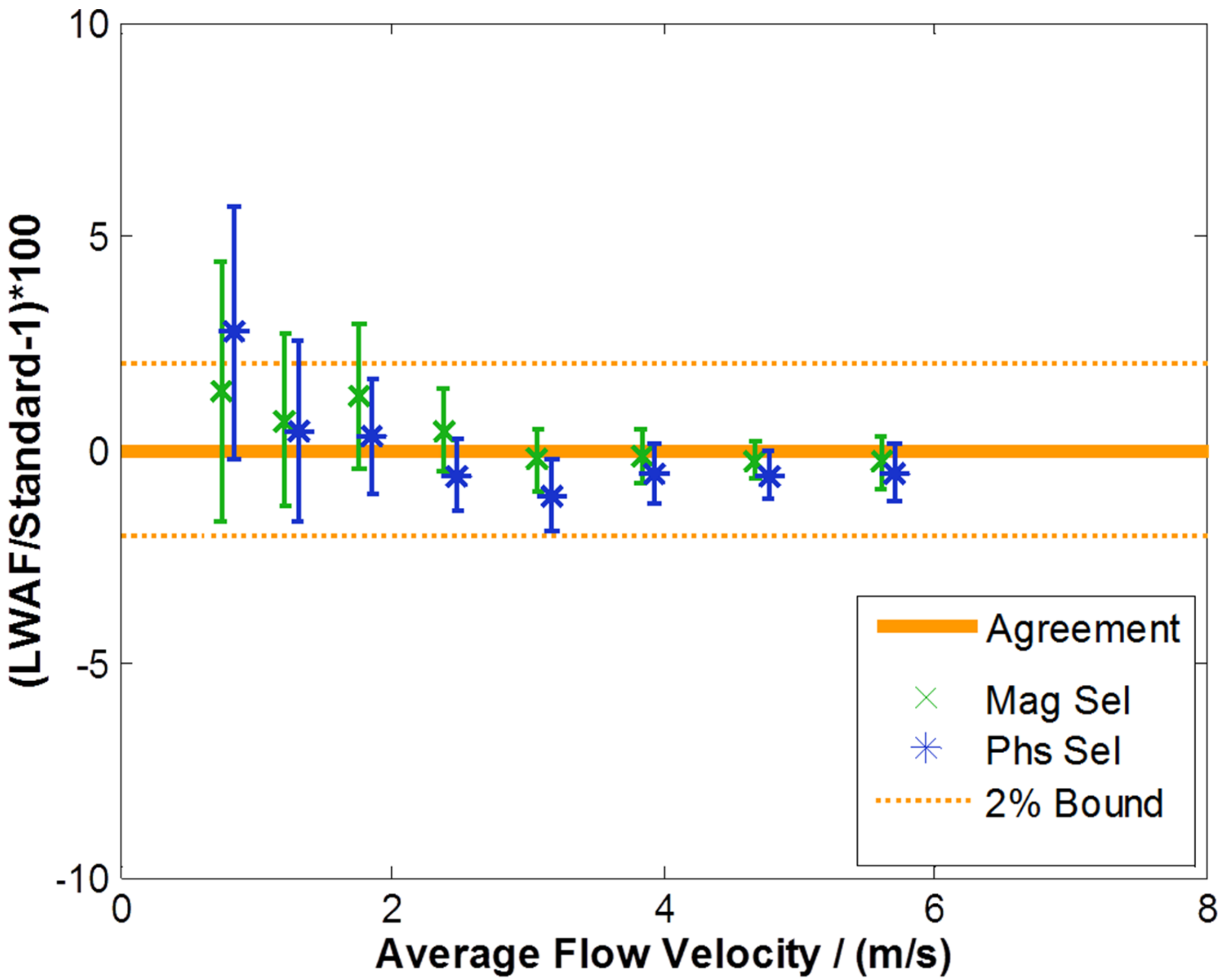
Measurements in distorted flow: It works!



Measurements in distorted flow: It works!



Scaling up to 20 cm diameter: It works!



Maximum flow is limited by fan's capacity

LWAF performance summary

The NIST 1/100th scale (10 cm diameter) LWAF facility was constructed to assess the performance and scalability

- $u(V) \approx 0.4\%$ and $u(c_0) \approx 0.01\%$ in symmetric flows up to 25 m/s
- $u(V) \approx 1\ \%$ in distorted flows with swirl, vortices, and recirculation up to 25 m/s
- scaling to 20 cm diameter: $u(V) \approx 1\ \%$ up to 6 m/s
- preliminary tests in humid air are promising

Challenges of implementing LWAF in smokestacks

- The LWAF approach is conceptually well suited for measuring ducted, low speed, highly distorted flows.

- Several difficulties arise when scaling the method to a power plant :
  - Low frequency operating conditions (~20 Hz)
  - Sound generation difficulties -> use noise correlations instead?
  - Signal to noise
  - Uncertain reflections from opening
  - Sound propagation through fog (dissipation, scattering)
  - Reynolds number scaling ($2x10^5$ -> $2x10^7$)
  - Compliance of duct liner (lowers apparent speed of sound)

Thank you for listening!

Bibliography

Testing long-wavelength acoustic flowmeter concepts for flue gas flows, L.J. Gorny, K.A. Gillis, and M.R. Moldover, 8th International Symposium on Fluid Flow Measurements, Colorado, 2012.

Calibration of a long-wavelength acoustic flowmeter using a lumped impedance acoustic model, L.J. Gorny, K.A. Gillis, and M.R. Moldover, Noise-Con 2013, Denver, CO.