Metrology for Monitoring Emissions from Coal-Burning Power Plants

NIST Greenhouse Gas & Climate Science Measurements Workshop

August 1, 2014 (9:00-9:30)

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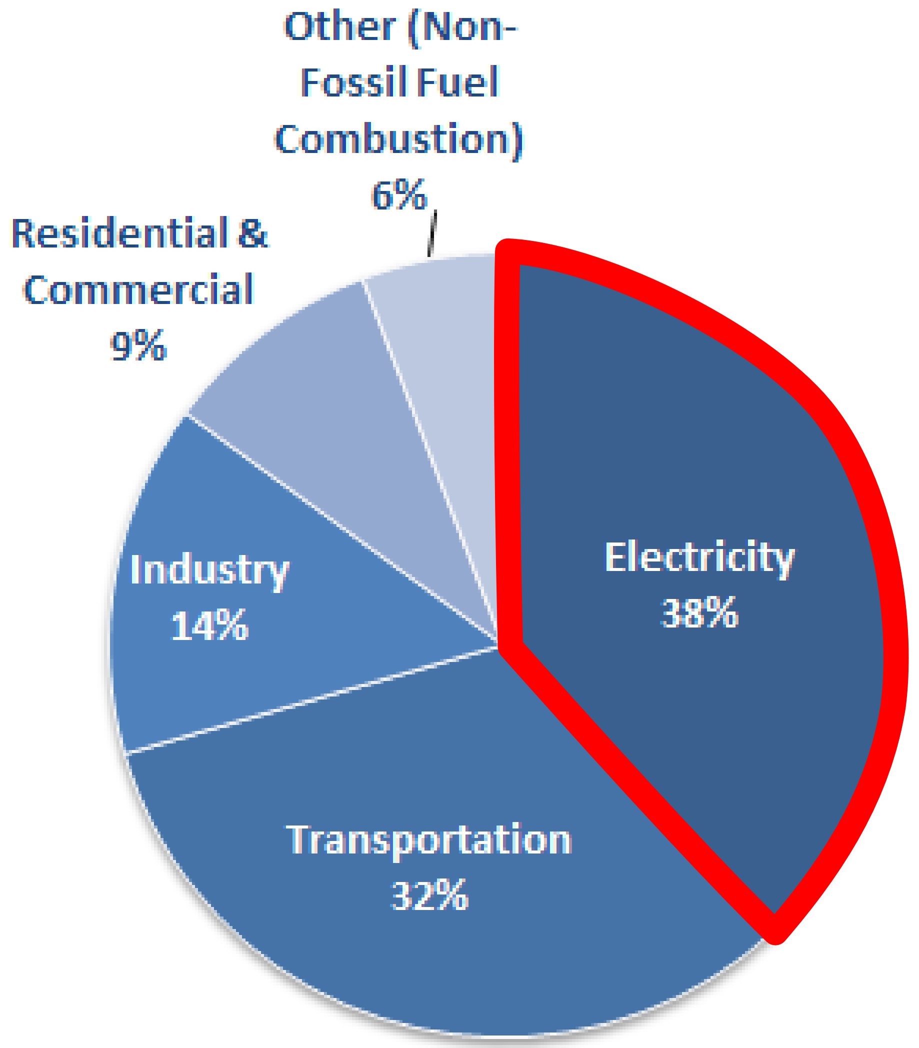
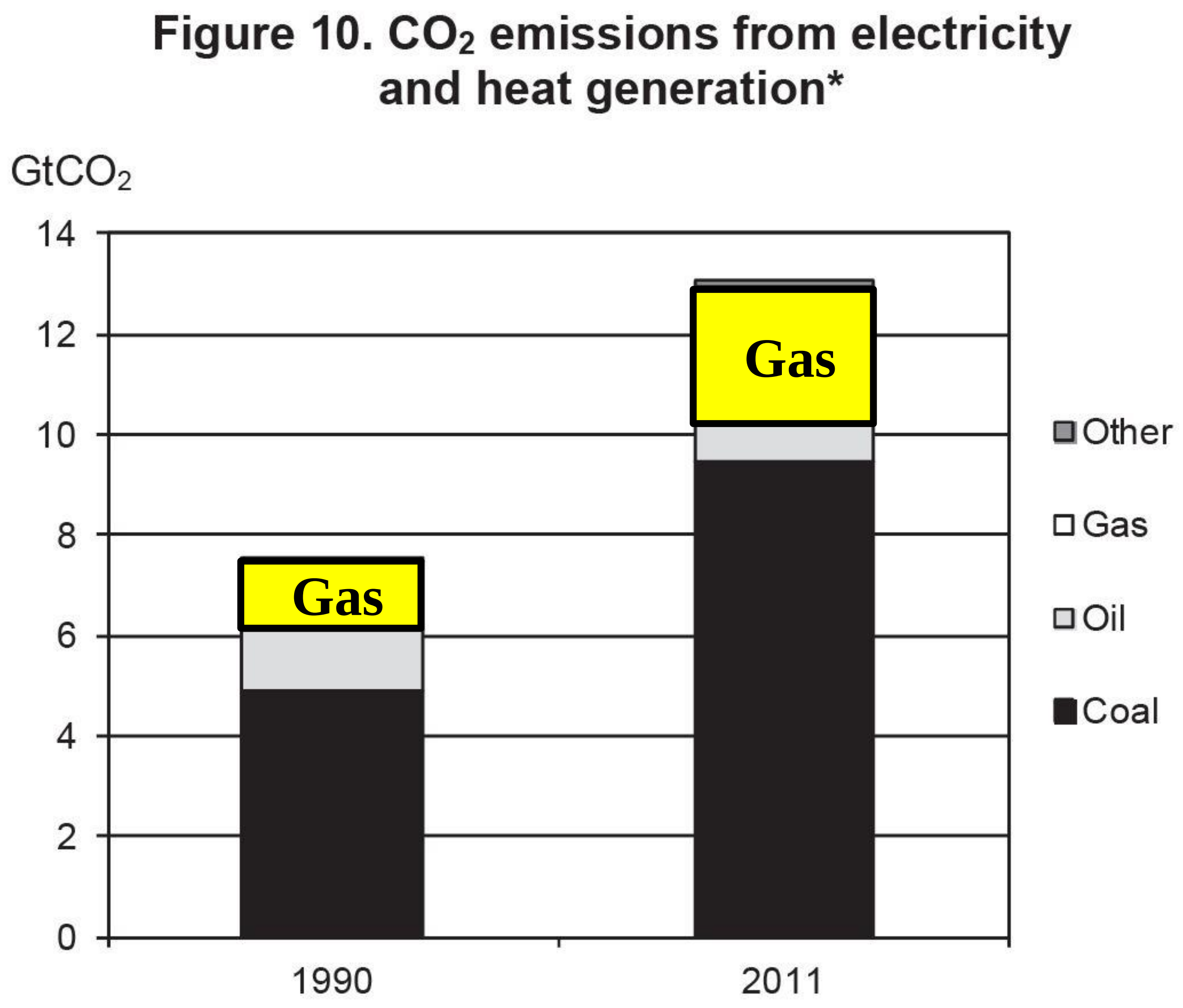
What is the Problem? Why is it Important?

U.S CO_2 Emissions, By Source (EPA, 2012)



World-Wide, Coal is Most Important, IEA (2013)



Power Plants Fueled With Natural Gas

- **Volume of natural gas flowing into a power plant can be metered to better than 1 % with traceability to NIST (and SI)**

- **Energy content of natural gas is determined within ~1 % from composition analysis *via* gas chromatography. Can be checked by calorimetry.**

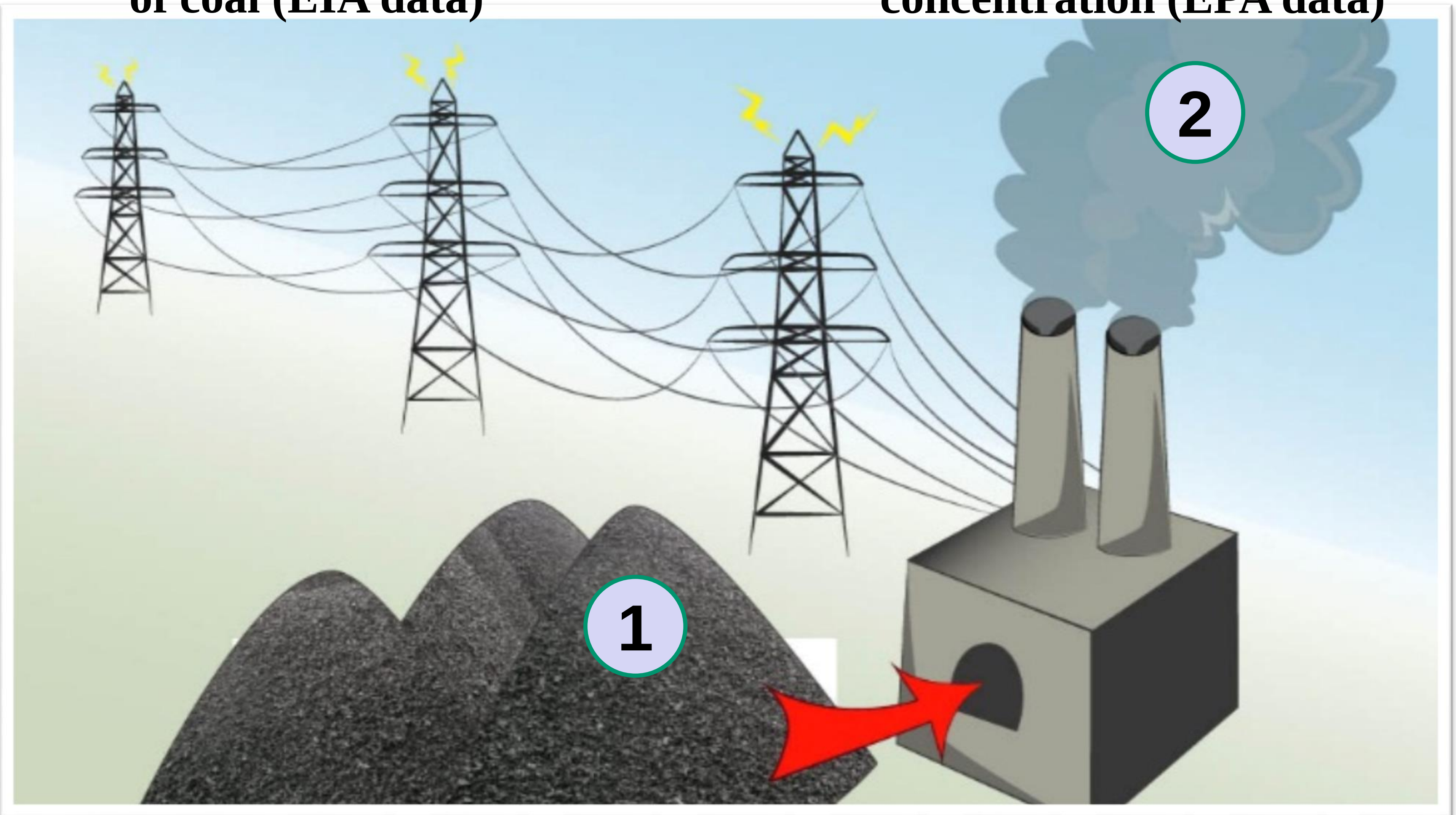
- **If required, on-line composition metering could be adopted (Rhurgas) with a reasonable cost**

- **Only minor measurement problems, if combustion is complete**

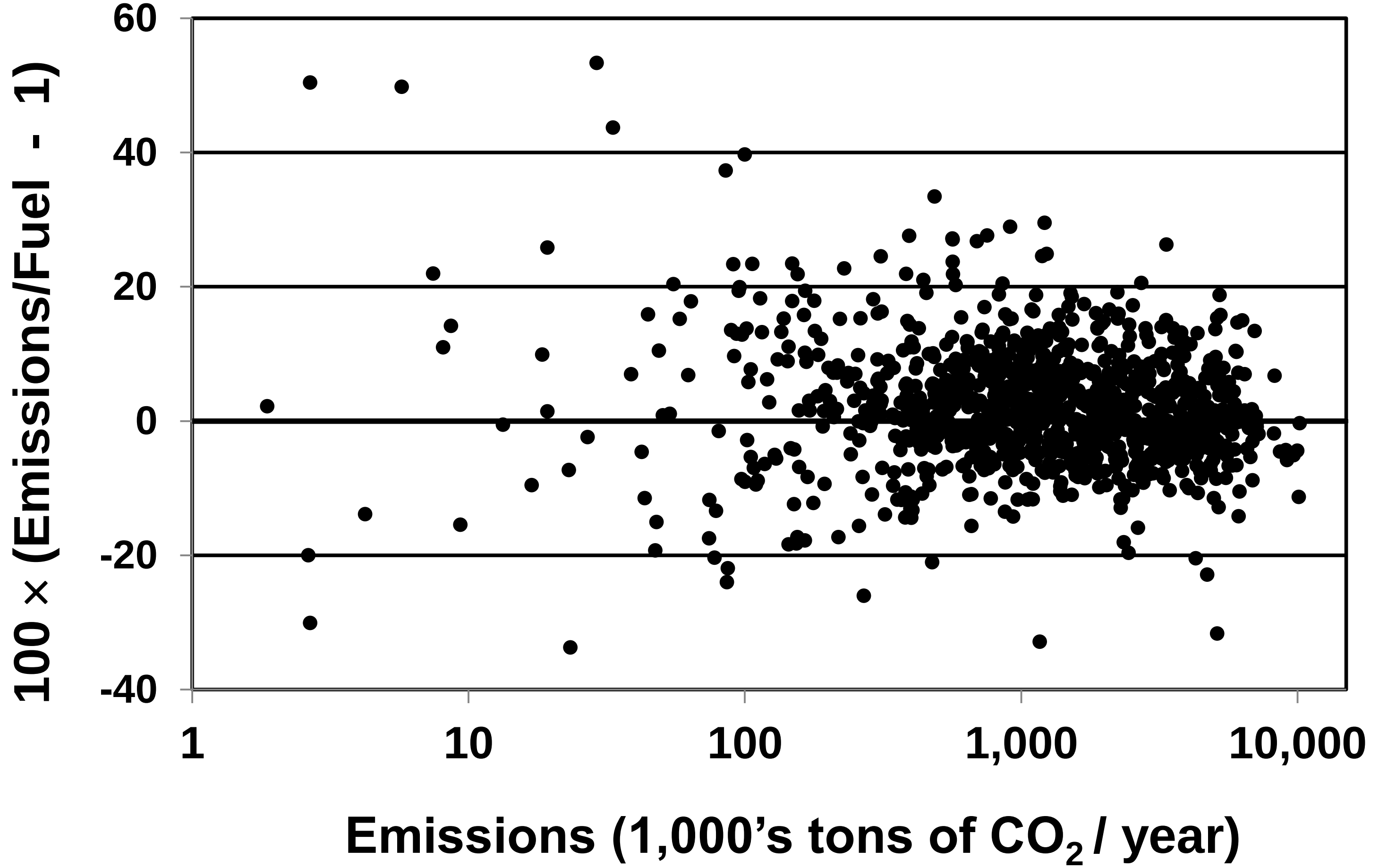
Coal-Fired Plants: Two methods to determine CO_2

1 ***Fuel:***
Amount & quality of coal (EIA data)

2 ***Emissions:***
Flow and CO_2 concentration (EPA data)

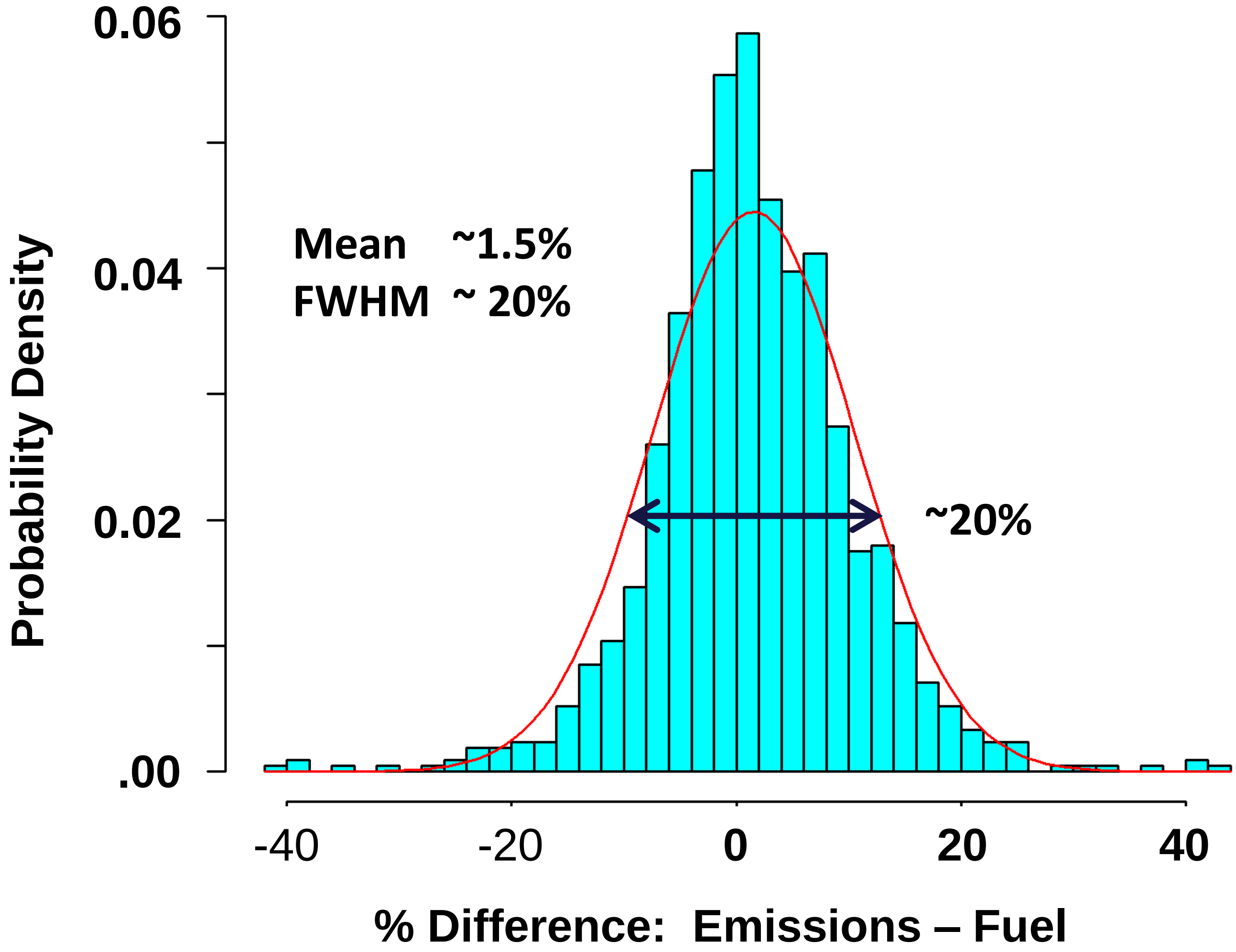


Coal-Fired Plants: Two methods to determine CO_2 Do they agree?



Coal-Fired Plants: Two methods to determine CO_2

Do they agree? **No!**



Measurement Need

- **Carbon controls (carbon tax, cap and trade) require accurate, *SI-traceable*, measurements of the CO_2 flux emitted by coal-burning power plants.**

- **Coal is too heterogeneous to serve as a surrogate for CO_2**

- **Current CO_2 flux measurements may be biased too high.**

- **NIST Objective: *SI-traceable*, CO_2-flux measurements with 1 % uncertainty at a reasonable cost,**
  to provide the technical basis for carbon control in US and internationally

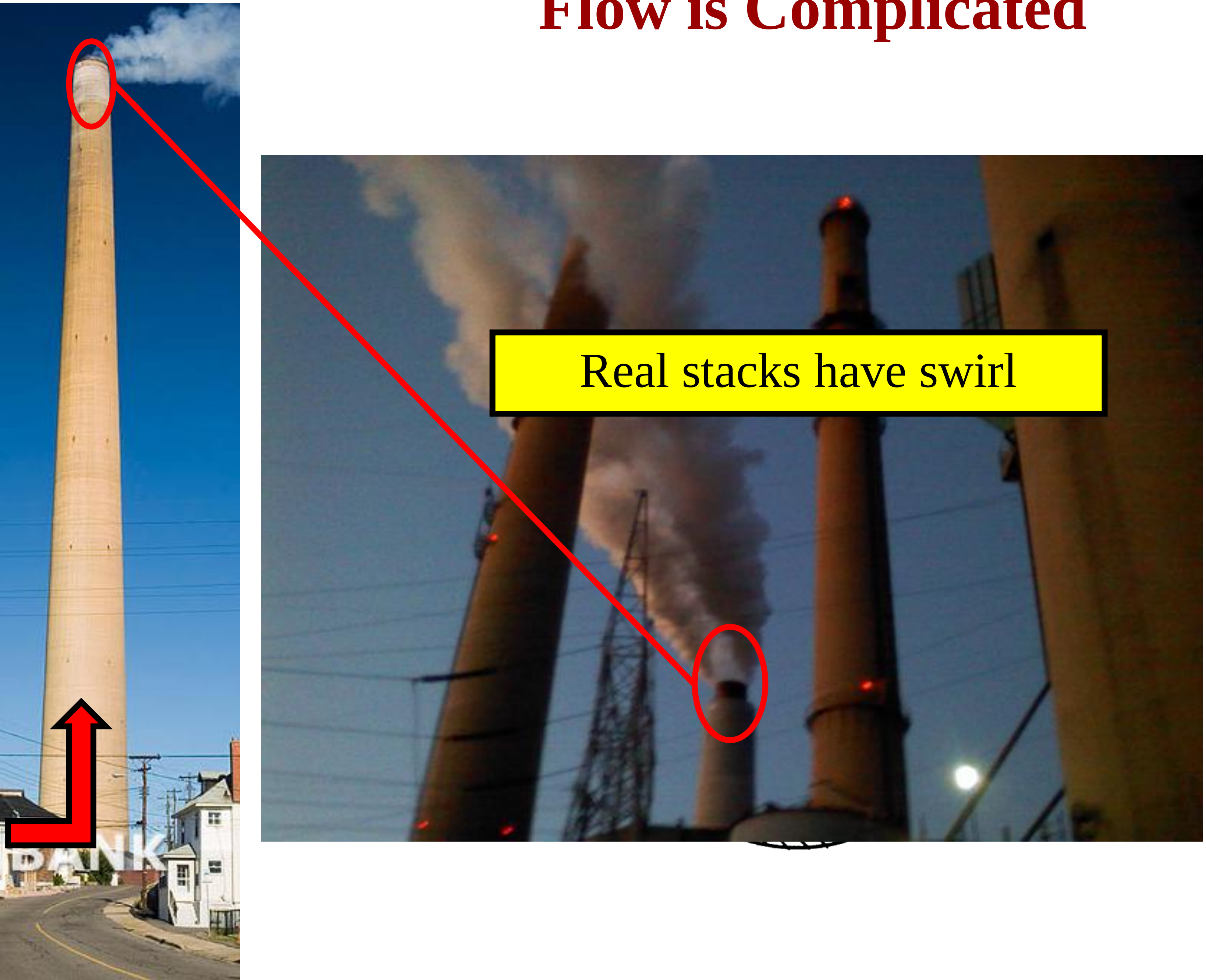
Why are Emissions Measurements Difficult?

- **Stacks are big: cannot calibrate a 10 m diameter meter in any lab**
- **Flow is fast: 5 m/s to 25 m/s**
- **High Reynolds number ~ 10^7; cannot be simulated.**
- **Nasty conditions:**
  - **Access via outside cat-walk on older stacks**
  - **Noisy**
  - **Gas is either "hot" (no scrubber 90+ °C) or "ambient & raining" (scrubber)**
  - **Gas is asphyxiating: composition (by volume)**

13.7 %	**CO_2**
3.4 %	**O_2**
74.8 %	**N_2**
8.0 %	**H_2O**

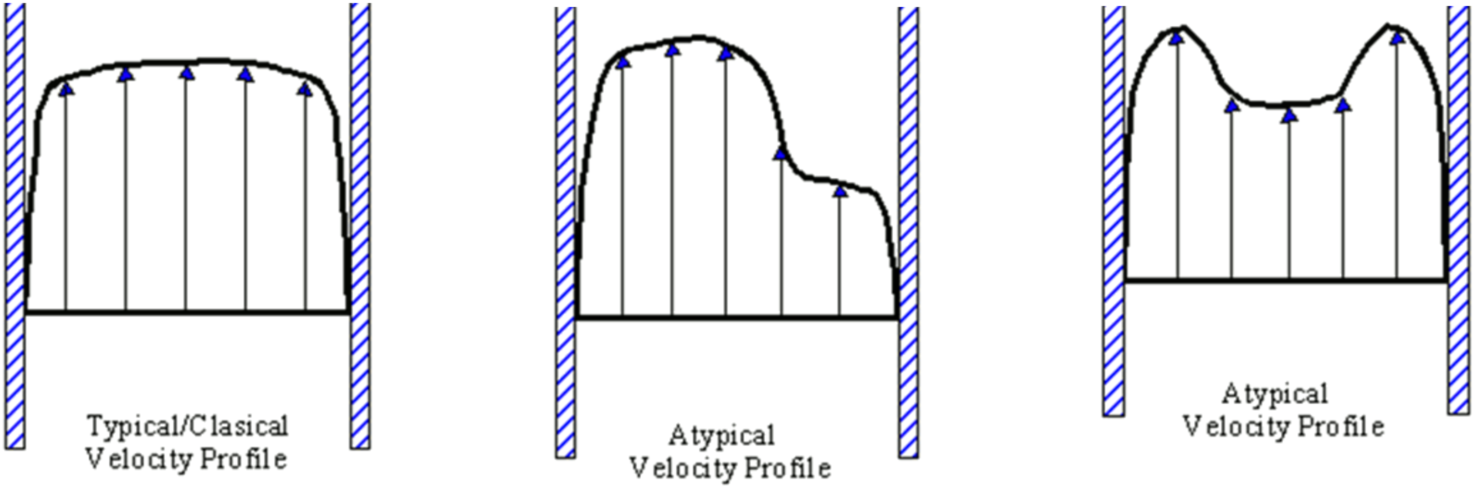
- **Flow is complicated**

Flow is Complicated



Flow is Complicated

Real stacks have skew



How are Emissions Measurements Made Today?

1) Using EPA-approved protocols, flue gas
   flux is continuously monitored
   composition is continuously analyzed for O_2, Hg, S, NO_x
   to comply with emission controls for Hg, S, NO_x

2) The instruments used for 1) comprise the
   CEMS = Continuous Emissions Monitoring System

3) Typical CEMS uses two ultrasonic meters to monitor flow

4) Annual "Relative Accuracy Test Audit" (RATA) "calibrates" ultrasonic CEMS flow monitors. Typically, the flow is surveyed with a S-probe, that is temporarily installed on the stack.

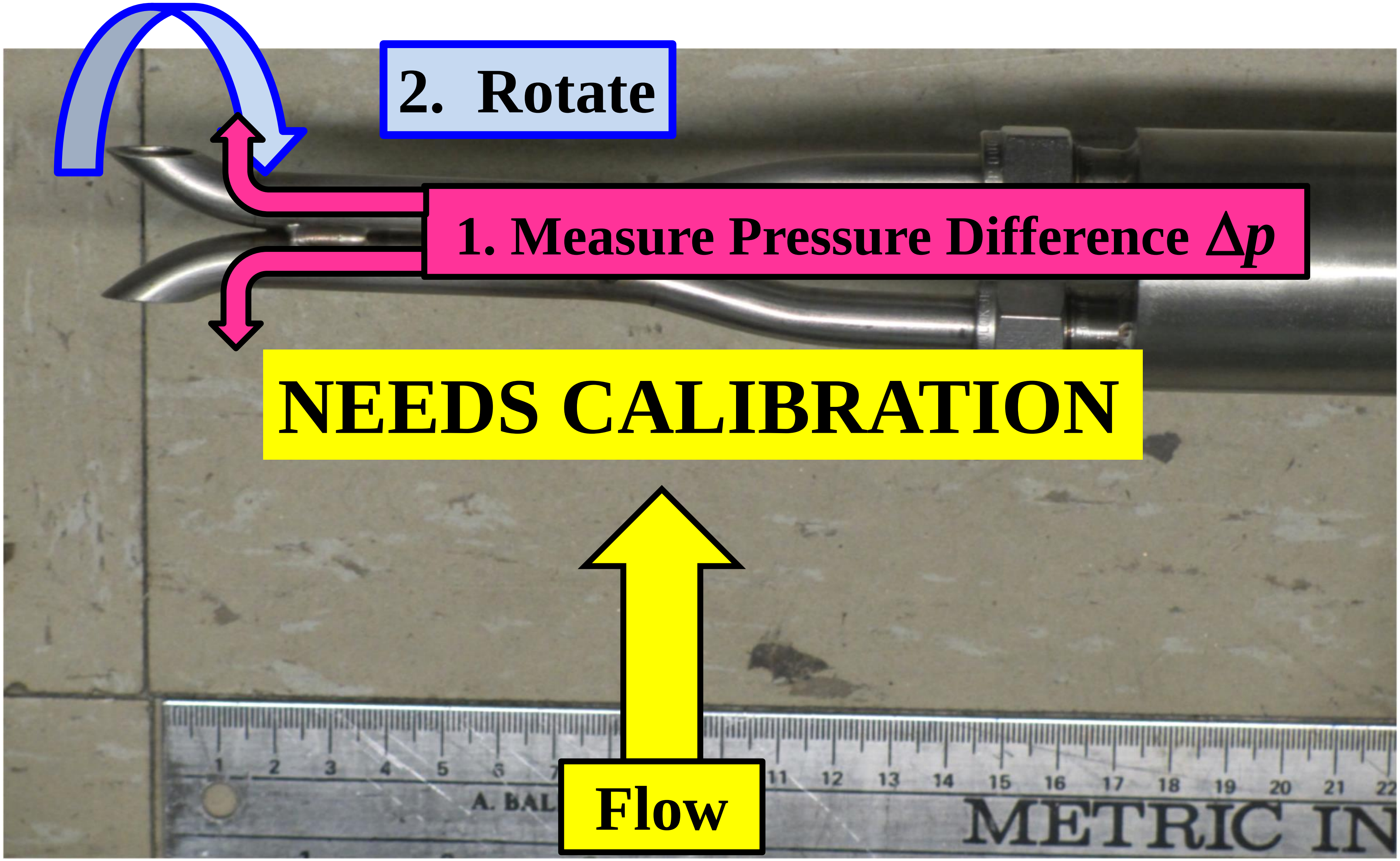
5) As the name suggests, the EPA protocols provide only relative accuracy, not uncertainty relative to primary standards.

What is NIST Doing?

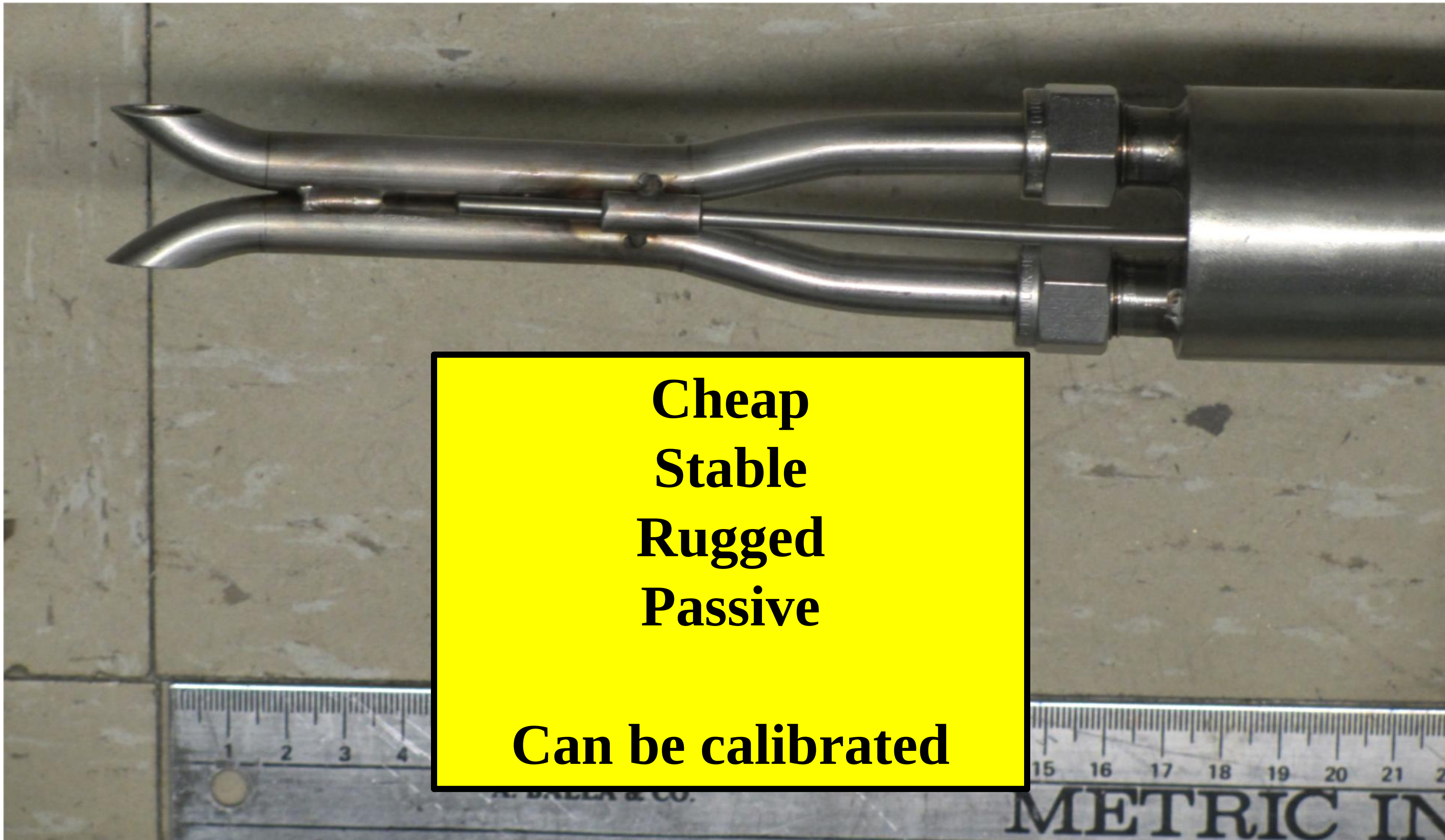
1) **Tie EPA-CEMS instruments and protocols to primary standards**
   (*Essential for International Recognition*)
   A. Calibrate Pitot probes under realistic conditions
   B. Measure sensitivity of ultrasonic flow meters to complex flows
   C. Understand/model results to generalize and scale up

2) **Invent alternative flow standards for flue gas stacks**
   (*to check entire measurement chain*)
   A. Long Wavelength Acoustic Flow Meter
   B. Tracer Dilution

S-probe: workhorse for stack flow measurements



S-probe: workhorse for stack flow measurements



Cheap
Stable
Rugged
Passive

Can be calibrated

NIST's wind tunnel generates well-defined airspeeds to calibrate anemometers

NIST Wind Tunnel: BTW Parameters

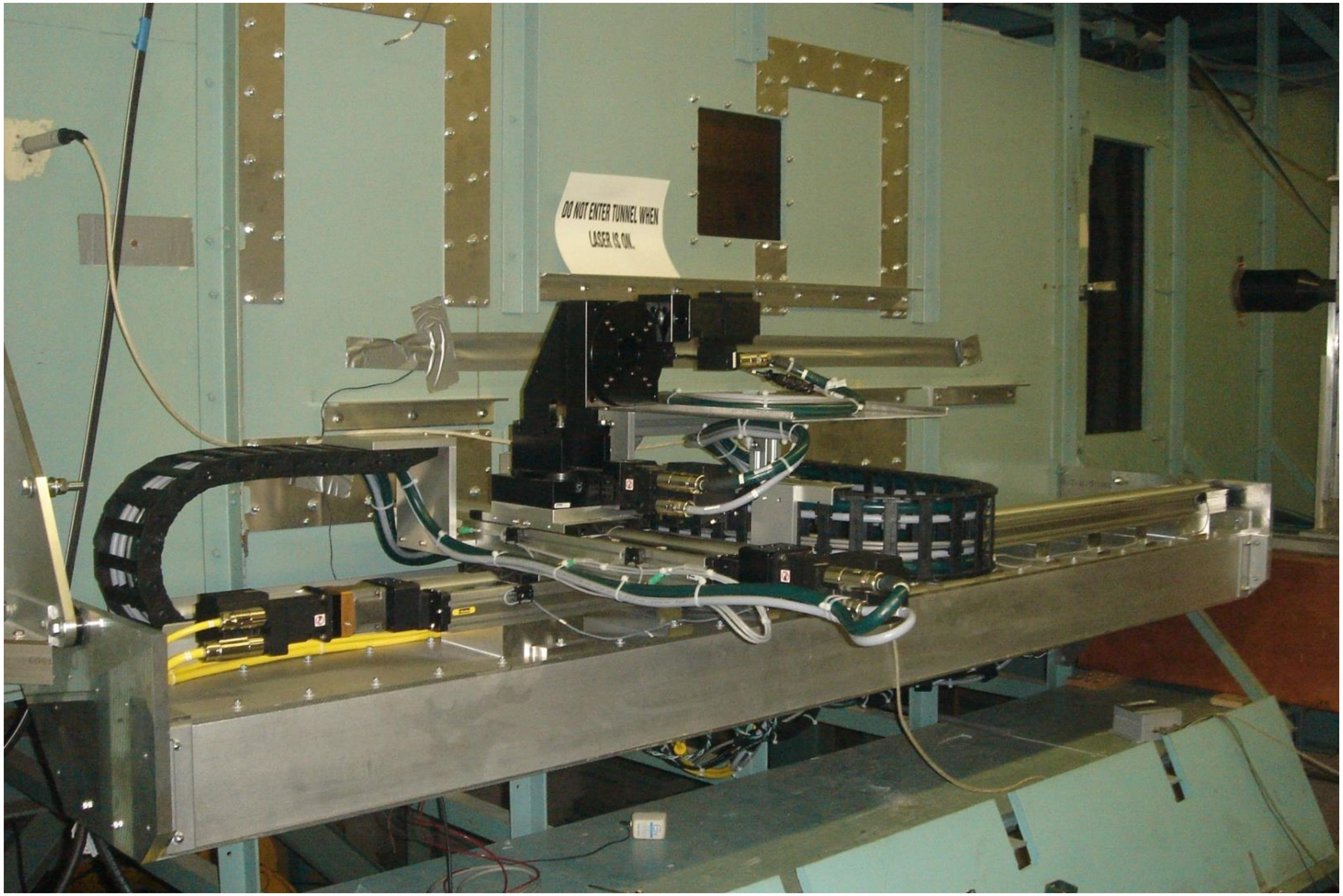
- **Large test volume ⇒ small wall effects**

- ***k* =2 uncertainty of 0.42%, 5 m/s to 25 m/s**

- **Low (0.1 %) turbulence intensity**

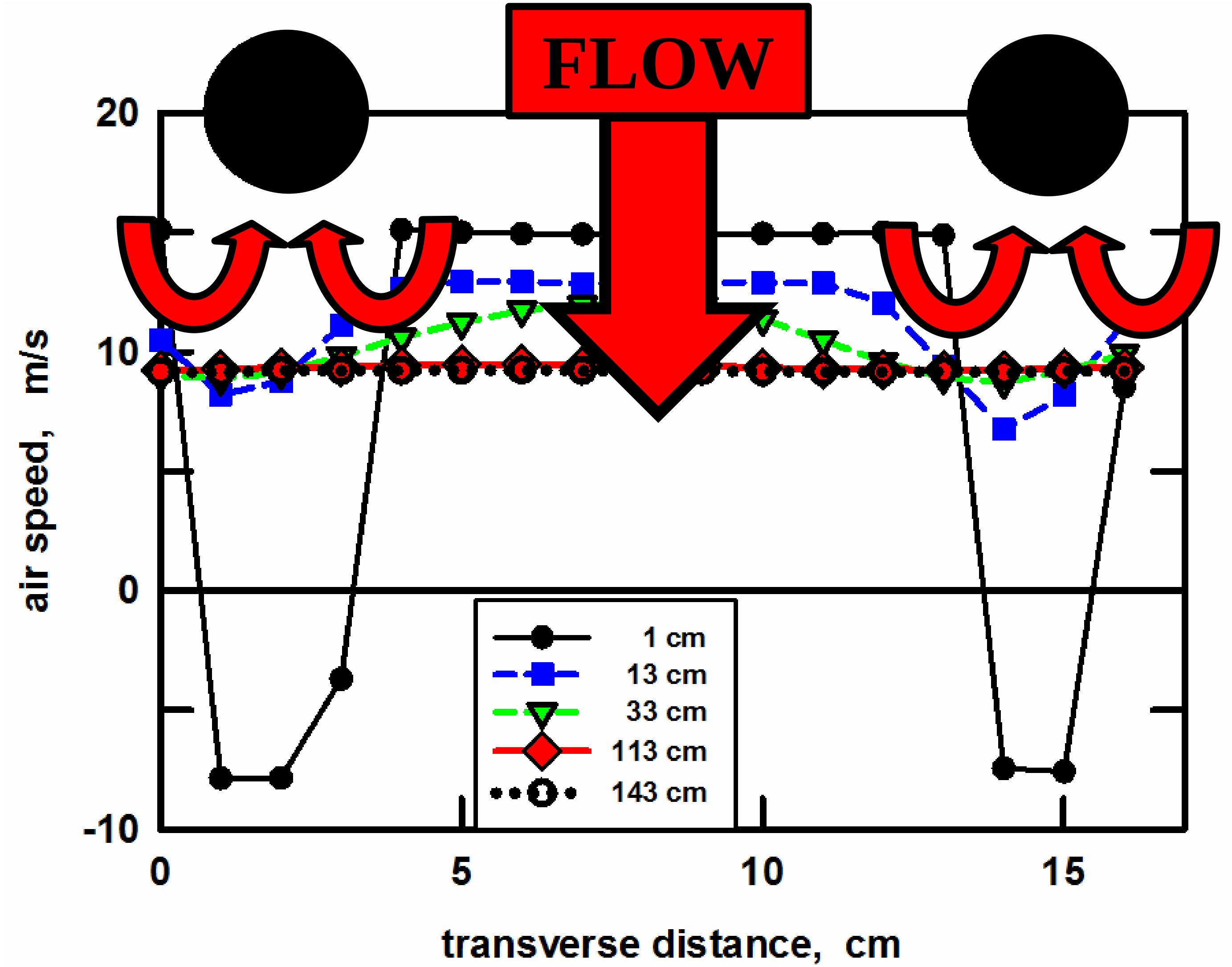
- **Uniform flow along tunnel axis (1-dimensional flow)**

Automated stage for changing pitch angle and yaw angle



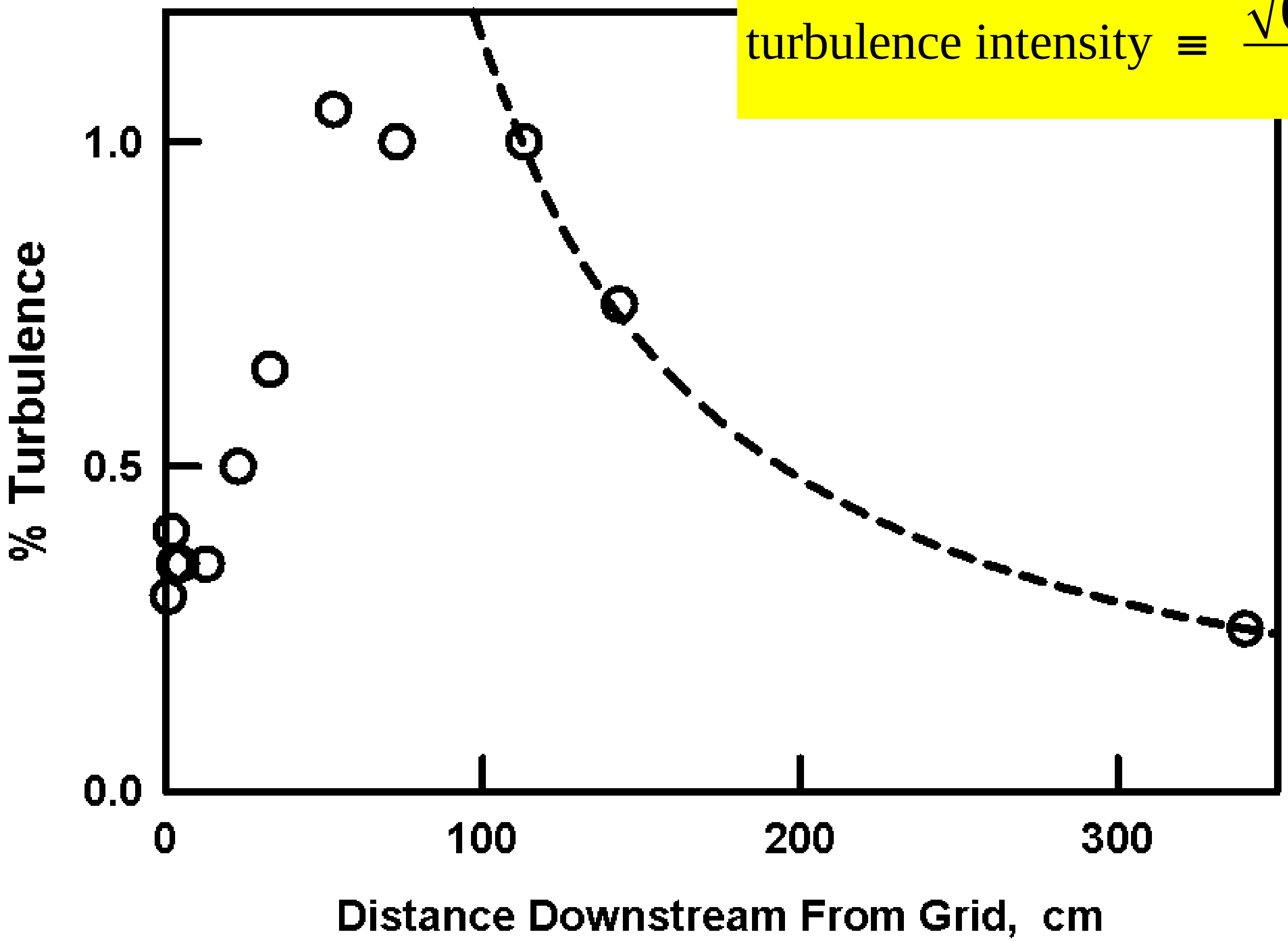
Modify wind tunnel: add Grid to Generate Turbulence

Measure Effects of Grid



Measure Effects of Grid

turbulence intensity $\equiv \dfrac{\sqrt{(\vec{u}-\langle\vec{u}\rangle)^2}}{\langle\vec{u}\rangle}$



S-Probe, (used in EPA protocol 2)

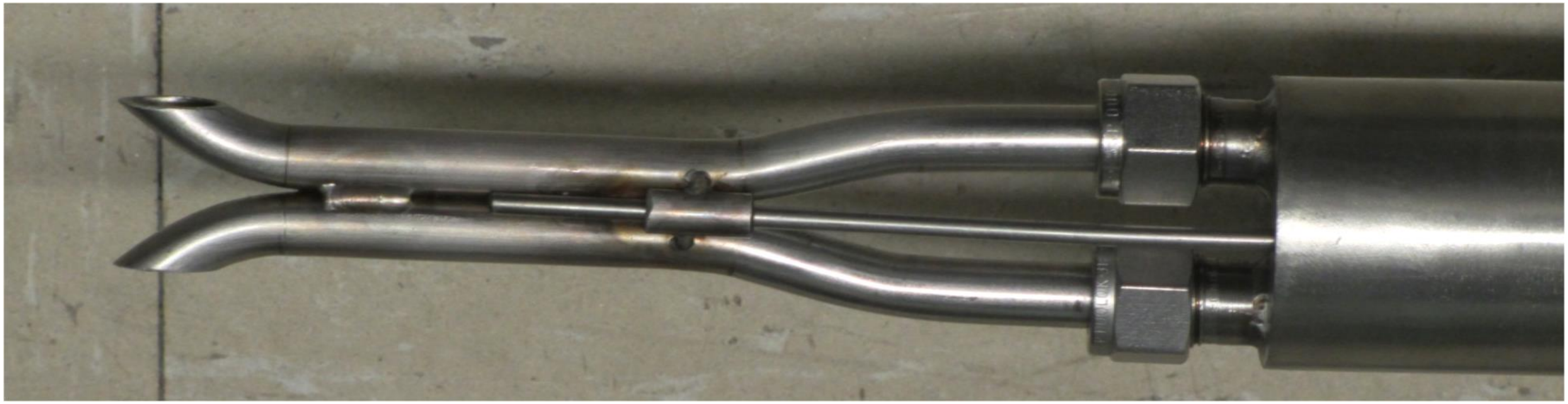
Calibration Factor is a Function of 4 variables

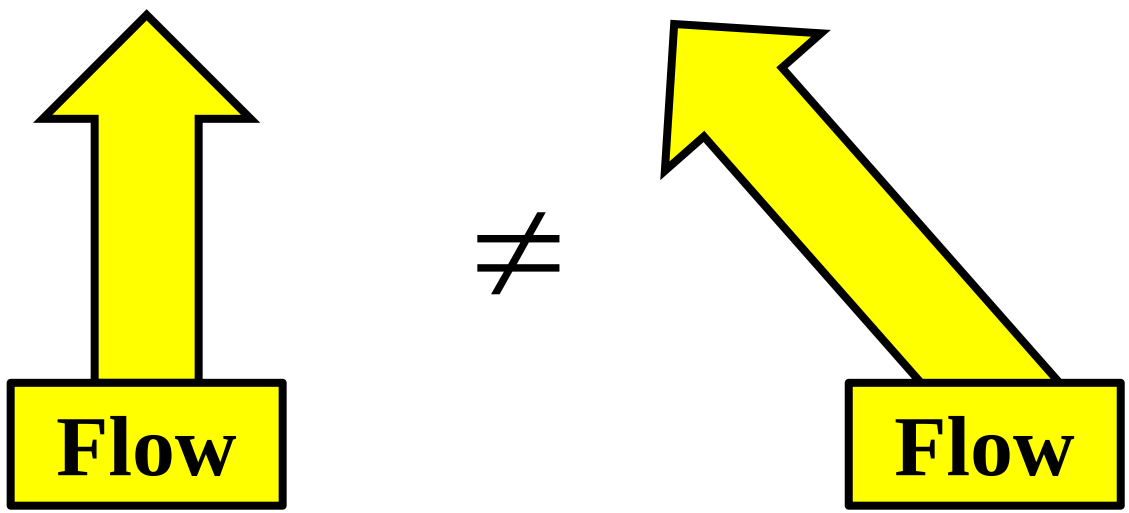
1. **Air speed**
2. **Pitch angle**
3. **Yaw angle**
4. **Turbulence intensity**

EPA protocol assumes calibration factor = 0.84

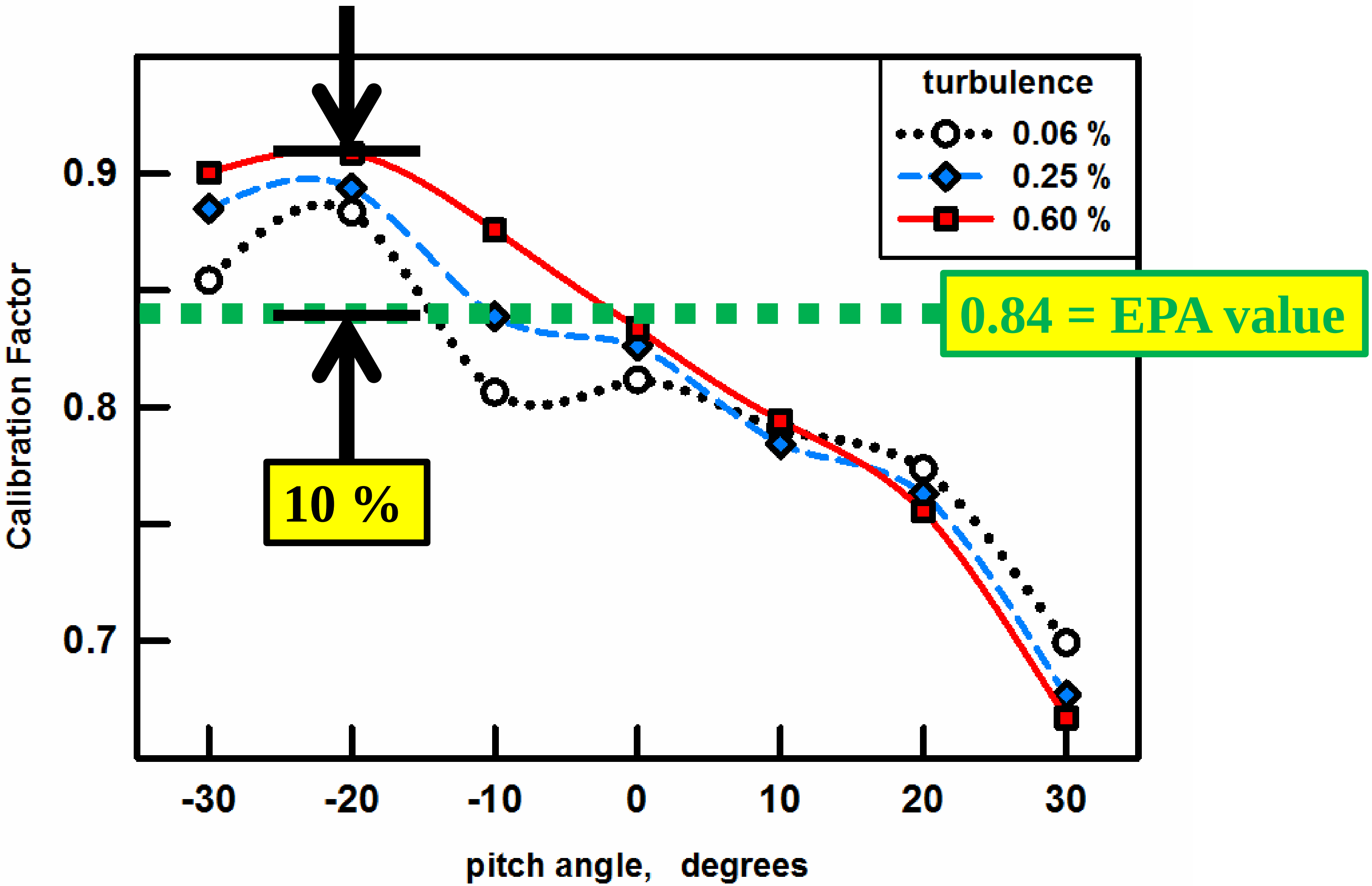
(literature shows small, linear dependence on air speed)

S-probe: cannot detect pitch

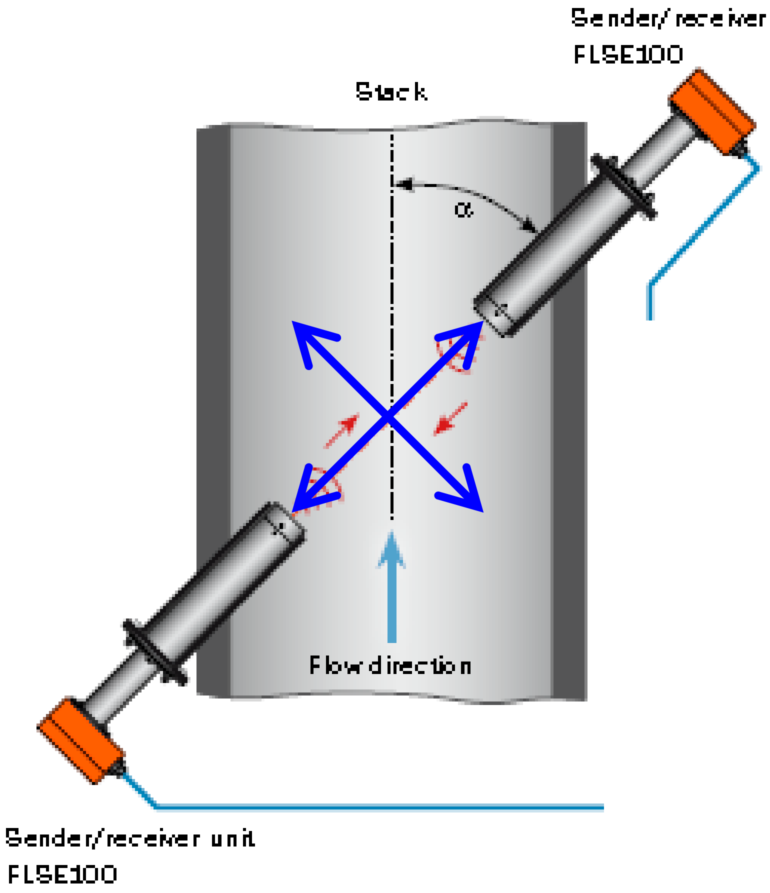




Results for “typical” S-probe at 10 m/s



Typical CEMS Ultrasonic Flow Meter



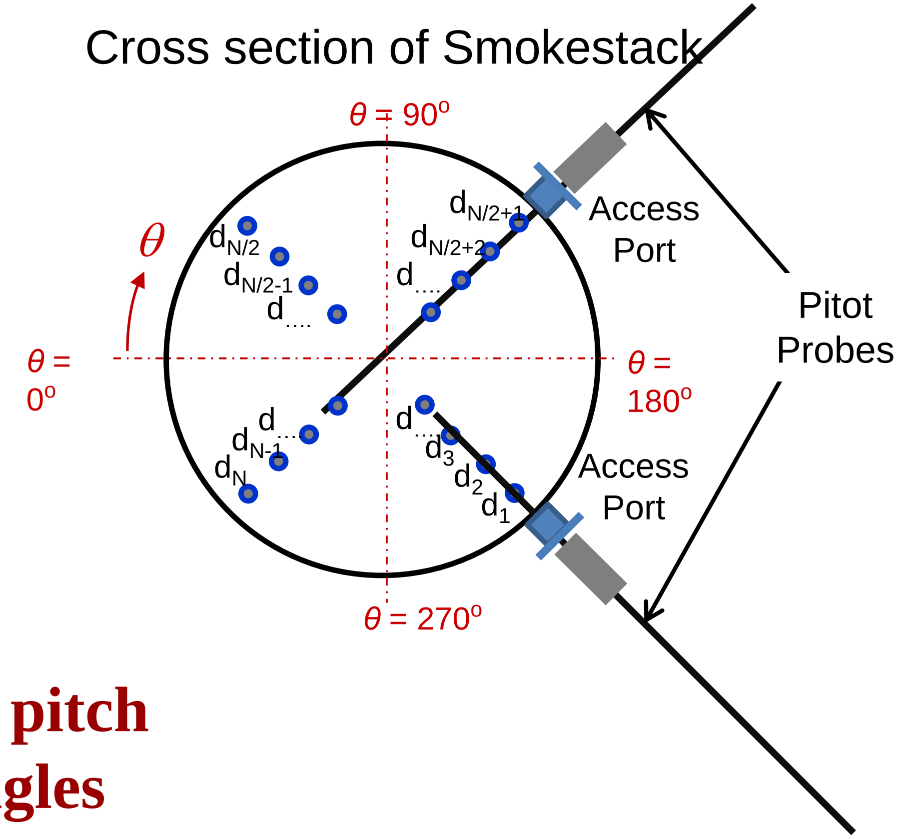
Typically, 2 crossing paths

Measures time of flight of ultrasonic waves “sound beam” moving with and against flow ⇒ velocity component along beam and sound speed

Does not detect swirl or velocity profile distortions. If these change between calibrations the results will be biased

"Calibrate" CEMS using Calibrated Pitot Tube

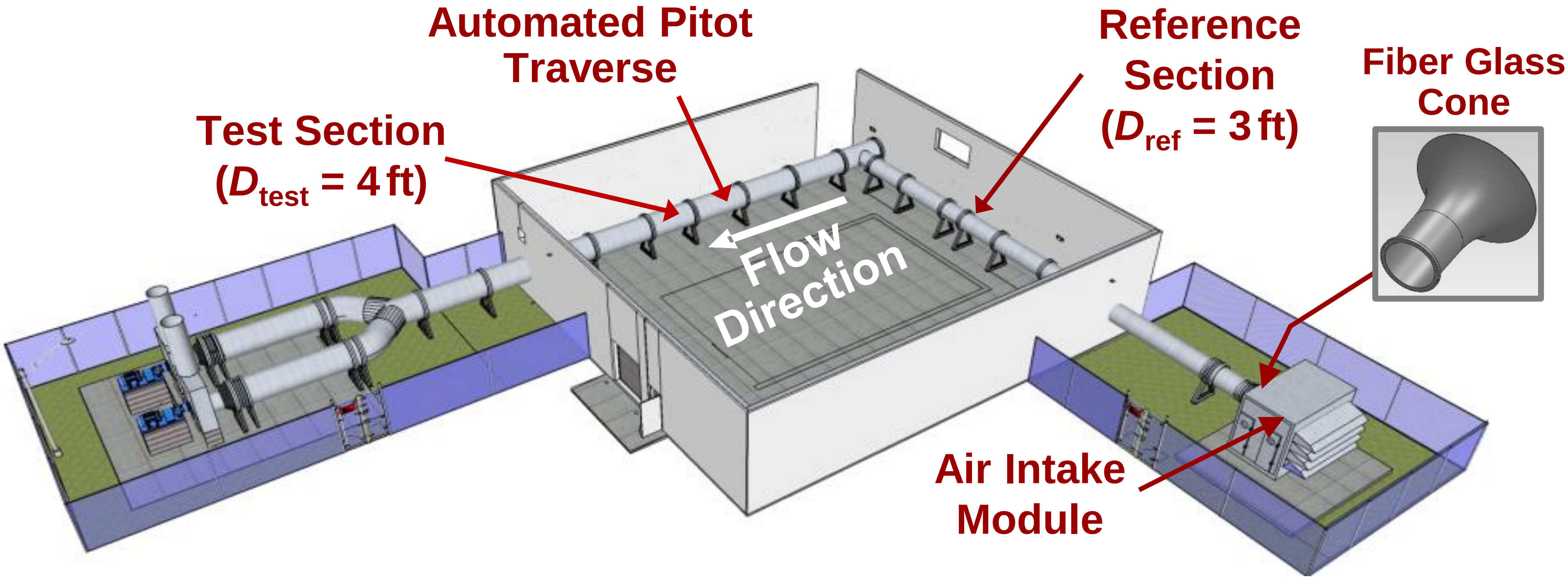
- **Pitot Probe traverse along two diameters in stack cross section**
- **Traverse Protocol Based on EPA Documents**
  - 40 CFR Part 60
  - 40 CFR Part 75 (2F, 2G, 2H)



Measurement problems:

- **Pitot probes not calibrated for pitch**
- **Velocity measured at only 2 angles**
- **Integration errors**

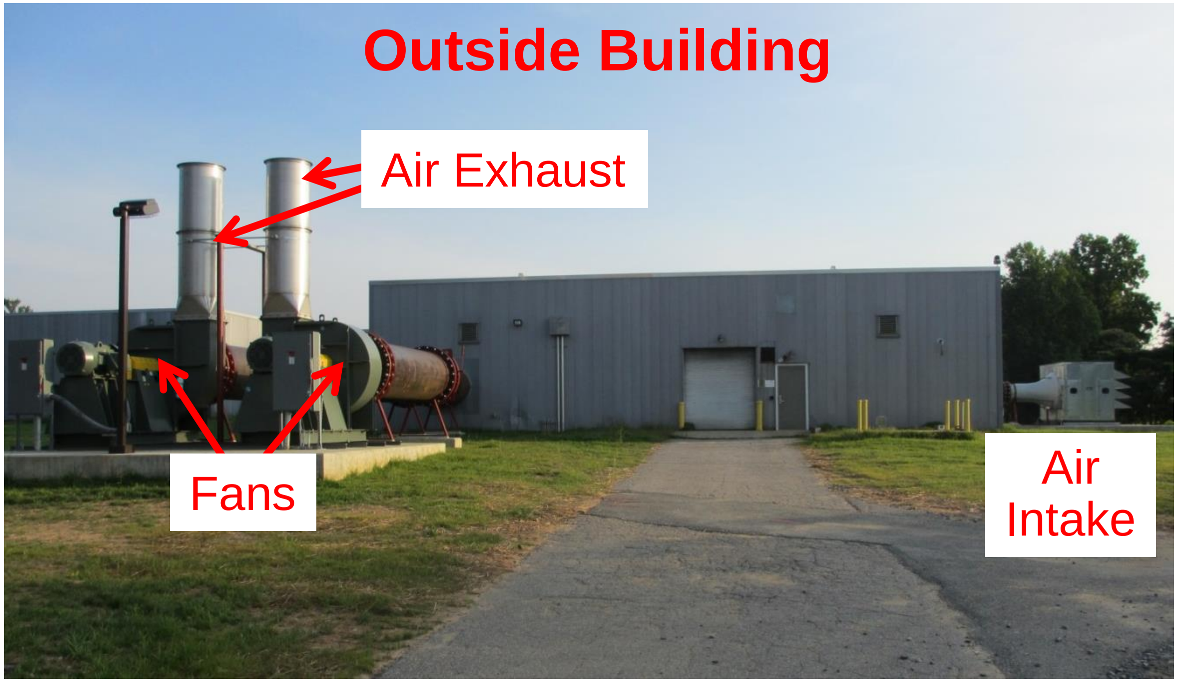
Facility to study/solve measurement problems must generate known, turbulent, swirling flows

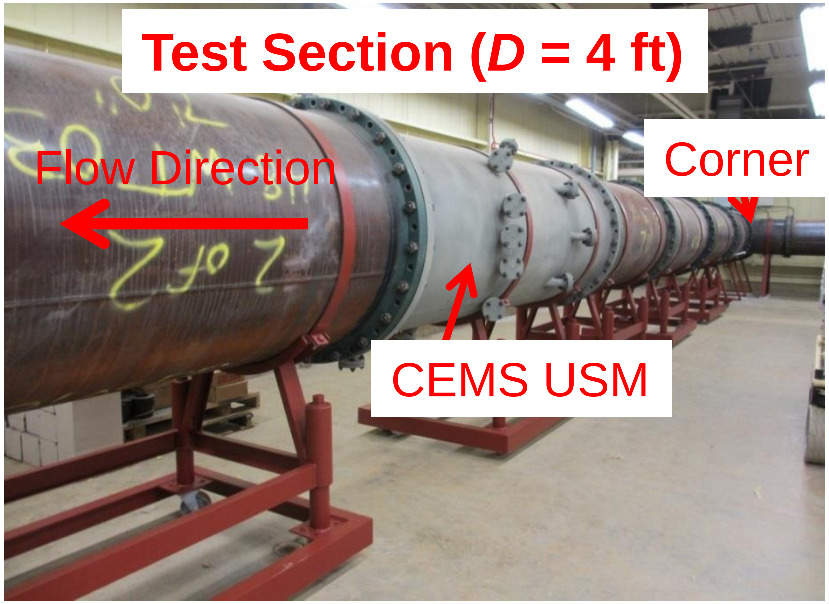


Horizontal orientation for cost and safety

Smokestack Simulator is 1/10th the diameter of typical stack

Smokestack Simulator





Design of Smokestack Simulator

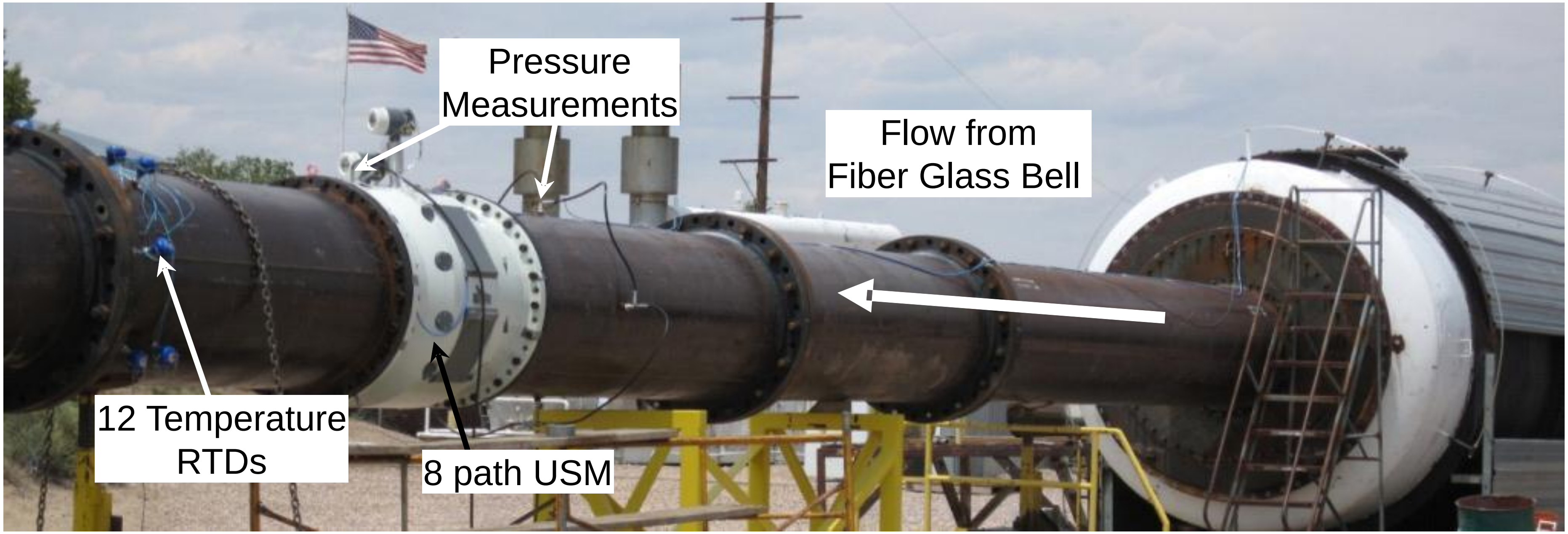
8 Path ultrasonic flow meter

Installed after 19 D of straight pipe (good flow)

Calibrated against NIST flow standards

Determines bulk flow to 0.5%

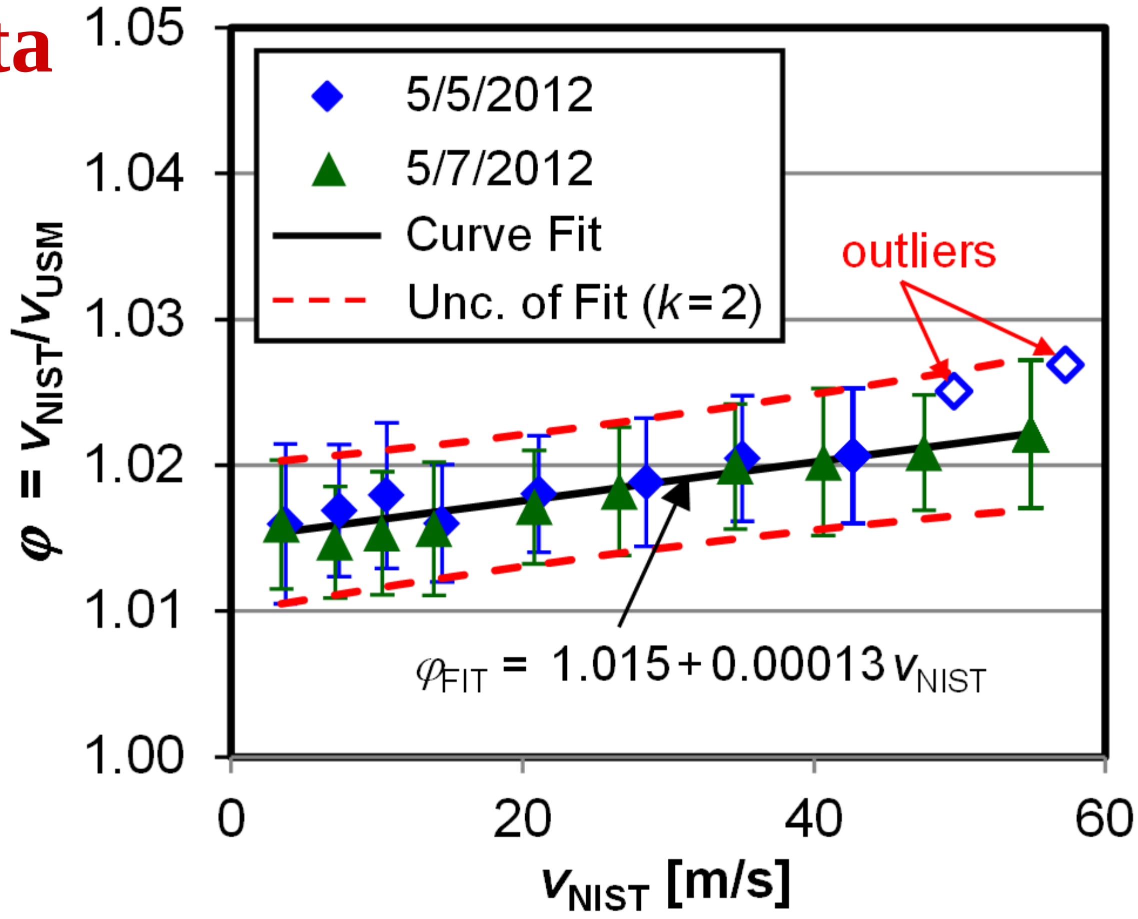
Calibration of USM at CEESI in Colorado



$$\varphi = \frac{V_{\mathrm{NIST}}}{V_{\mathrm{USM}}}$$

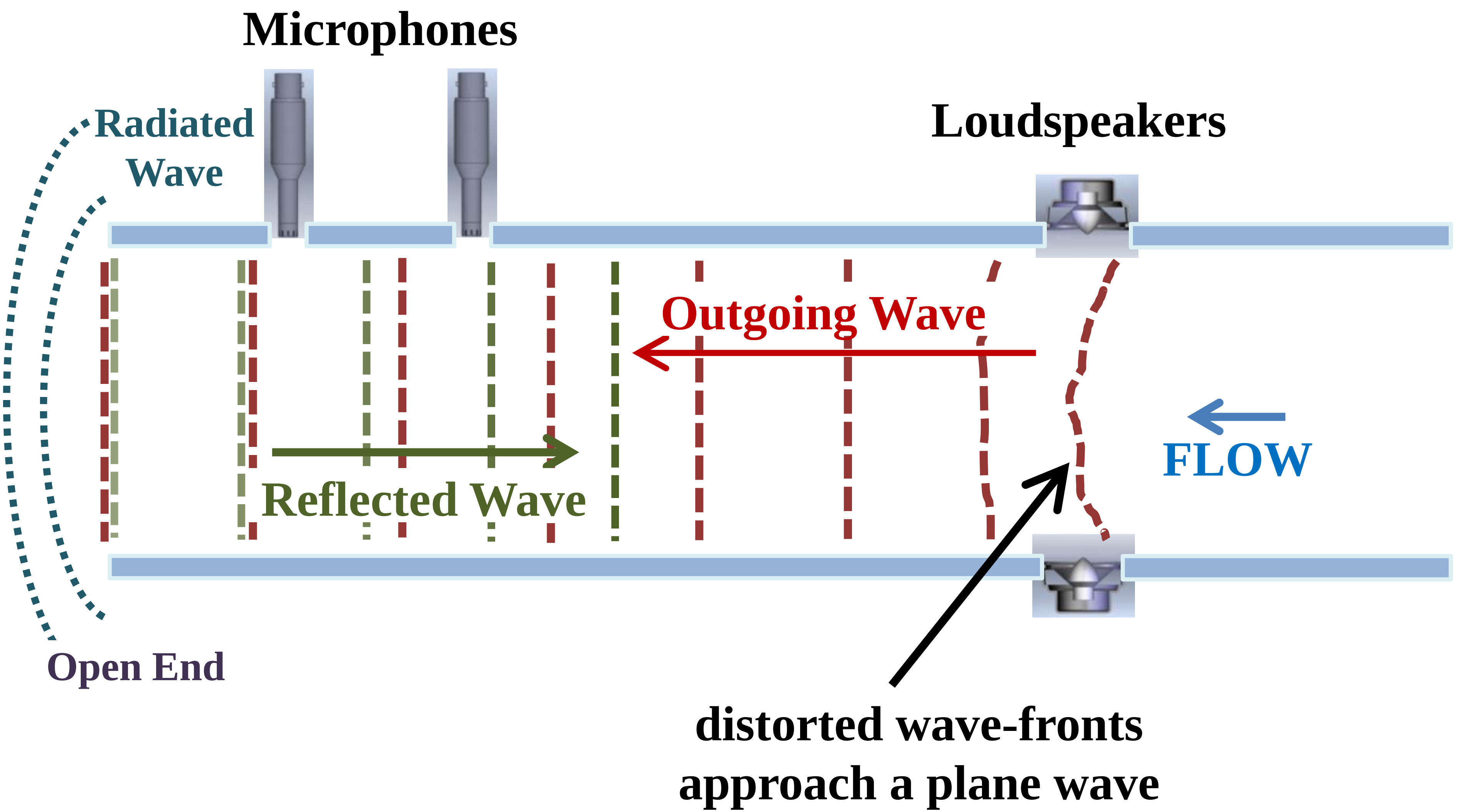
Calibration Factor

Calibration Data



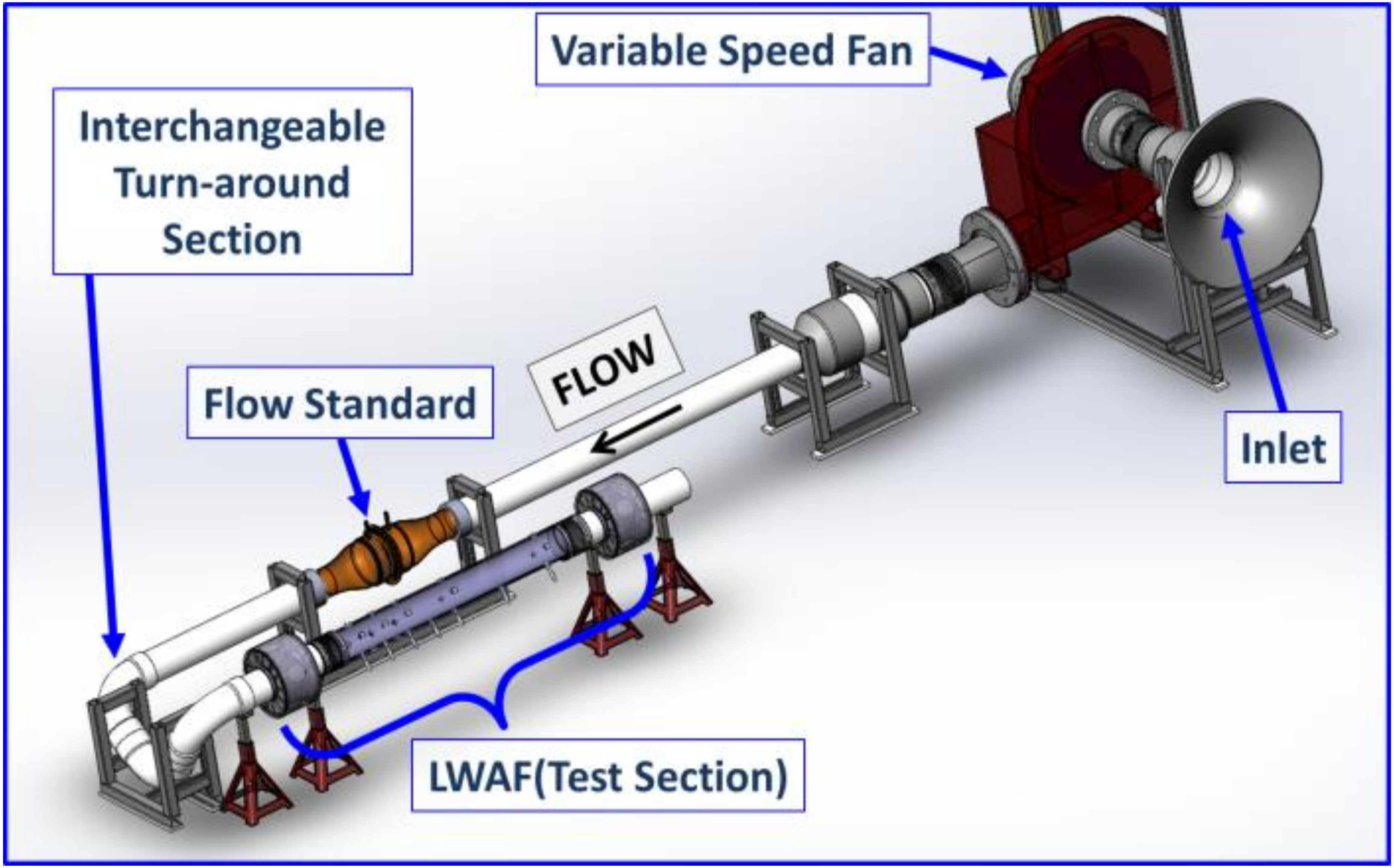
- **Excellent Reproducibility < 0.075 %**
- **Expanded Uncertainty: 0.45 % to 0.58 %**
- **Best-ever calibration in air in this size**

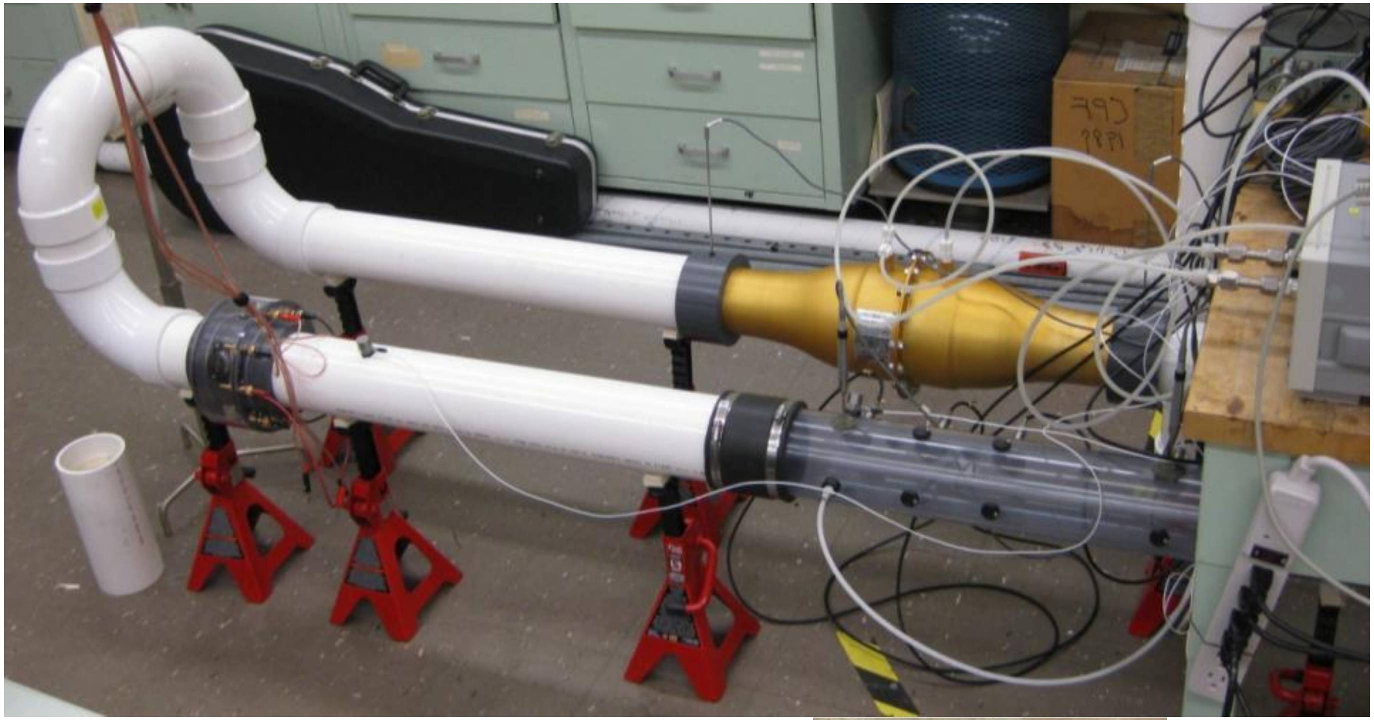
Long Wavelength Acoustic Flowmeter



Velocity of plane wave averages over flow distortions

Long-Wavelength Acoustic Flowmeter

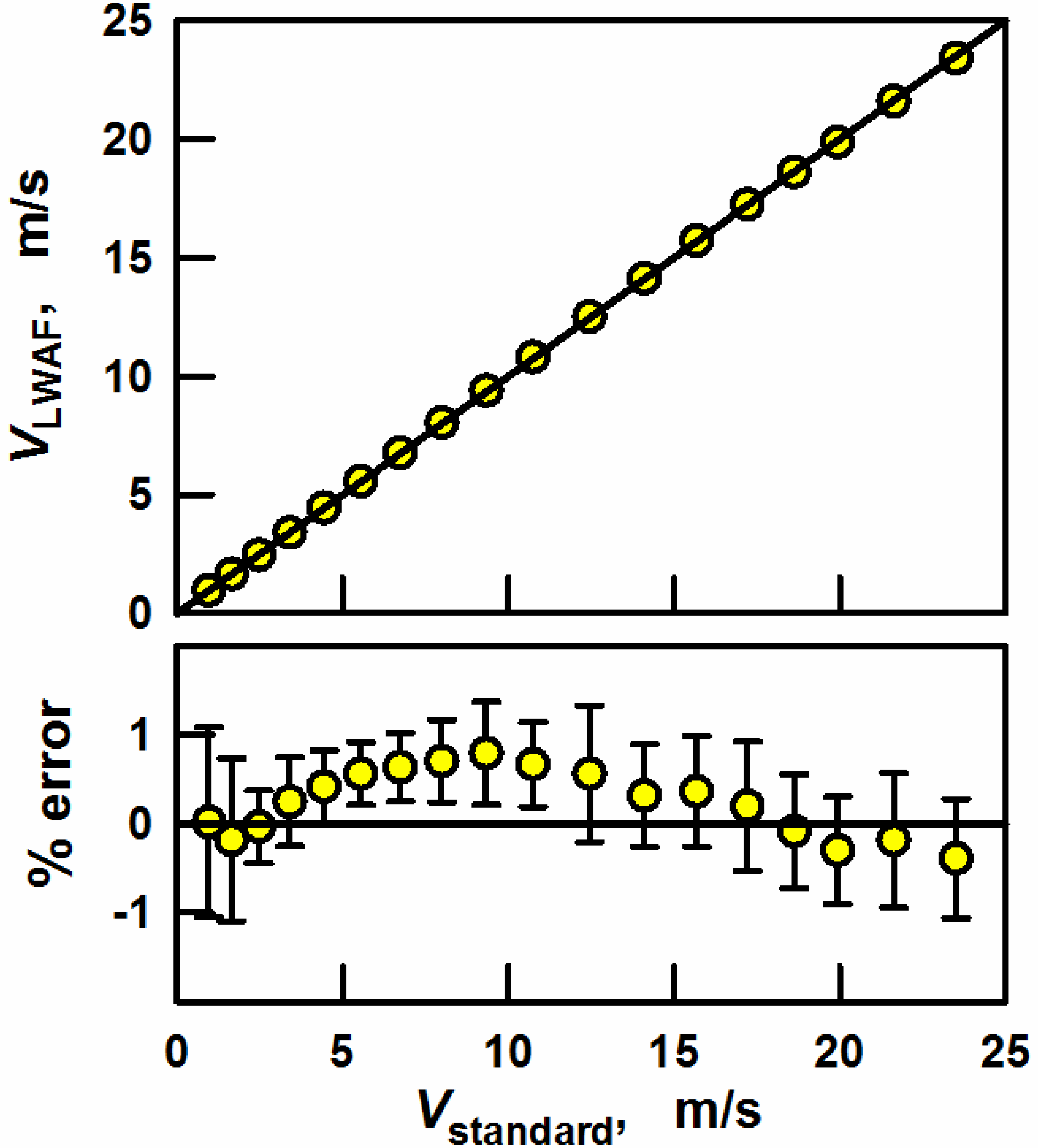




LWAF
1/100th Scale

It works with
- obstacles
- complex bends
- water spray

Can we scale up to 1/10th ?



Plans

- Document performance and uncertainty of existing flow measurements in swirling and skewed flows
  - **EPA Pitot traverse method**
  - **CEMS flow meters (Ultrasonic Flow Meters)**

- Develop alternative/improved stack flow measurement techniques
  - **Multi-chord and 3-D pitot traverses, advanced integration**
  - **Multi path ultrasonic flow meters**
  - **Long Wavelength Acoustic Flow Meter**
  - **Differential absorption LIDAR ?**
  - **Tracer Dilution Methods**

- Develop benchmark data to validate Computational Fluid Dynamic (CFD) models to facilitate scale-up

Thank You

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