NIST's New 3D Airspeed Calibration Rig Addresses Turbulent Flow Measurement Challenges

National Institute of Standards and Technology NIST

...working with industry to foster innovation, trade, security and jobs

Physical Measurement Laboratory

Fluid Metrology Group

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Is this research important?

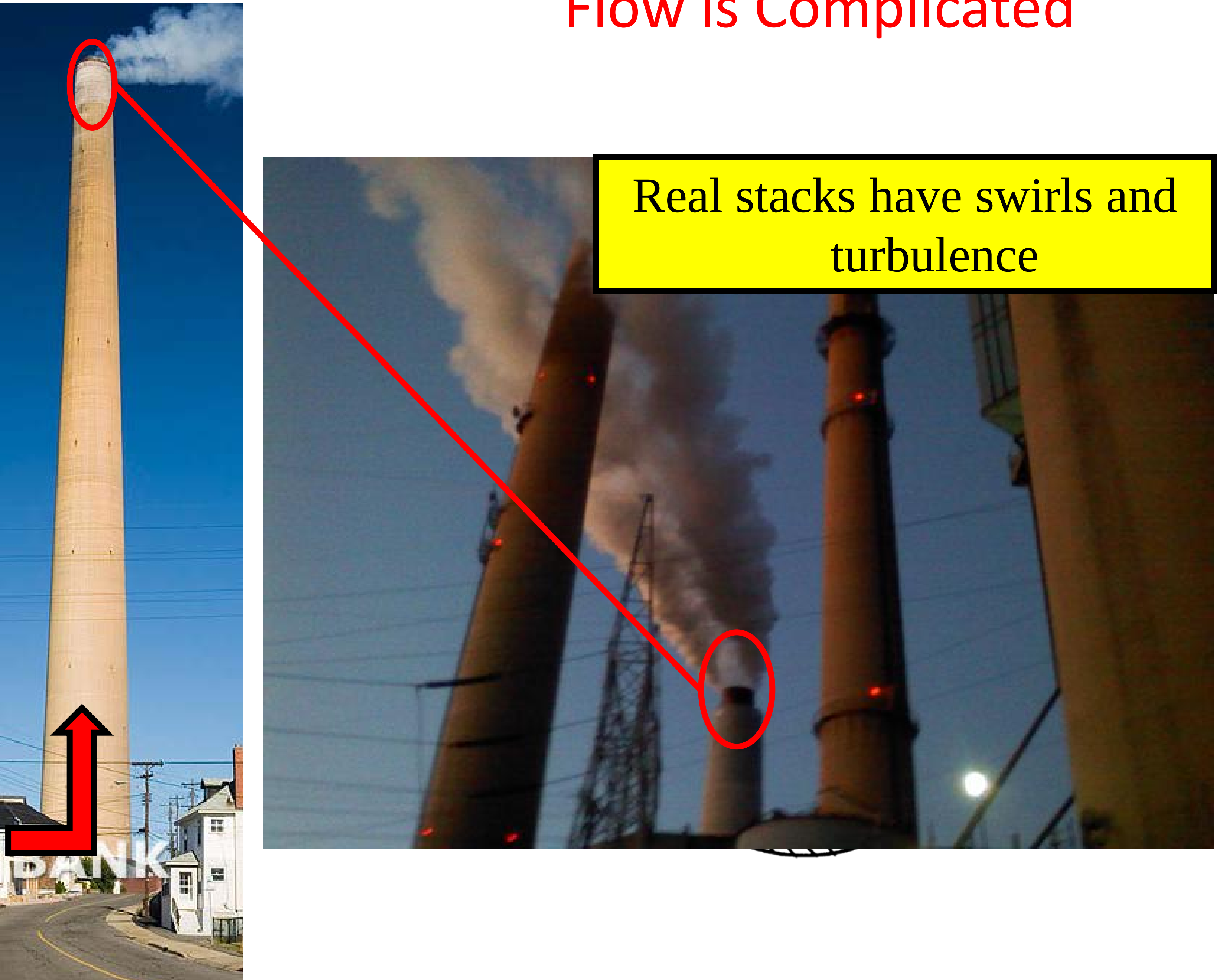
There are at least two reasons why it is important:

1. Humanitarian: Let’s keep the Earth a habitable place for future generations!
2. Mercantile: A lot of money involved!

What is this talk about?

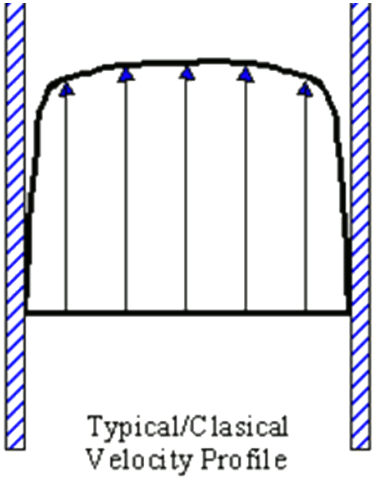
- Why we are doing 2-D and 3-D calibrations?
- 3-D Calibration Rig.
- How turbulence intensity affects calibration.
- Traditional turbulence generators.
- Flag-like turbulence generator.
- How to measure turbulence?
- Low turbulence s-probe calibration.
- Pitot tube and s-probe in turbulent flows.

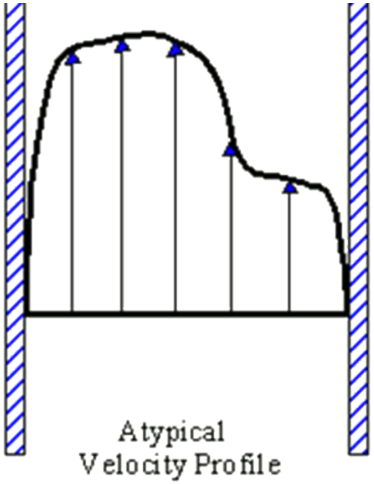
Flow is Complicated

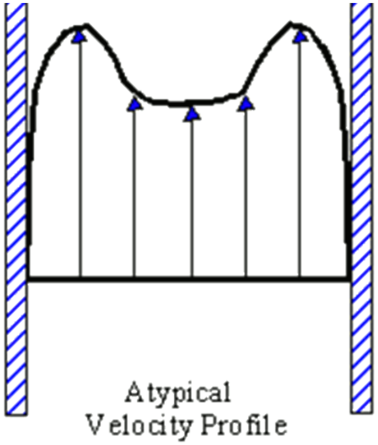


Flow is Complicated

Real stacks have skew







How are Emissions Measurements Made Today?

Emission is a product of concentration and flow

Flow Problems:

No Traceability to NIST

There is so called: Annual “Relative Accuracy Test Audit” (RATA) which “calibrates” continuous emission flow monitors (usually ultrasonic flowmeter). Typically, the flow is surveyed with S-probe and 5-hole pitot static probes, which are temporarily installed on the stack.

For S-probes the calibration factor is fixed and these probes can be used without calibration for certain specified geometries.

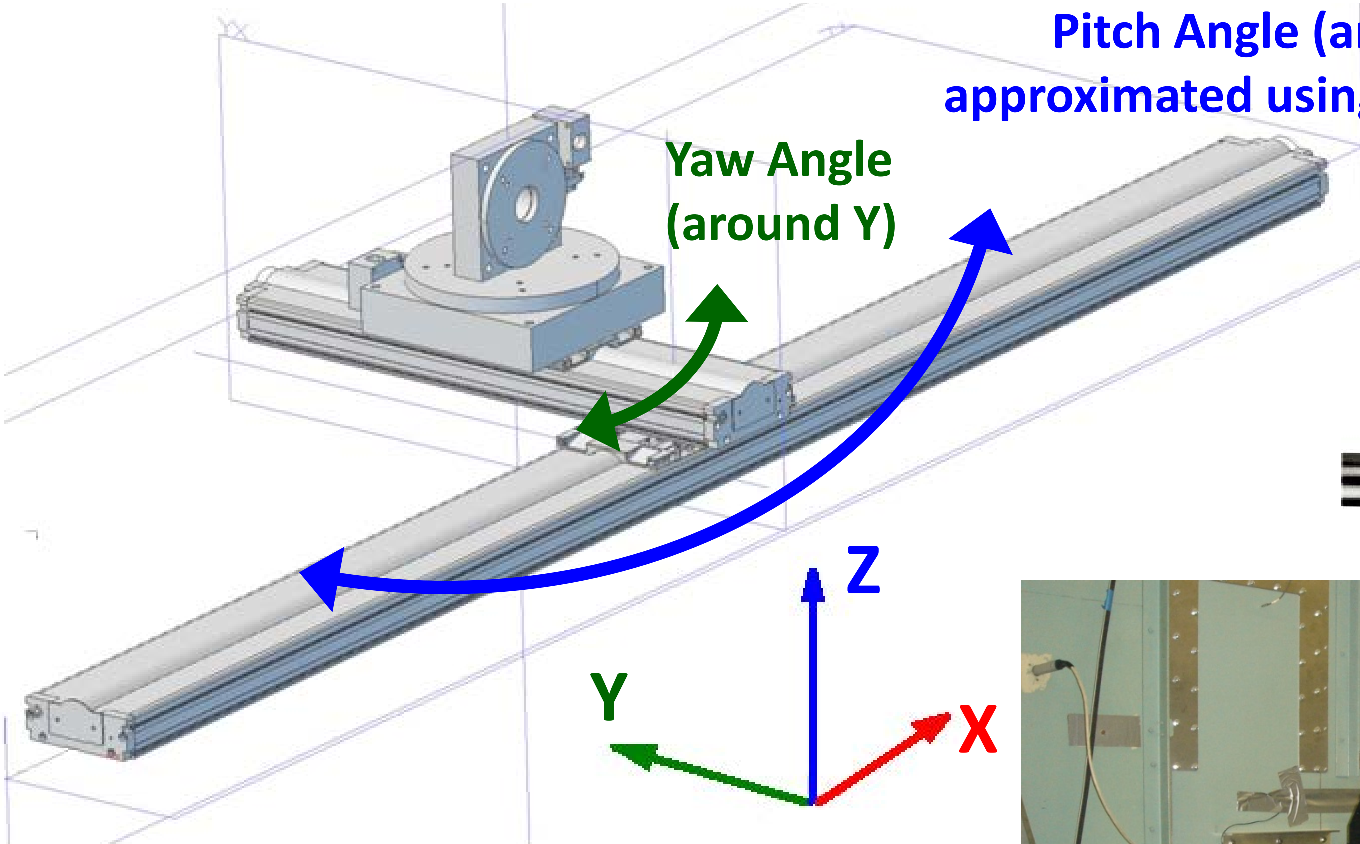
As the name suggests, the EPA protocols provide only relative accuracy, not uncertainty relative to primary standards.

Wind Tunnel Parameters

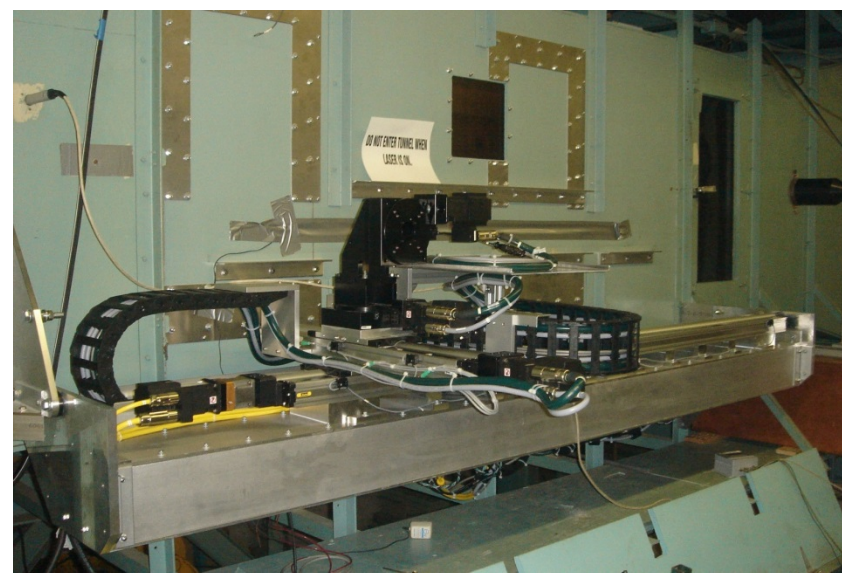
- Test volume: 2 m long × 1.5 m wide × 1.2 m high
- Airspeeds up to 75 m/s   (165 mi/hour)
- Uncertainties – 0.42% increasing to 1% near 1 m/s
- Low (0.1 %) turbulence intensity; to increase turbulence, we install turbulence generators upstream of the test volume

$$Tu = \frac{\sigma_{\tilde{V}}}{\bar{V}}$$

Automated 3D Pitot Tube Calibration Rig (2013)

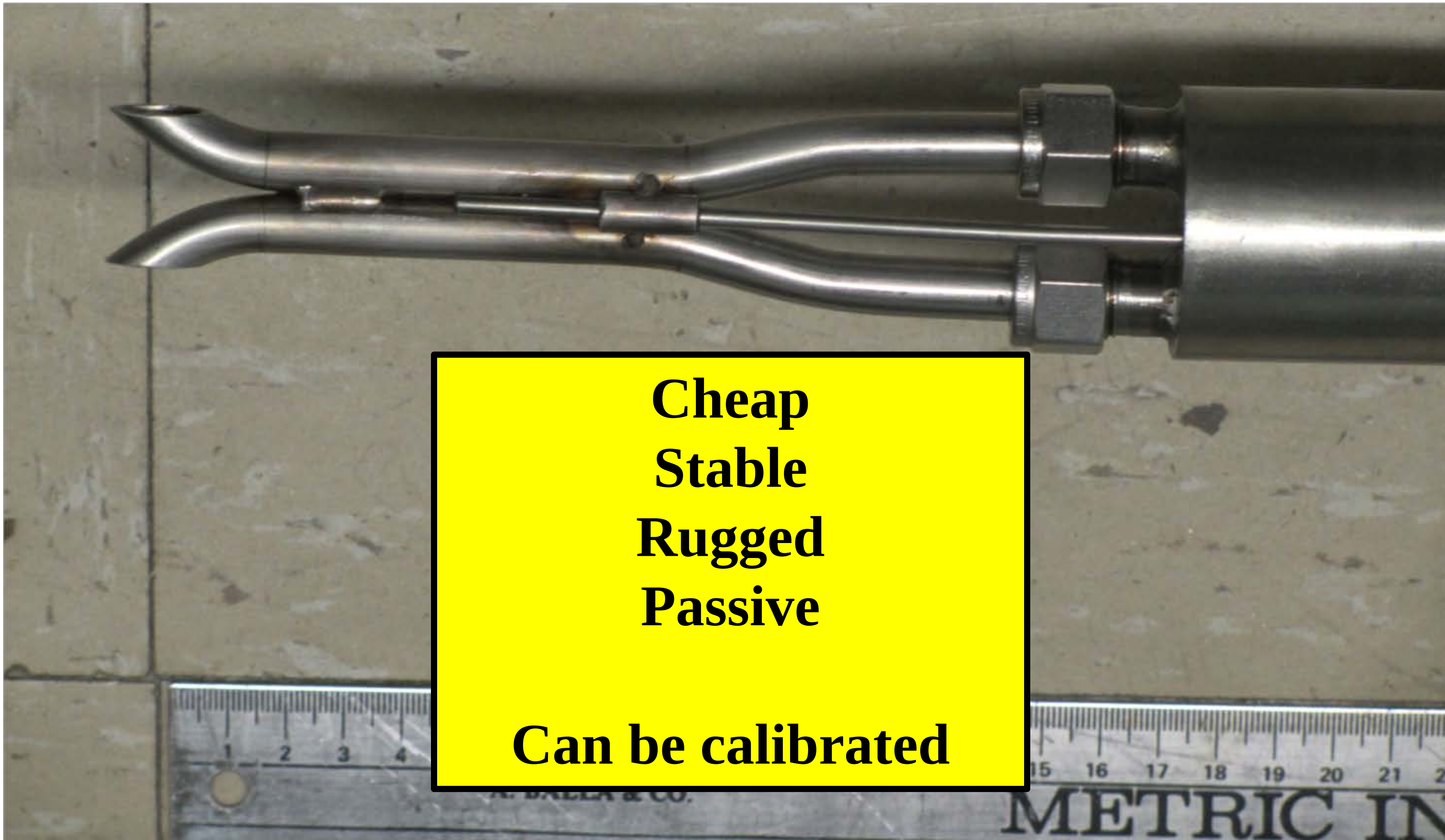


3D Conic Probe



2D S-Probe

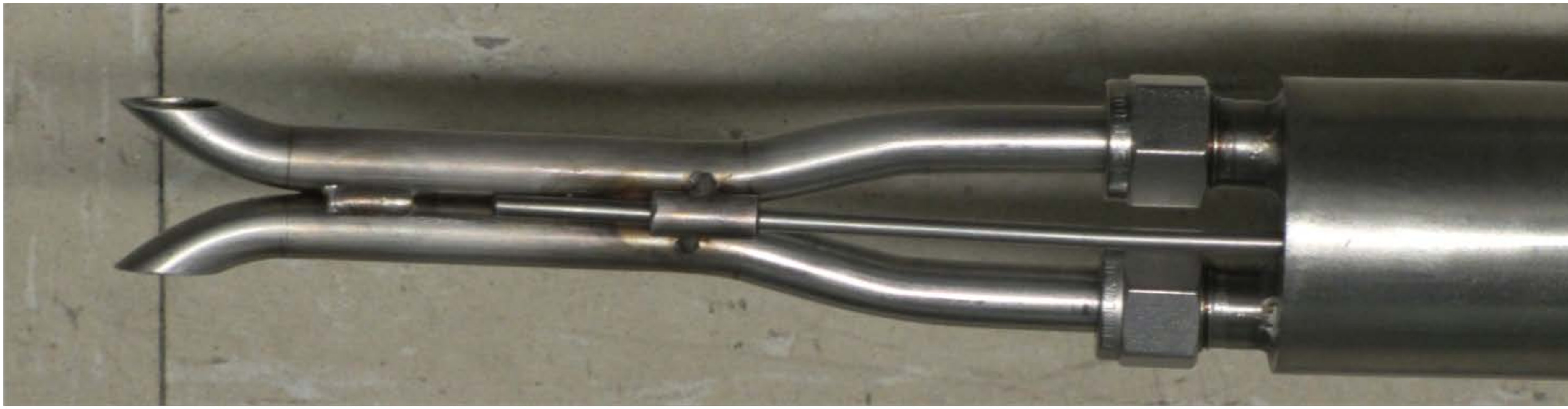
S-probe: workhorse for stack flow measurements

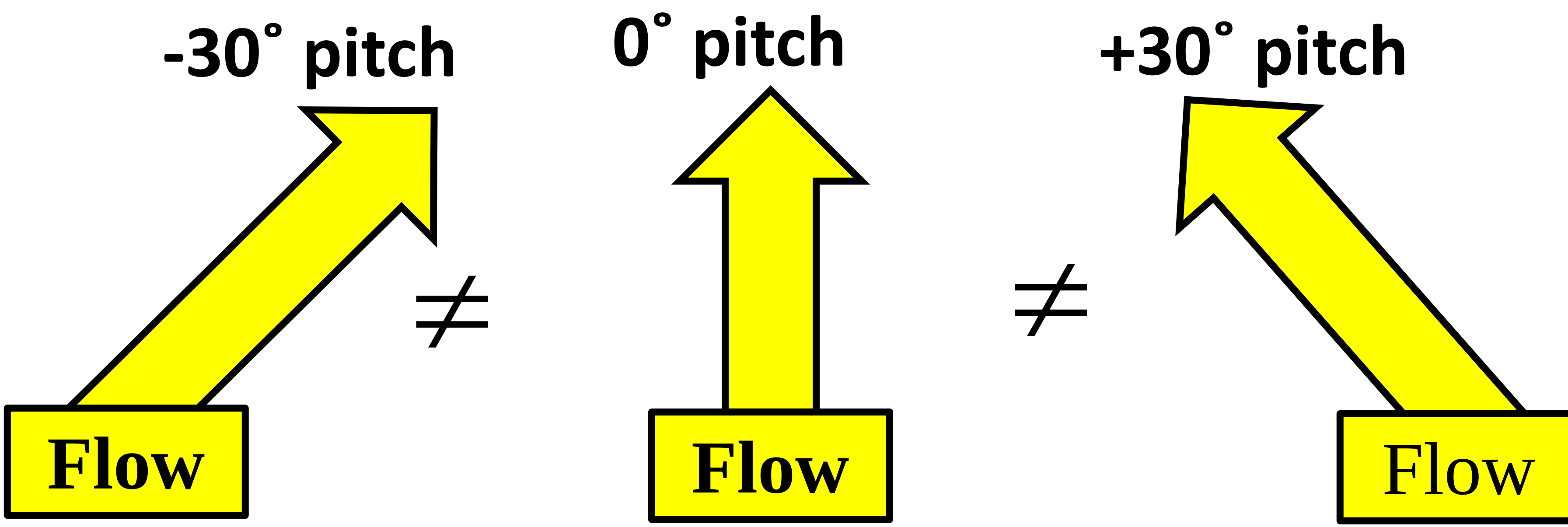


Cheap
Stable
Rugged
Passive

Can be calibrated

S-probe: cannot detect pitch





S-Probe, (used in EPA protocol 2)

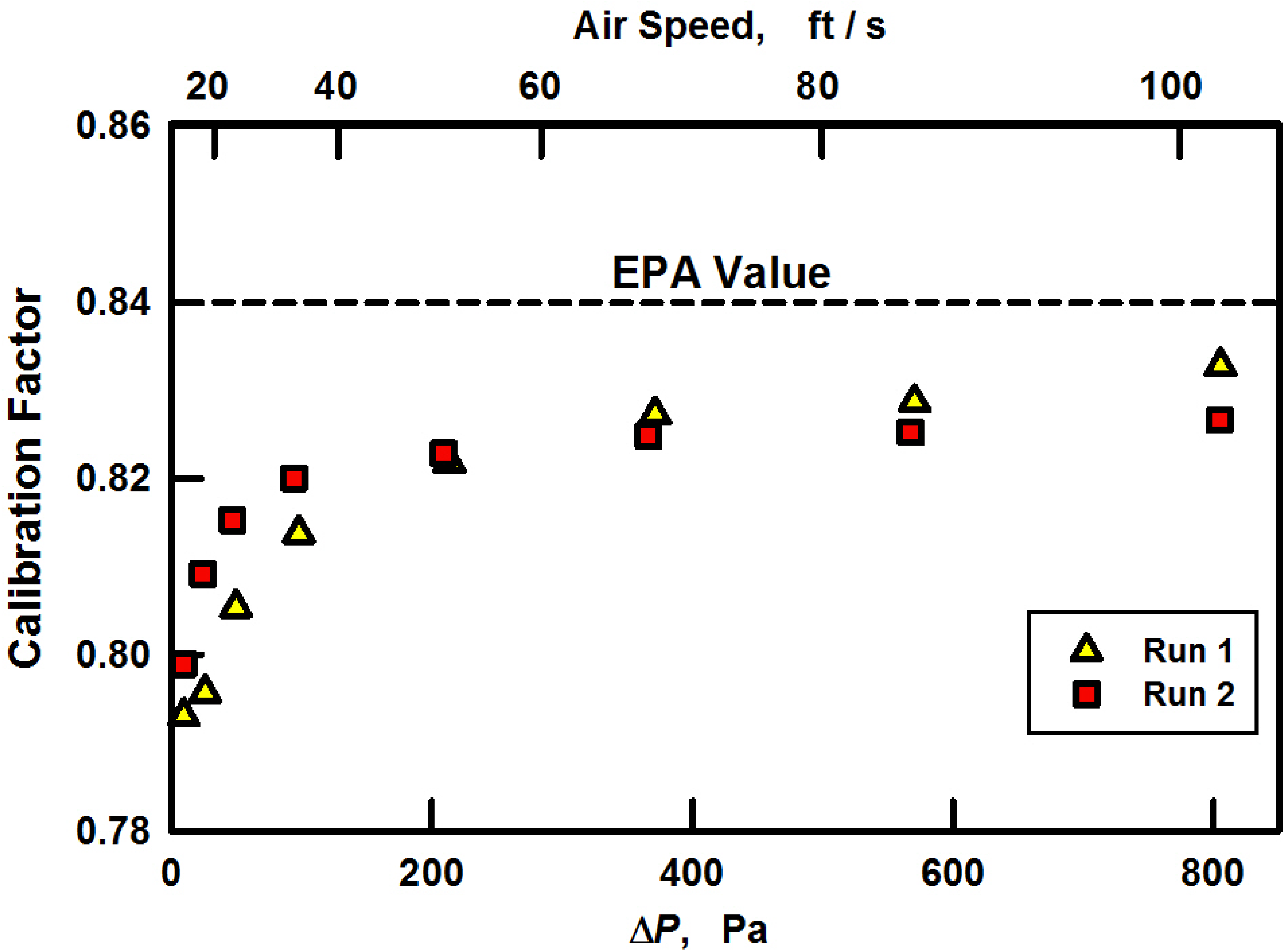
Calibration Factor is a Function of 4 variables

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

EPA protocol assumes calibration factor = 0.84

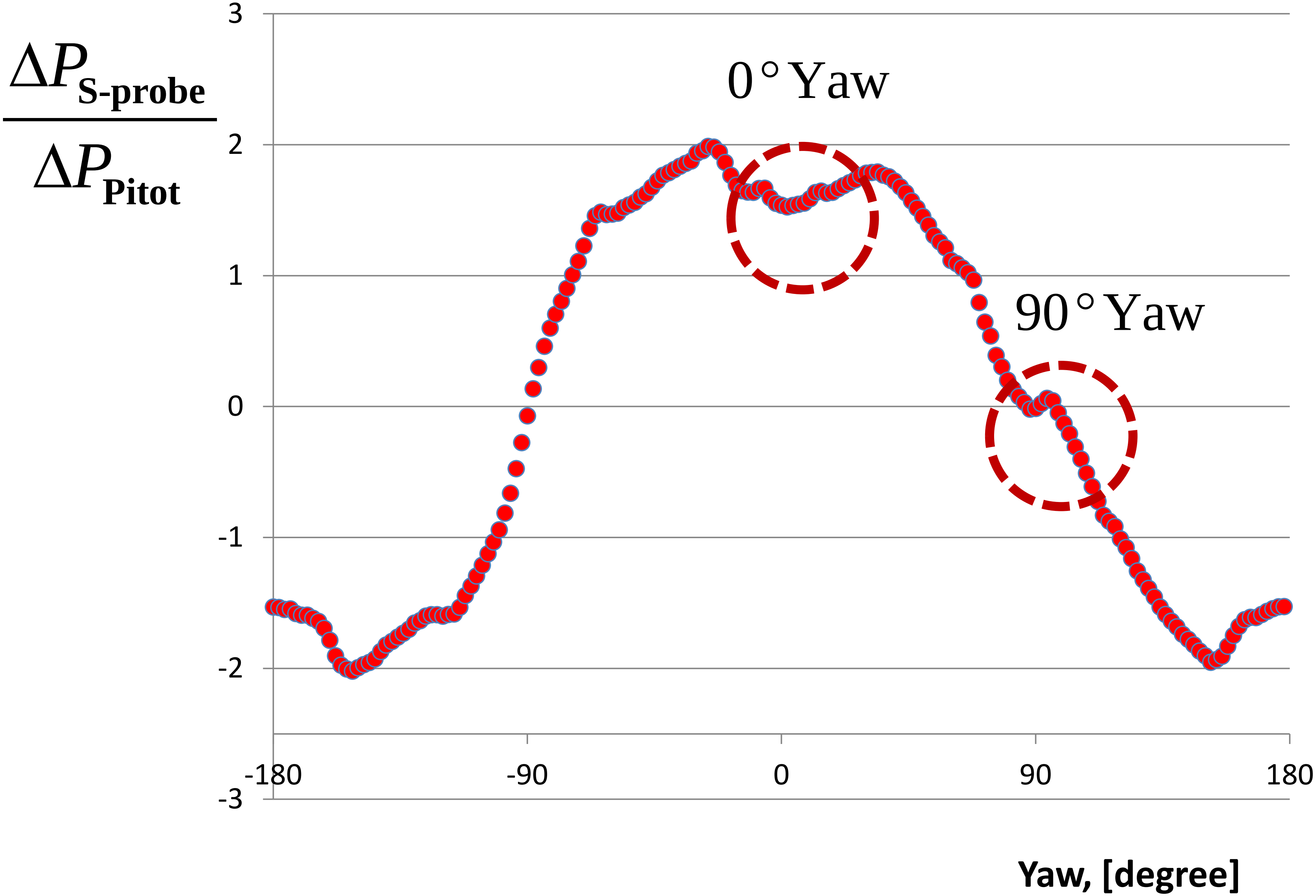
(literature shows small, linear dependence on air speed)

EPA Method 2: S-Probe Calibration



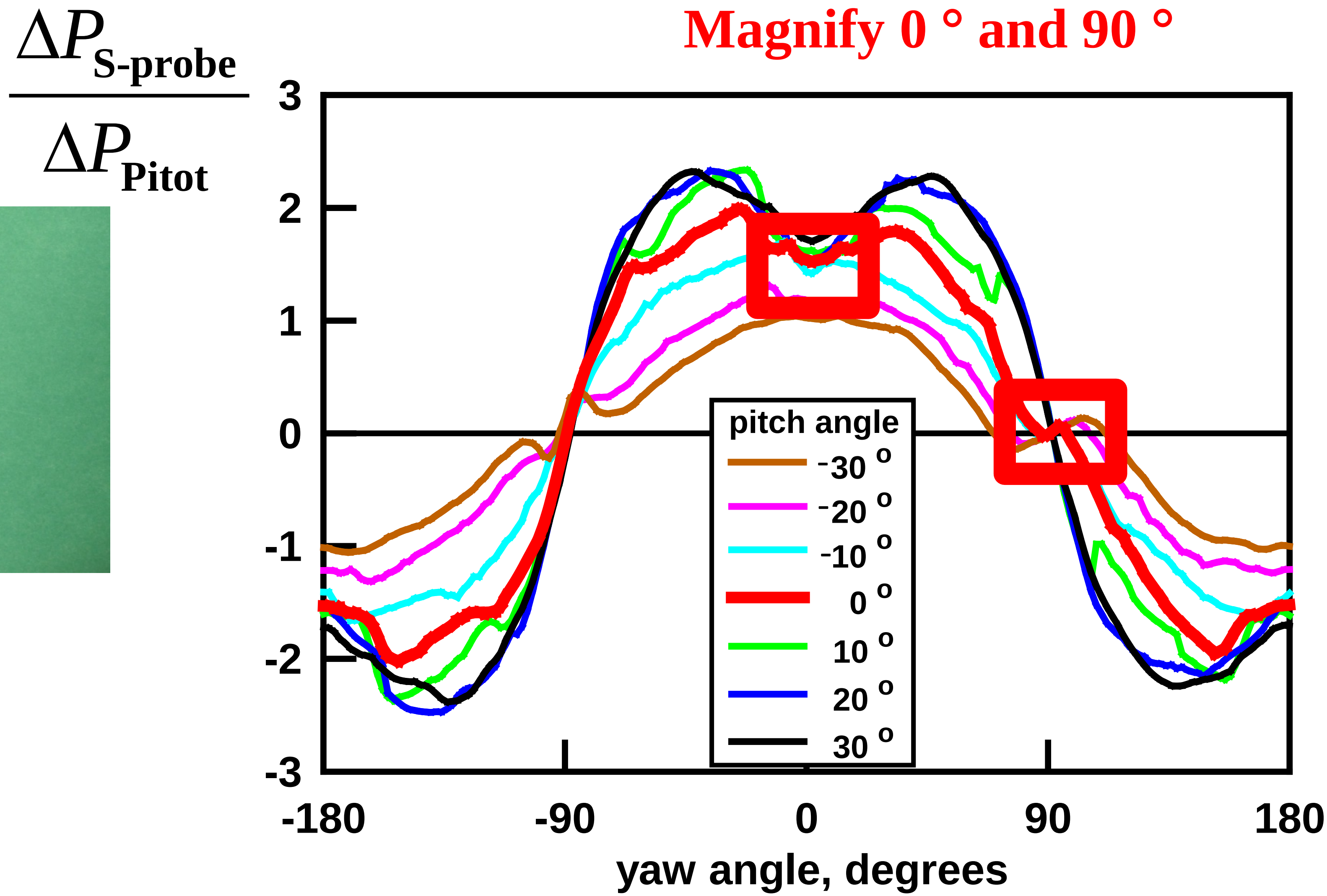
Calibration data for one probe; others might be different.

360˚ S-Probe response in 2˚ steps
10 m/s; 0 °pitch



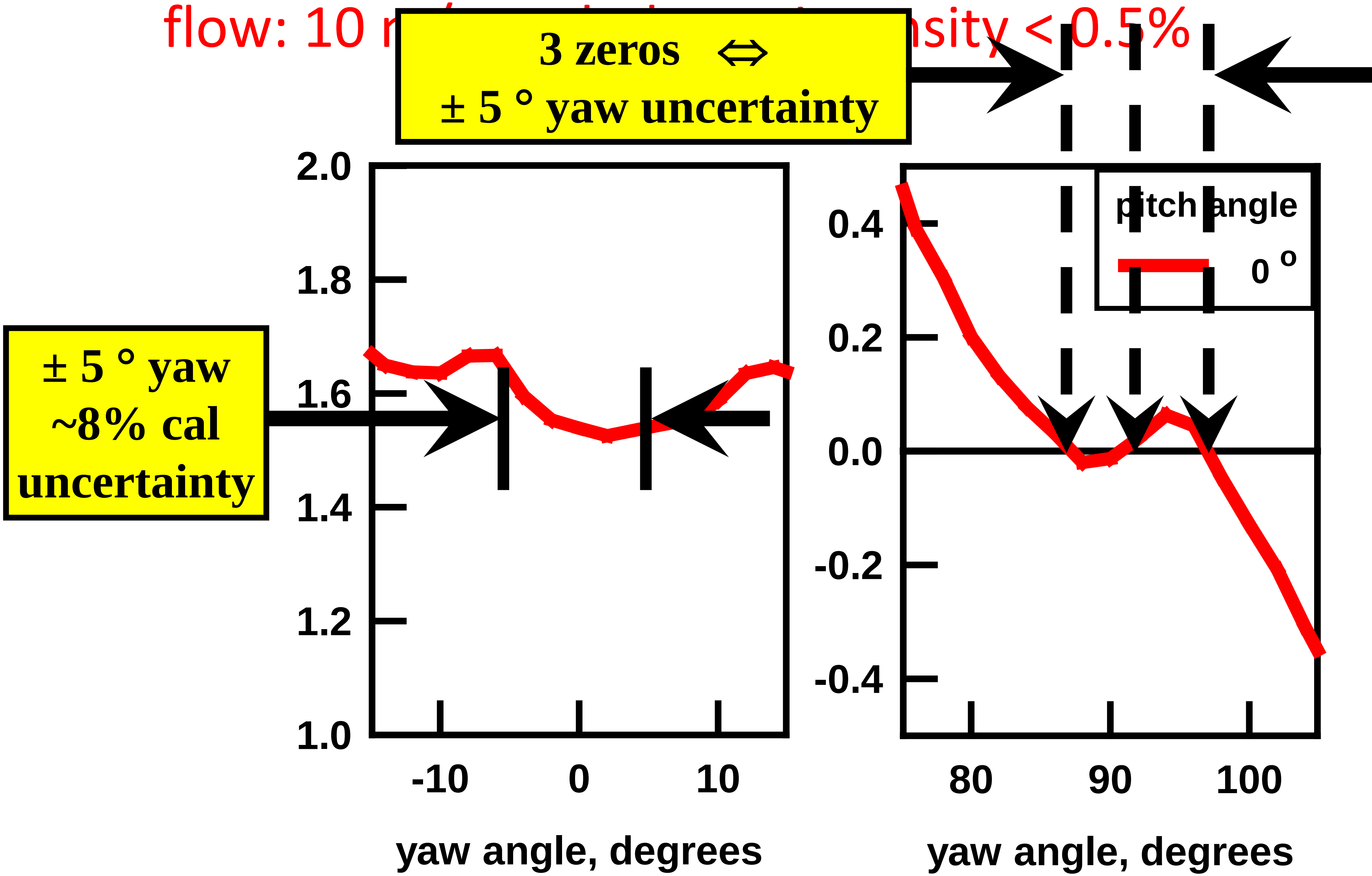
NIST Calibration of S-Probe

Flow: 10 m/s, turbulence intensity < 0.5%



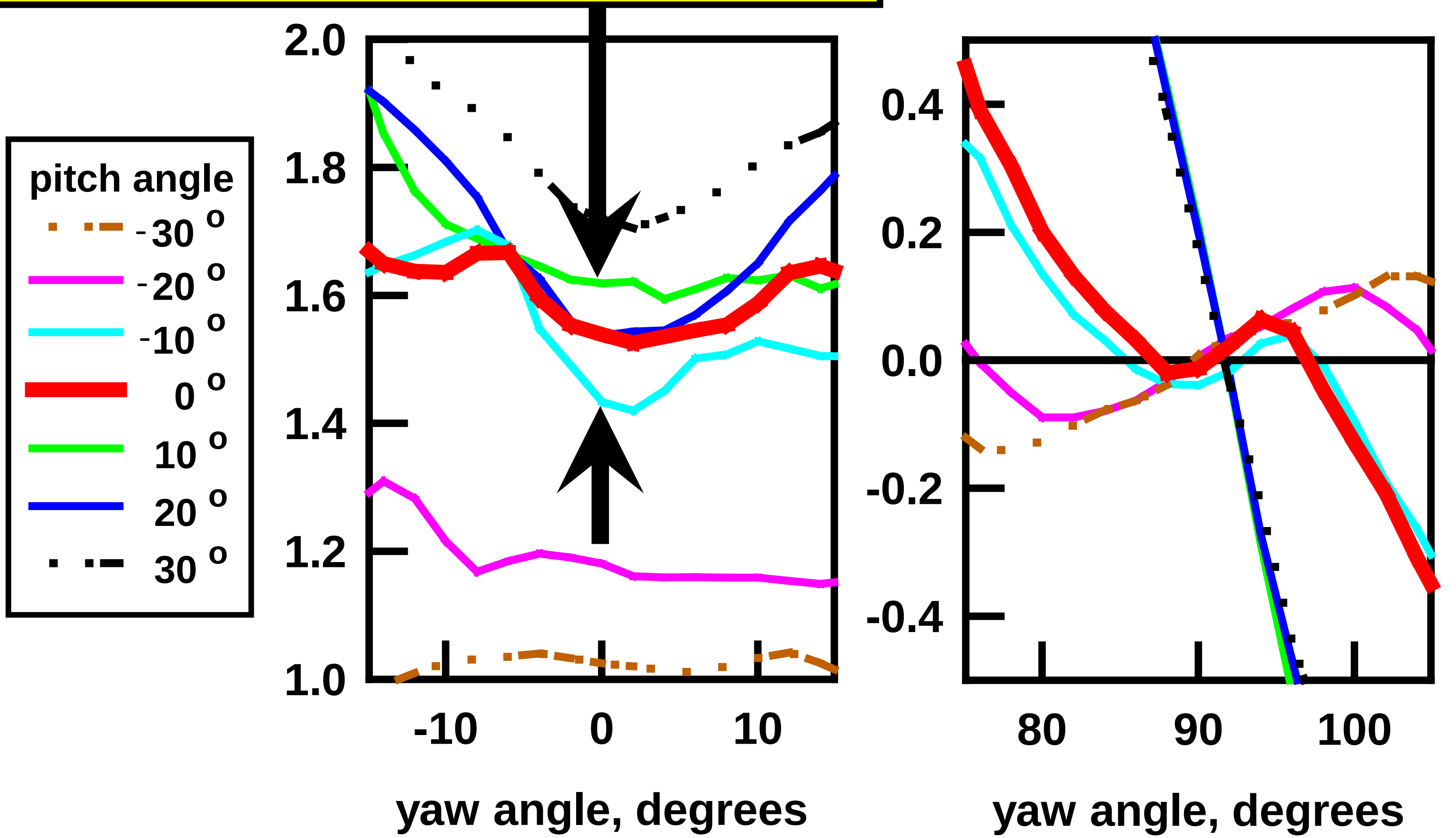
S-Probe (used for CEM per EPA protocol 2)

flow: 10 m … nsity < 0.5%

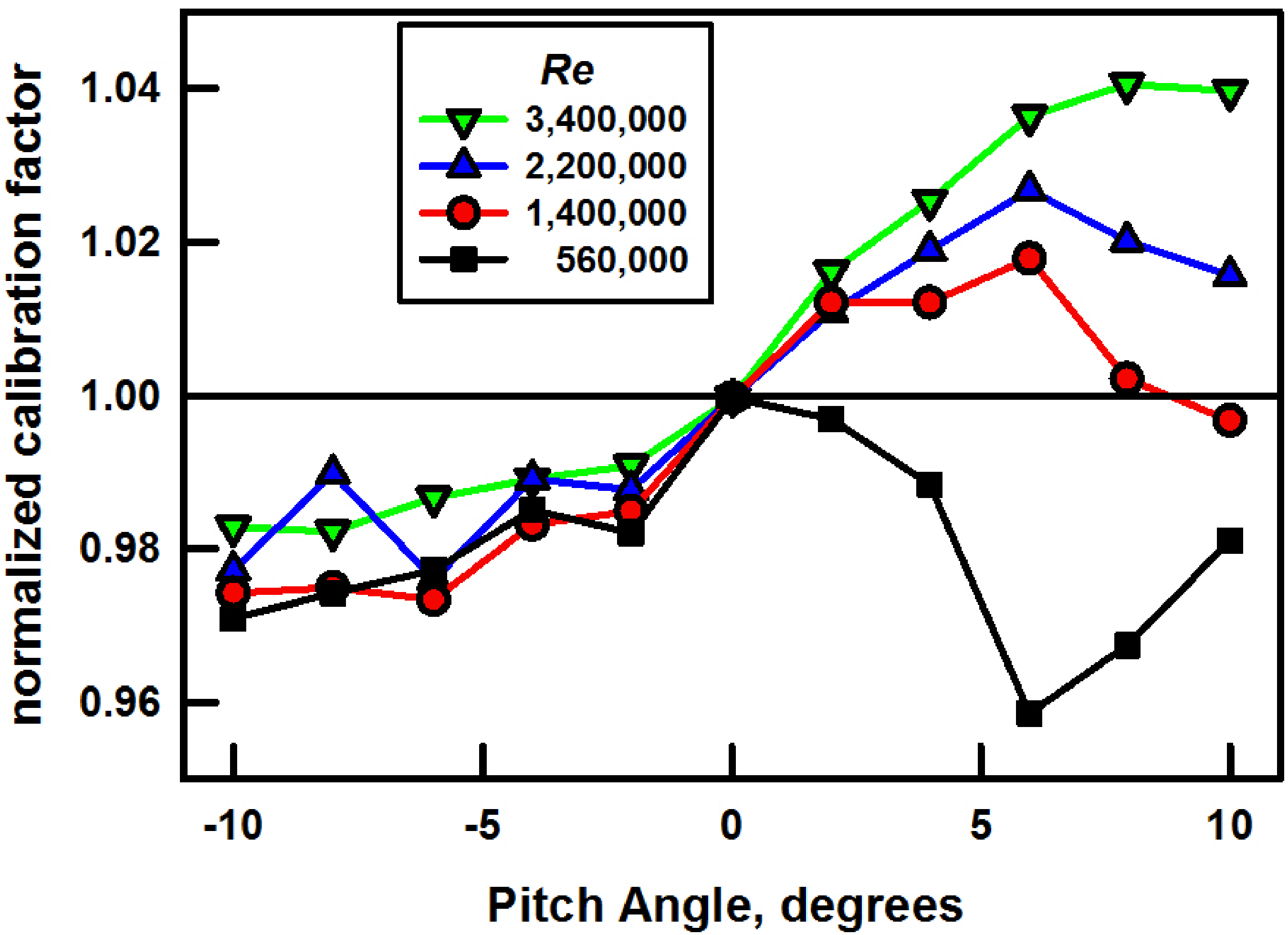


S-Probe (used for CEM per EPA protocol 2)
Flow: 10 m/s, turbulence intensity < 0.5%

Calibration depends upon pitch angle

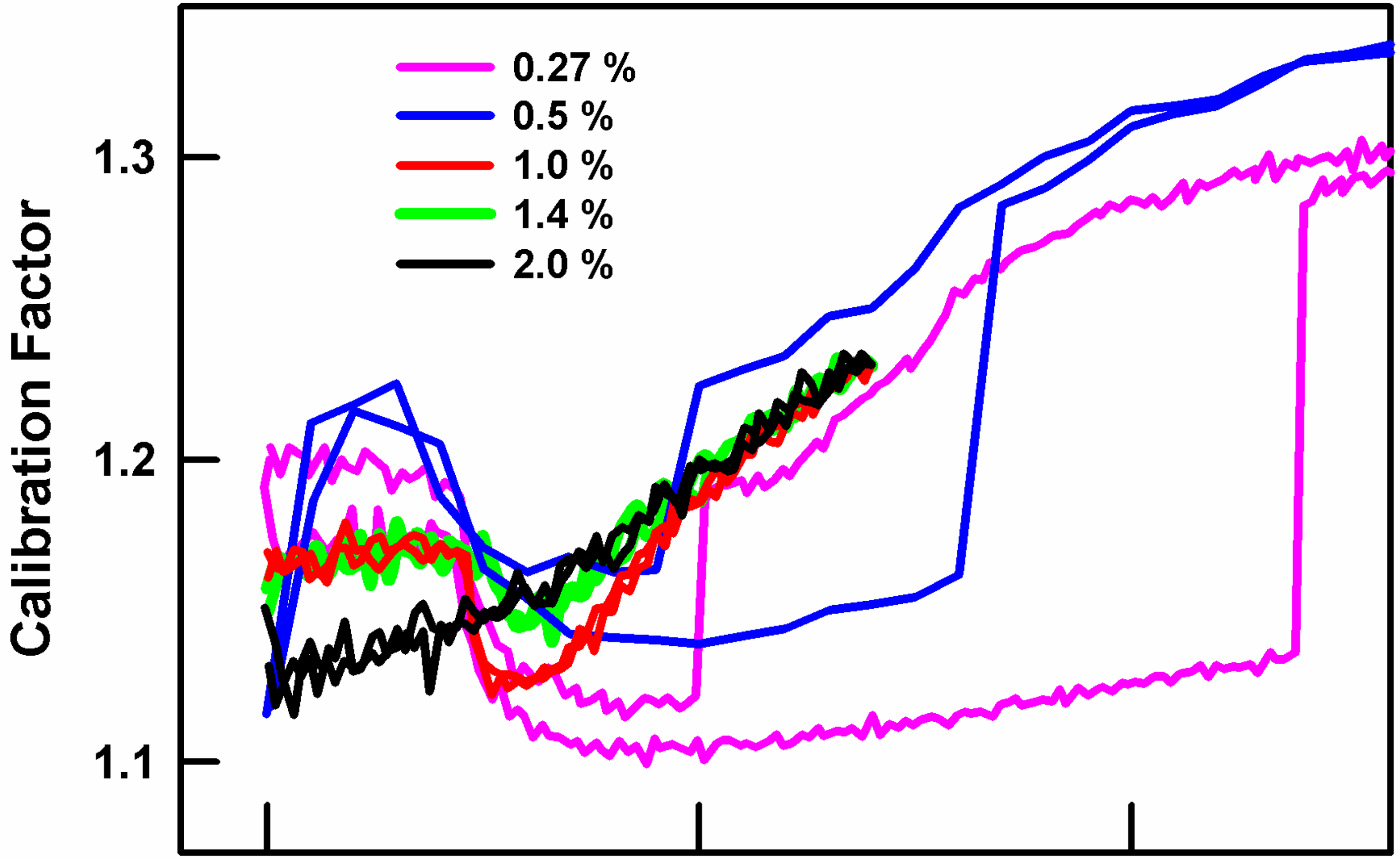


Effects of Pitch: Other Researchers



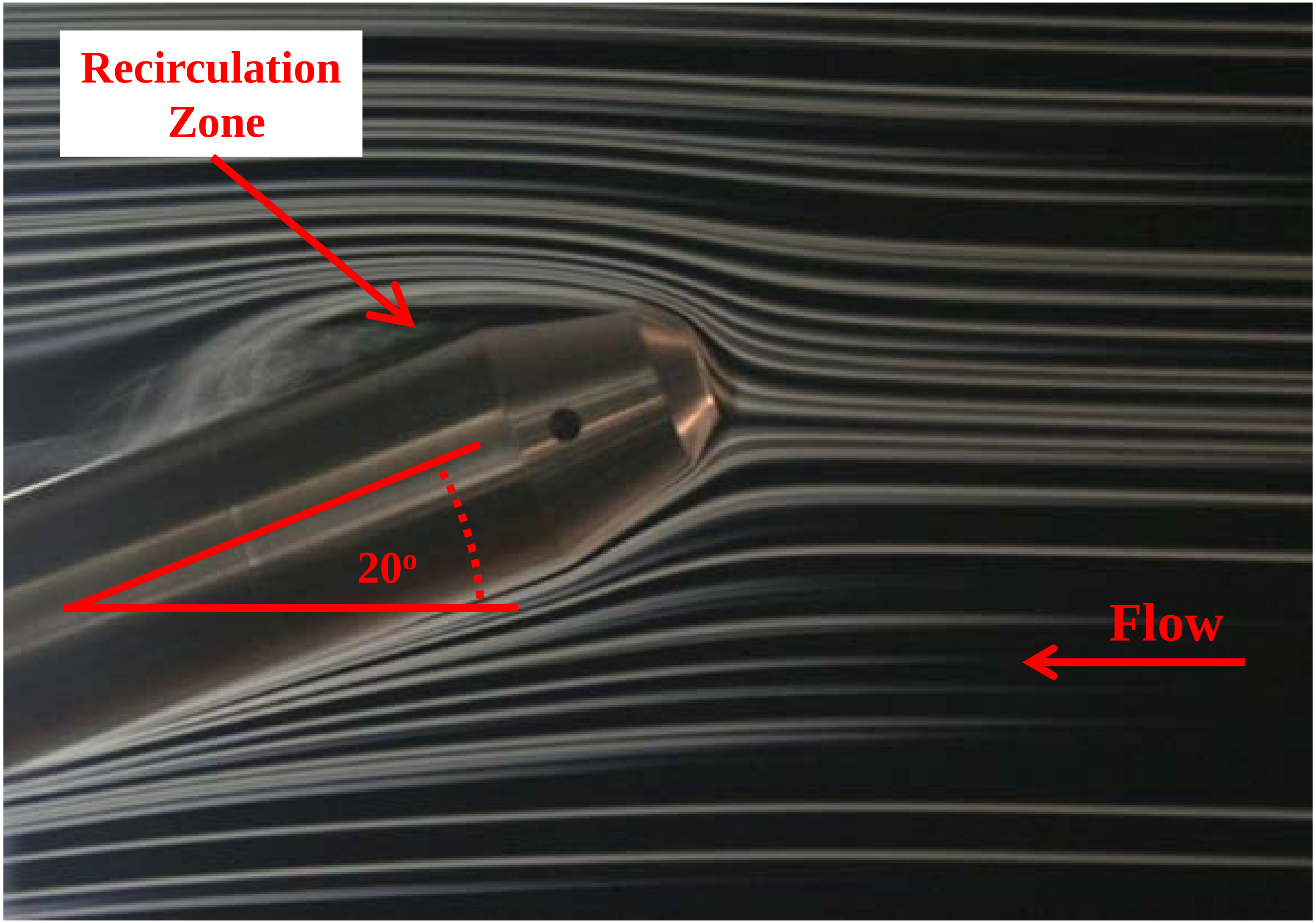
Adapted from:
"Experimental Study of the Factors Effect on the S type Pitot Tube Coefficient"
Nguyen Doan Trang *et. al*. XX IMEKO World Congress

Calibration factor has hysteresis in low turbulence
Increasing turbulence reduces hysteresis



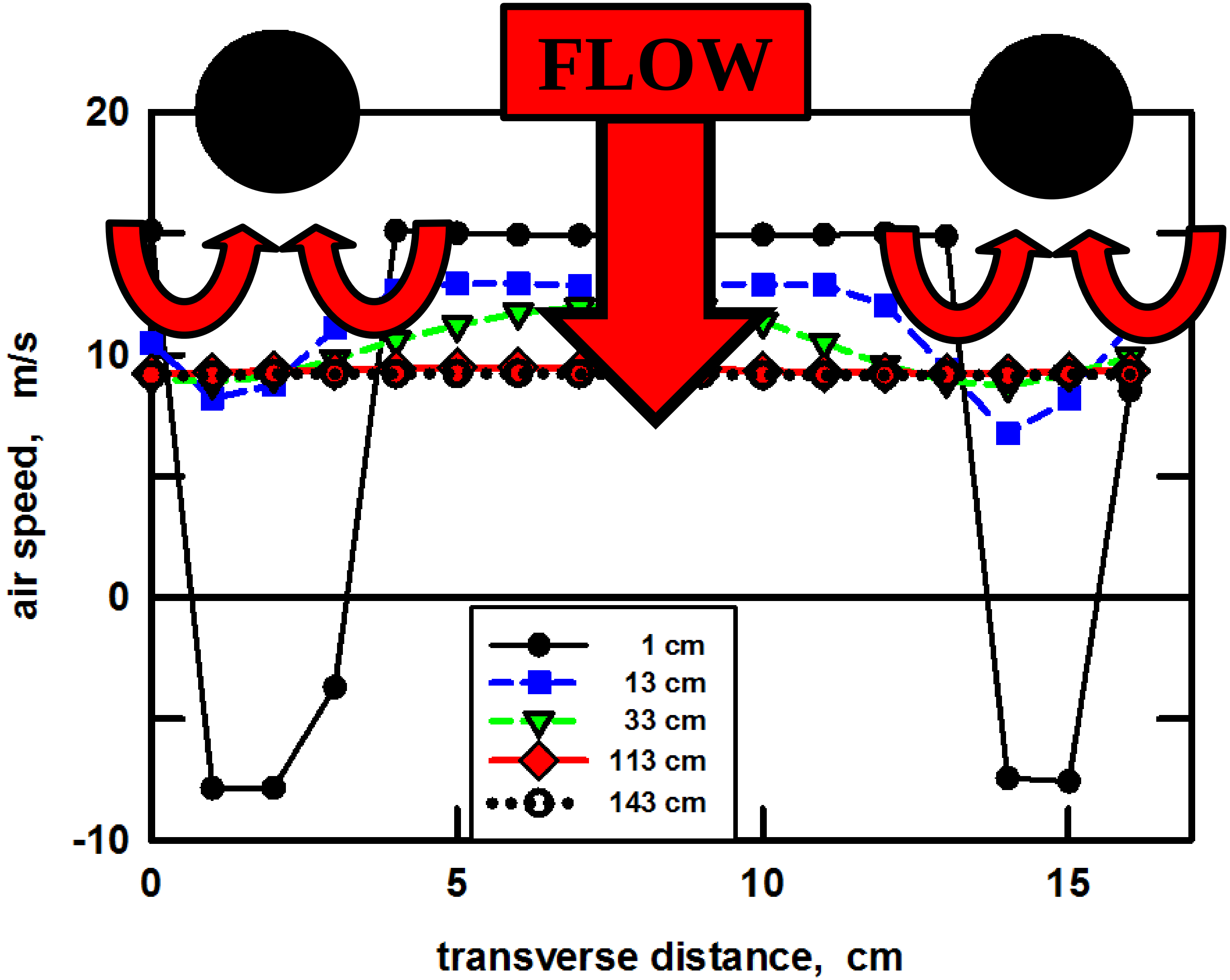
well-known for airfoils,
unknown in Pitot tube literature

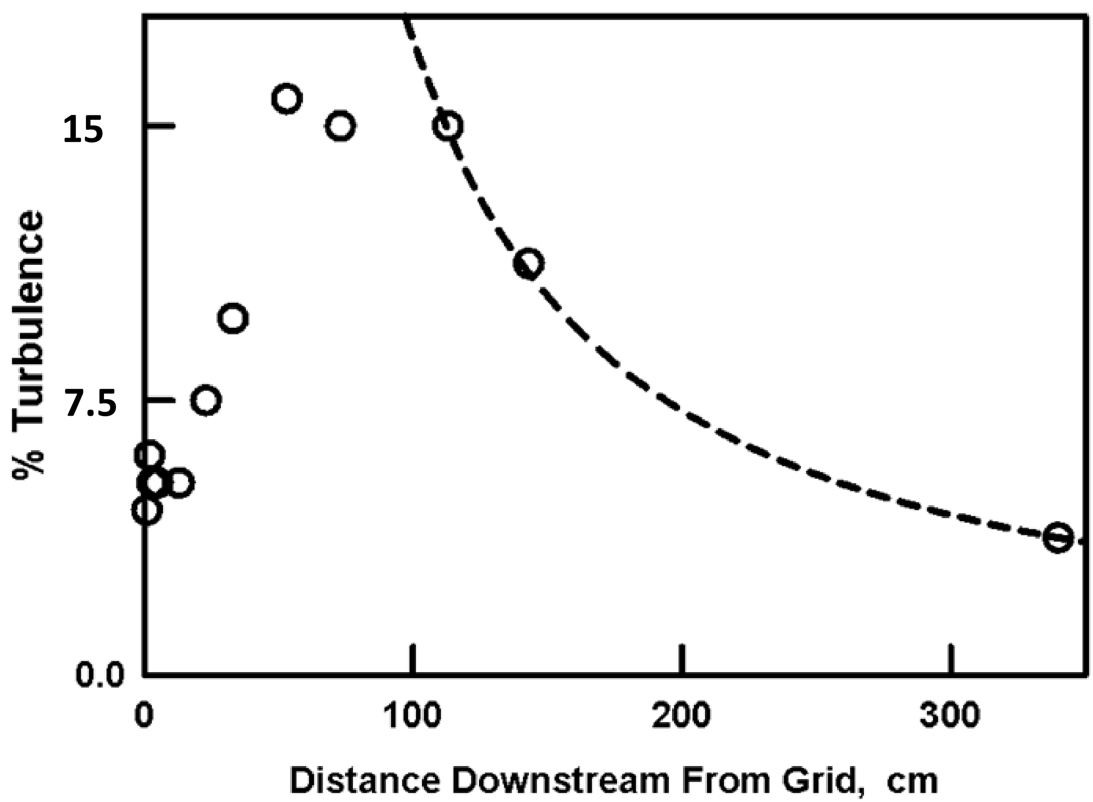
Calibration of Multi-Hole Pitot Tubes



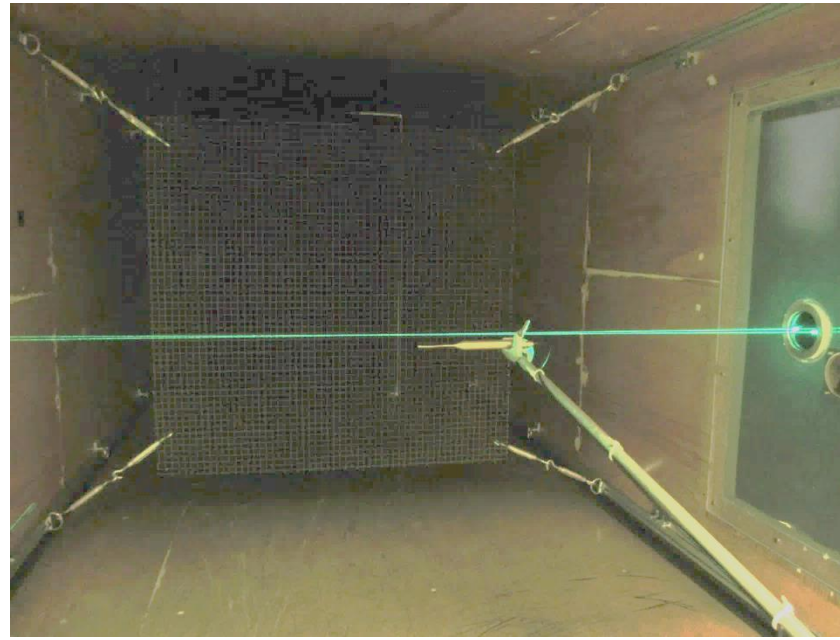
Modify wind tunnel: add Grid to Generate Turbulence

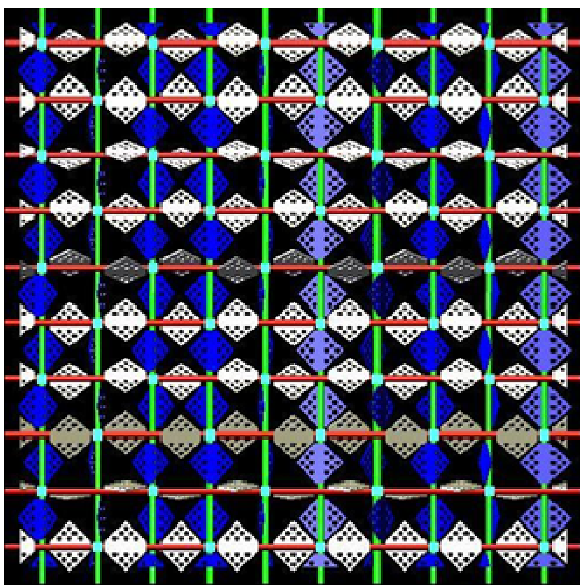
Measure Effects of Grid. Periodic Structure.

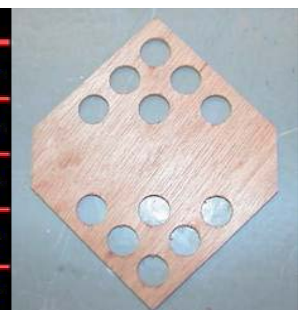




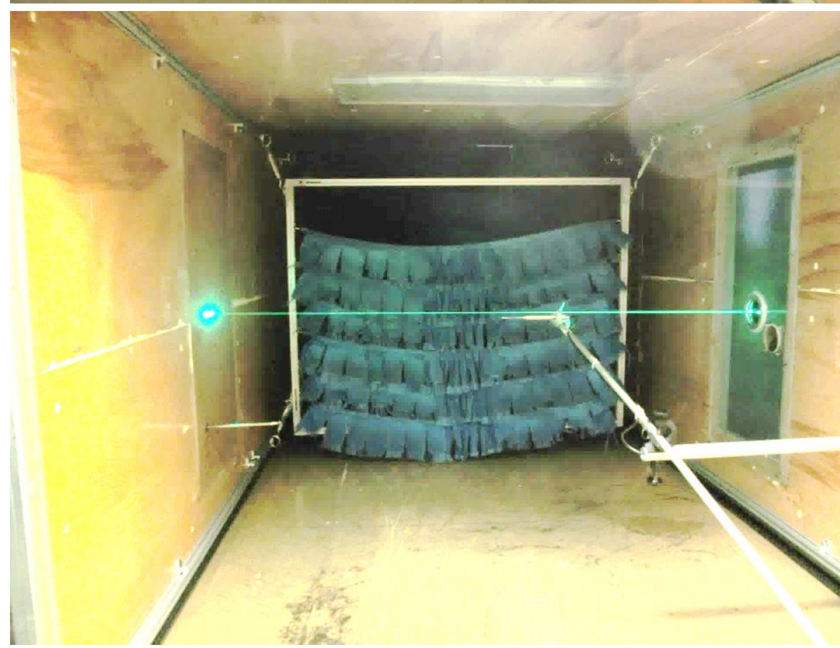
15
7.5
0.0
% Turbulence
0
100
200
300
Distance Downstream From Grid, cm



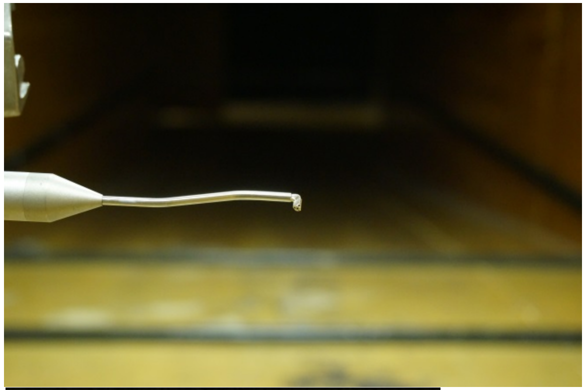


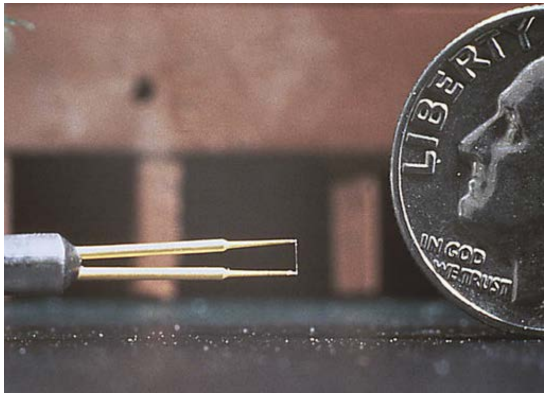


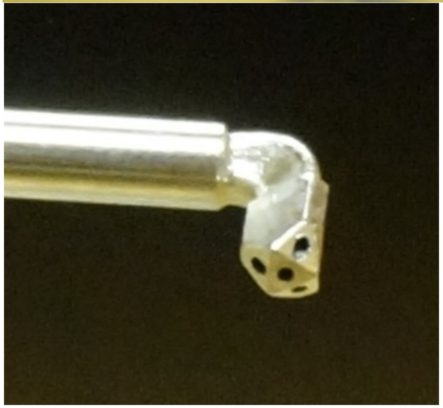
Large Scale Homogeneous Turbulence and Interactions with a Flat-Plate Cascade. Jon Vegard Larssen, Ph.D. Thesis.

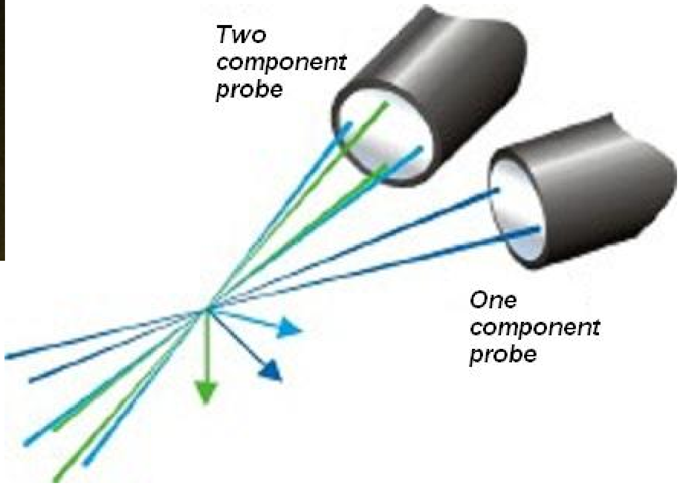


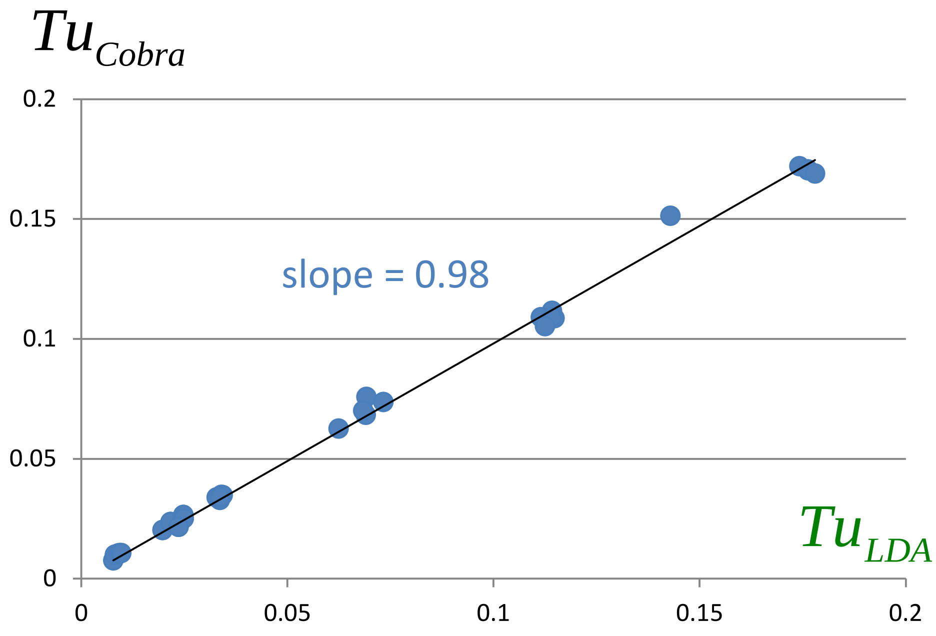
Turbulence intensity probes



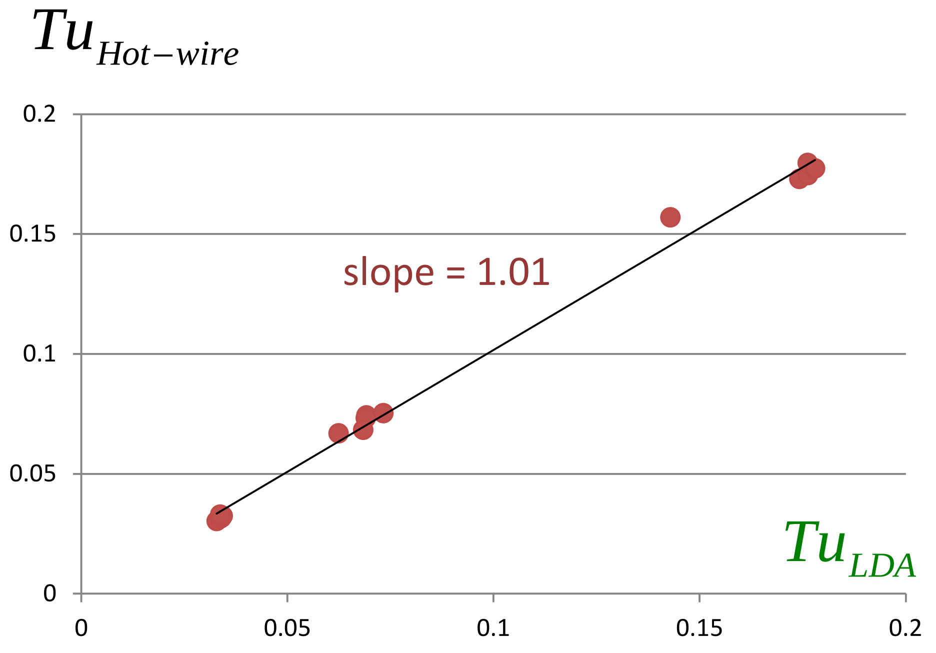






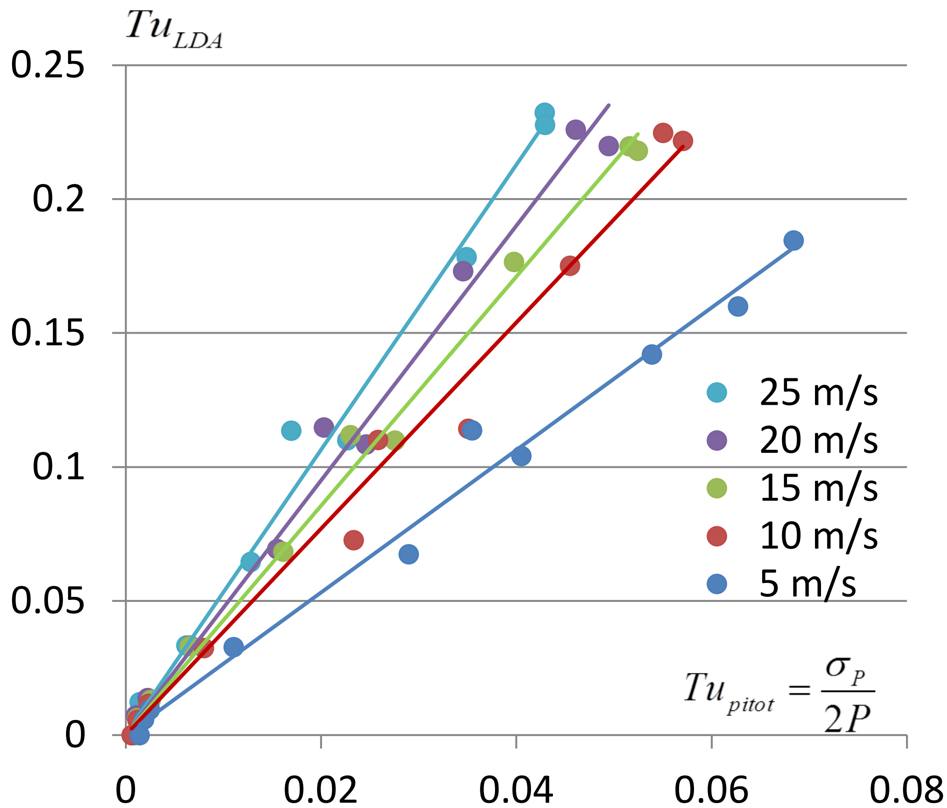


Tu_{Cobra}
0.2
0.15
0.1
0.05
0
slope = 0.98
Tu_{LDA}
0
0.05
0.1
0.15
0.2

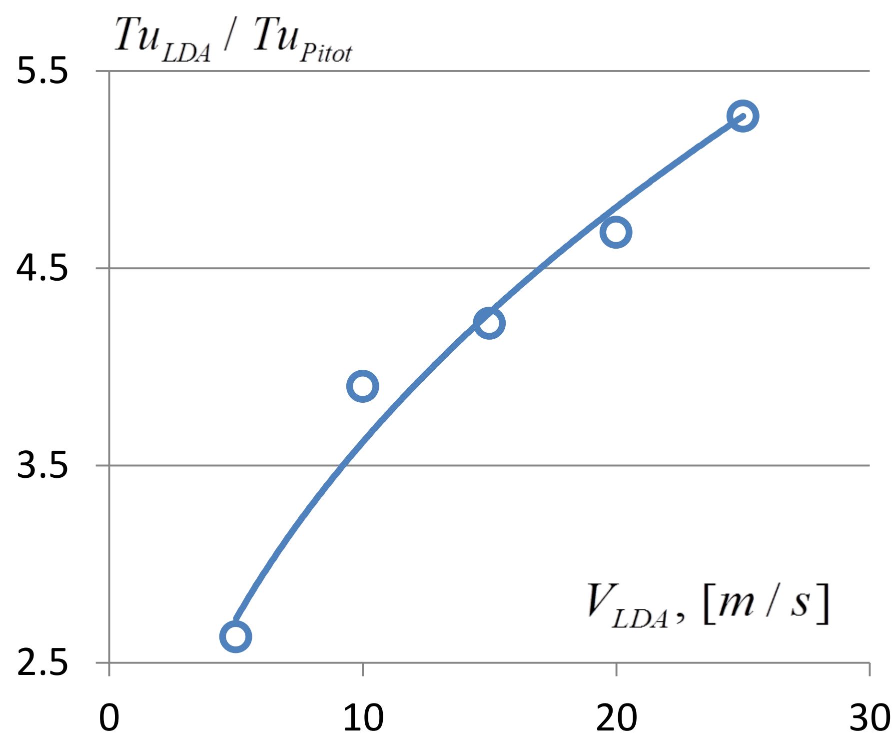


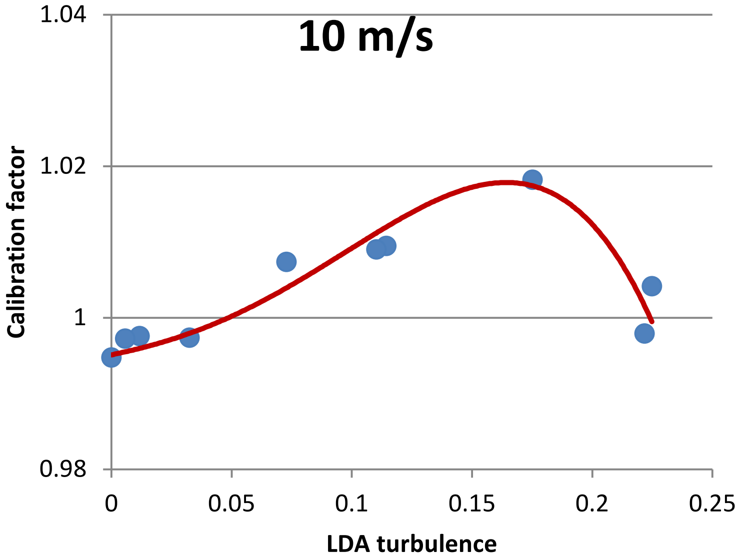
$Tu_{Hot-wire}$
0.2
0.15
0.1
0.05
0
slope = 1.01
Tu_{LDA}
0
0.05
0.1
0.15
0.2

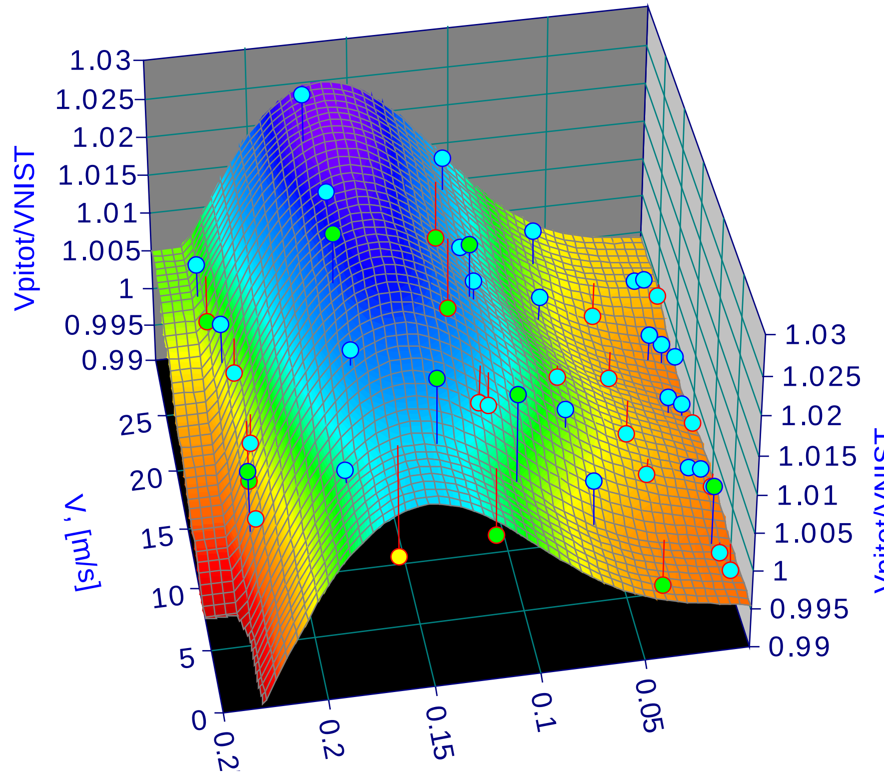
L-shape pitot tube turbulence calibration



$$\frac{Tu_{LDA}}{Tu_{Pitot}} = F_1(V)\ F_2(Tu)$$

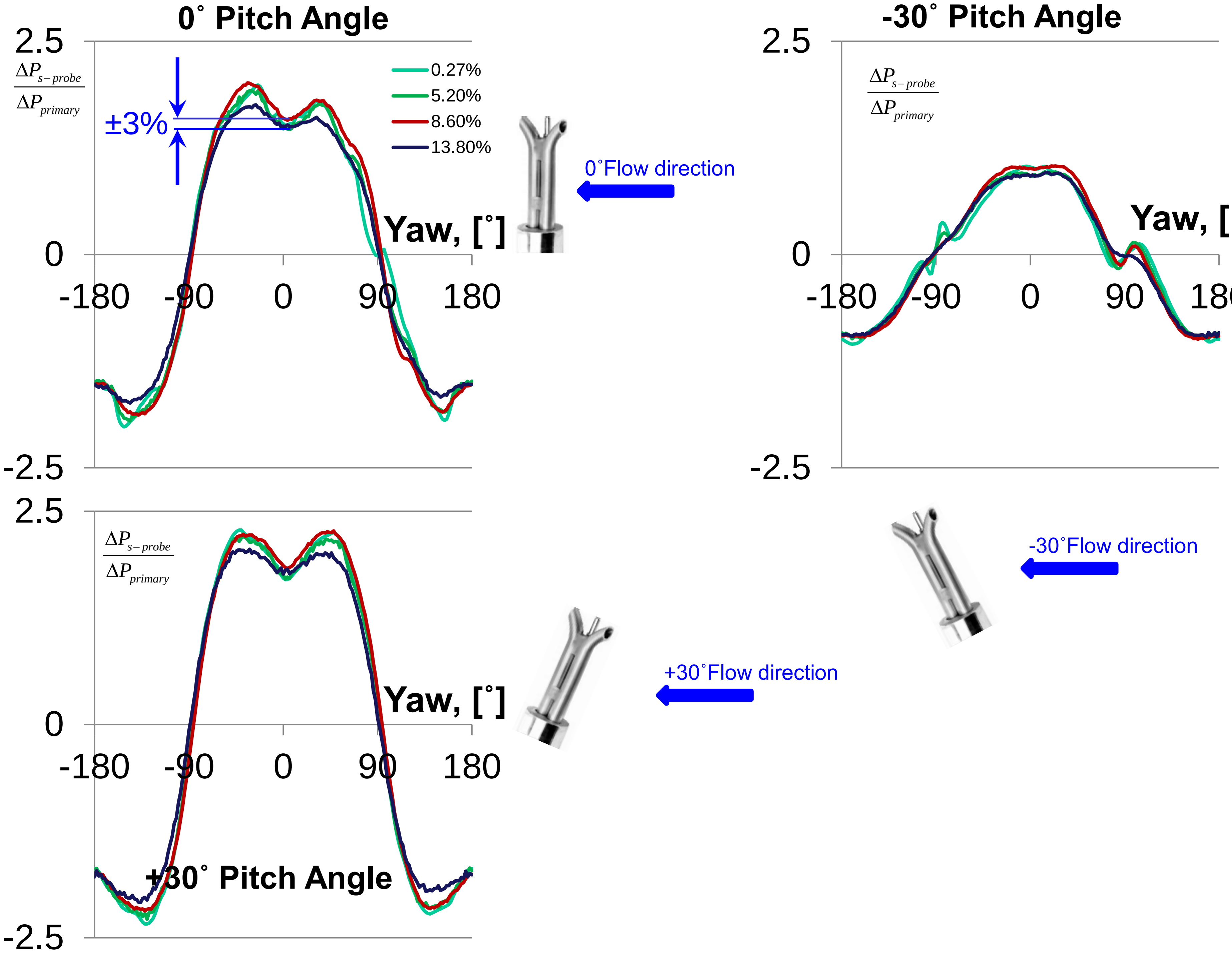






$$V_P / V_{NIST} = F_1(\mathrm{Re}) F_2(Tu)$$

$$\frac{\Delta P}{\left(\frac{\rho V^2}{2}\right)} = 1 + a(Tu)^2$$


0˚ Pitch Angle
-30˚ Pitch Angle
+30˚ Pitch Angle
$\frac{\Delta P_{s-probe}}{\Delta P_{primary}}$
±3%
0.27%
5.20%
8.60%
13.80%
Yaw, [˚]
2.5
0
-2.5
-180
-90
0
90
180
0˚Flow direction
-30˚Flow direction
+30˚Flow direction

Summary

1. **NIST calibrates S-probes and 3D (multi-hole) probes.**
2. **S-probes can have multiple nulls. Incorrect nulling may cause errors during calibrations and measurements.**
3. **S-probes are sensitive to pitch angle; therefore, calibration factors does not represent measured flow.**
4. **Five-hole pitot tubes are sensitive to turbulence intensity.**
5. **Regular pitot tube and s-probe much less sensitive to turbulence.**
6. **NIST has studied only a few probes. How sensitive are other probes to turbulence?**

We thank **Greg Scace** for design, assembly, and continuing support of the 3-D system

and

Jim Filla for writing 3-D system software and readiness to modify and improve it on first request.

The paper with the same title “NIST’s New 3D Airspeed Calibration Rig Addresses Turbulent Flow Measurement Challenges” was published in the proceedings of ISFFM, Arlington, Virginia, April 14-16, 2015