Probe Calibrations and RATA Results from NIST's Wind Tunnel and Stack Simulator

NIST Workshop

Improving Measurement for Smokestack Emissions

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Gaithersburg, MD

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Goals…

To Answer the Following Questions

1. **What is the accuracy of S-probe RATA?**

2. **Can 3-D probes make the flow RATA more accurate?**
   - By how much?
   - What parameters need to be considered in a 3-D probe calibration?
   - How accurate are non-nulling methods?

Goals…

To Answer the Following Questions

1. **What is the accuracy of S-probe RATA?**

   overpredicts by 5% - 10% Depending on Pitch

2. **Can 3-D probes make the flow RATA more accurate?** ***Yes!***

   - By how much? Expected accuracies of 1% - 3%
   - What parameters need to be considered in a 3-D probe calibration? Pitch, Yaw, ***Reynolds number*** & ***Turbulence***
   - How accurate are non-nulling methods? 1% to 3% for ± 12° Pitch and ± 33° Yaw

What is the Acceptable Accuracy of Stack Flow Measurements?

1) **Accuracy 10 %**
   - relax and skip this presentation ☺.

2) **Accuracy 5 %**
   - S-probes are not sufficient;
   - 3-D probes can provide better accuracy
   - better continue pay attention

3) **Accuracy 1-2 %**
   - challenging … but we get there if NIST and Industry cooperate
   - Two new parameters must be incorporated in probe calibration
     - ❖ Reynolds number (***Re***)
     - ❖ Turbulence Intensity (***Tu***)

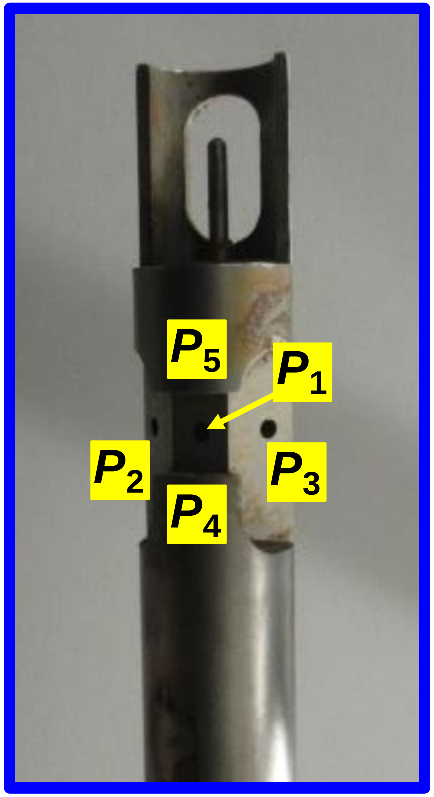
NIST Wind Tunnel

- **Closed loop recirculating wind tunnel**
- **Test volume:** 6.6 ft long × 4.9 ft wide × 3.9 ft high
  - Large test volume ⇒ small wall effects
- **Uncertainty = 0.42% for airspeeds from 16 – 100 ft/s (5 – 30 m/s)**
  - Uniform flow along tunnel axis (1-dimensional flow)
  - Automated staging to control pitch and yaw angles of pitot probes
  - Calibrations are automated

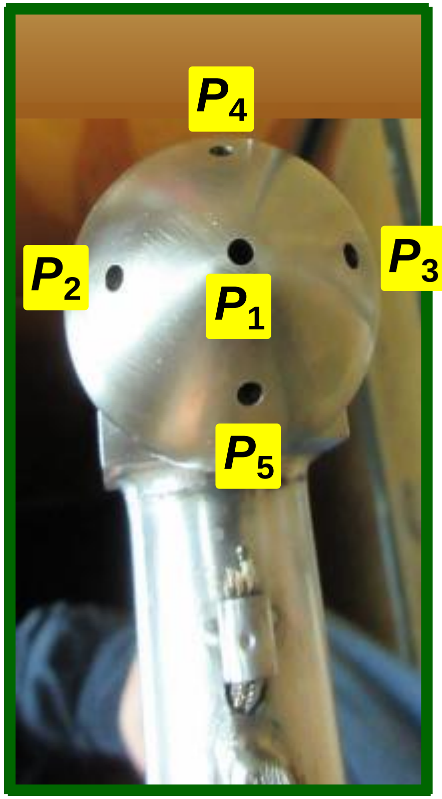
Calibration of 3 Conventional Probes

S-probe

Prism Probe

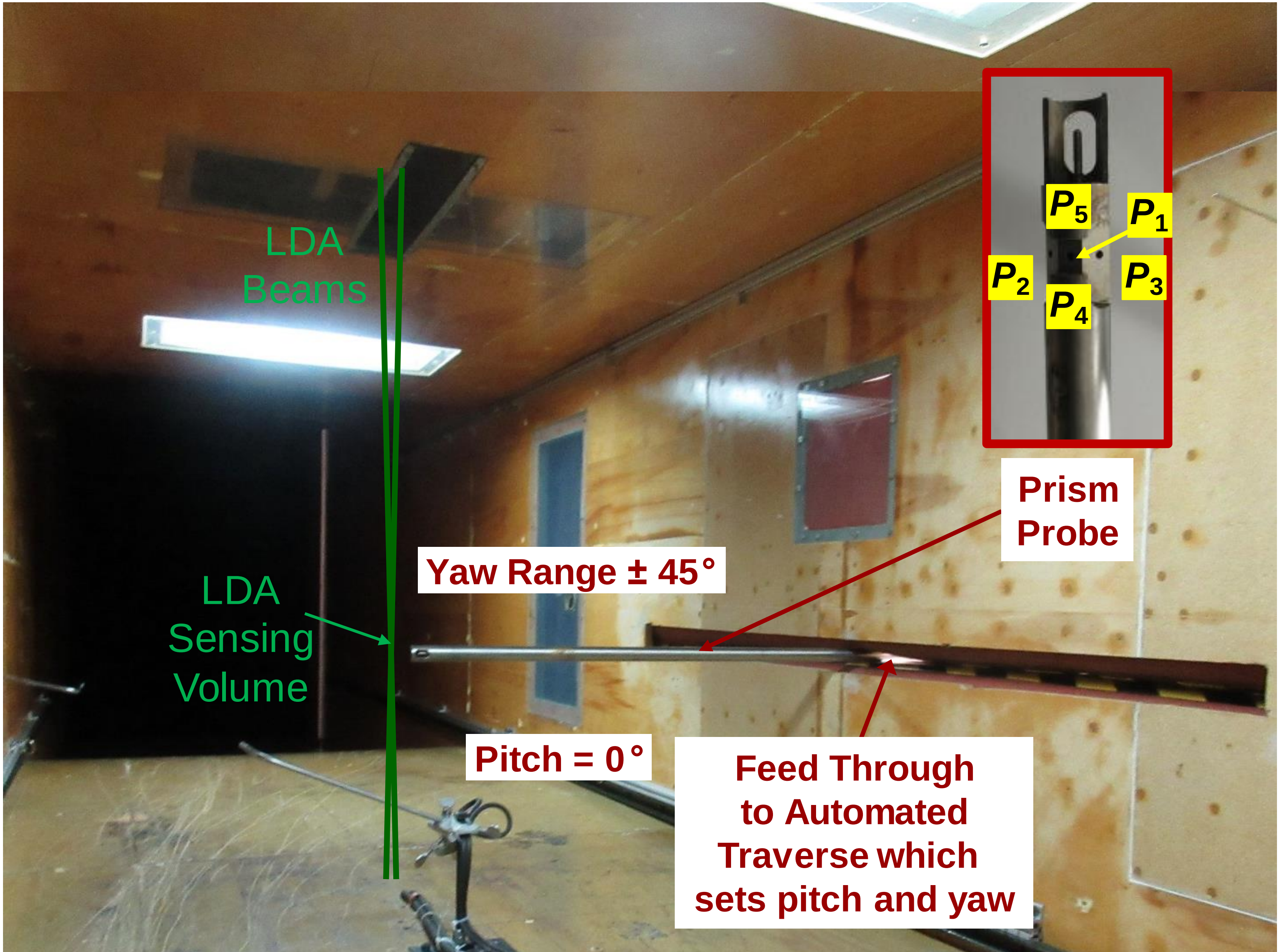


Spherical Probe

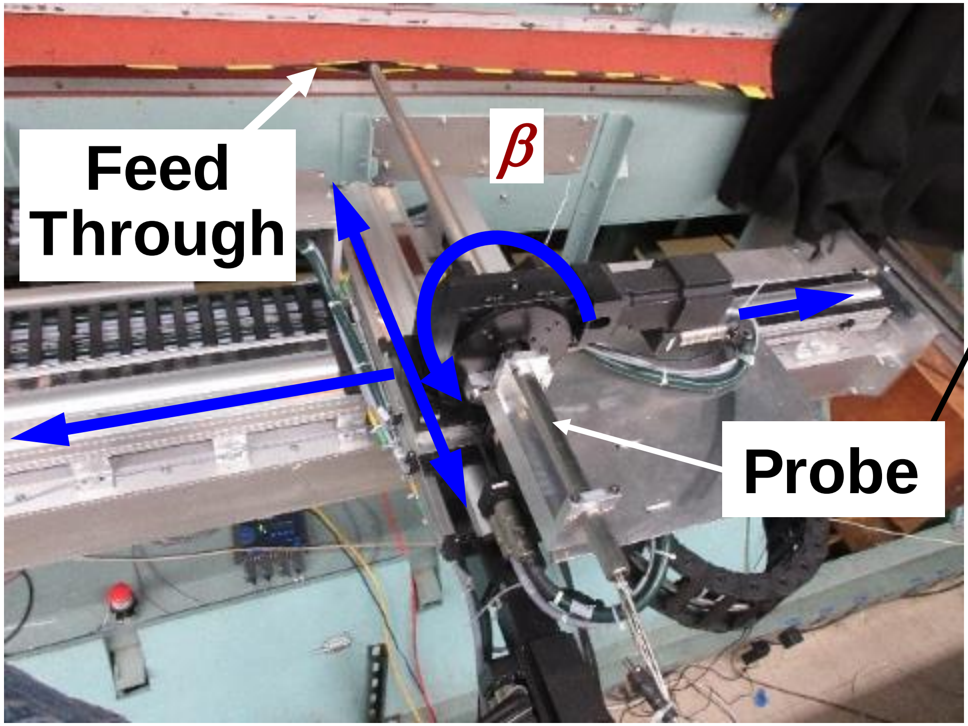


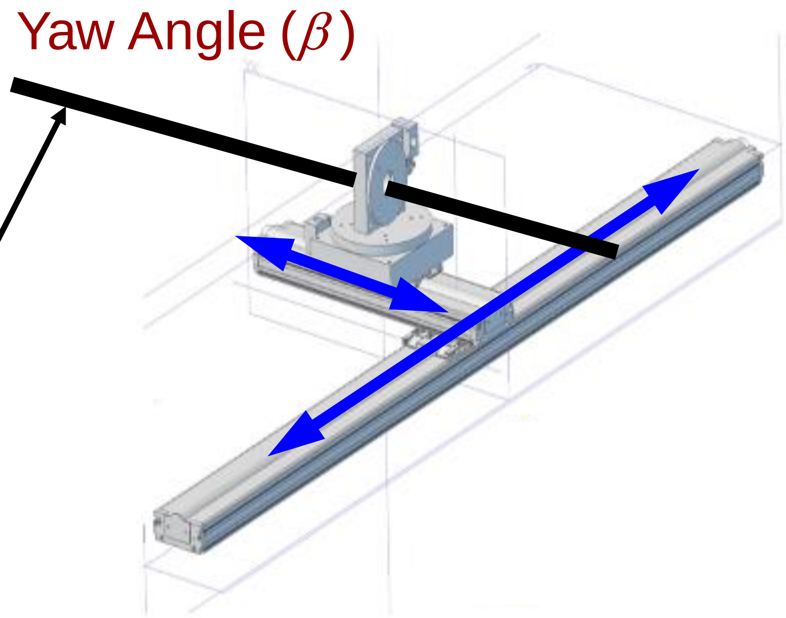
- Diameter of each probe shaft is D = 1 inch
- Length of each probe shaft is 6 ft

Probe Installation in Wind Tunnel



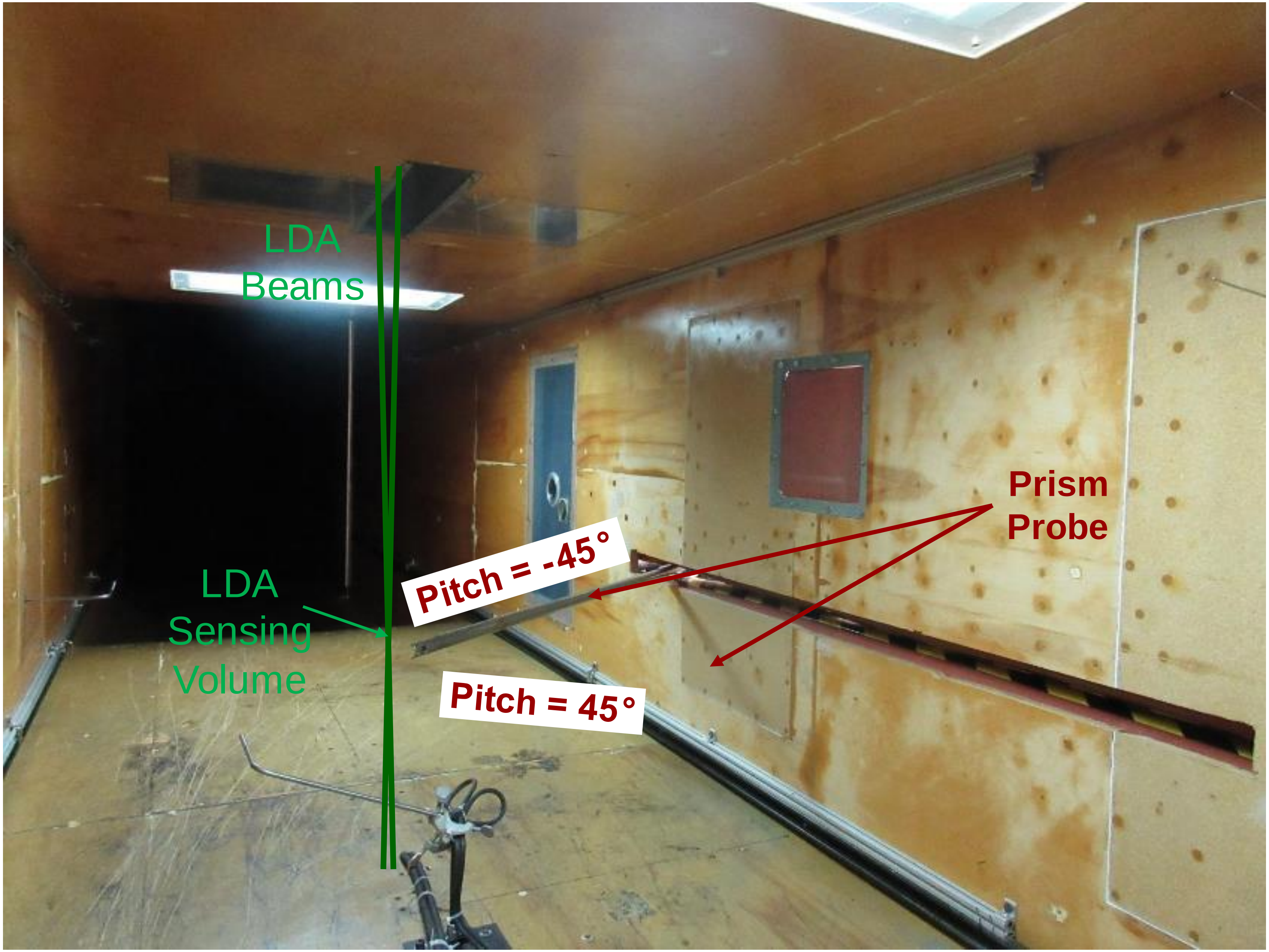
NIST Wind Tunnel 4 Axis Traverse System





- Installed on the side of Wind Tunnel
- Single axis rotation sets **Yaw Angle (β)**
- 2 Linear motions and a rotation adjust **pitch angle (α)** while maintaining **probe head at same position** in Wind Tunnel
- Completely automated and synchronized with airspeed measurement software

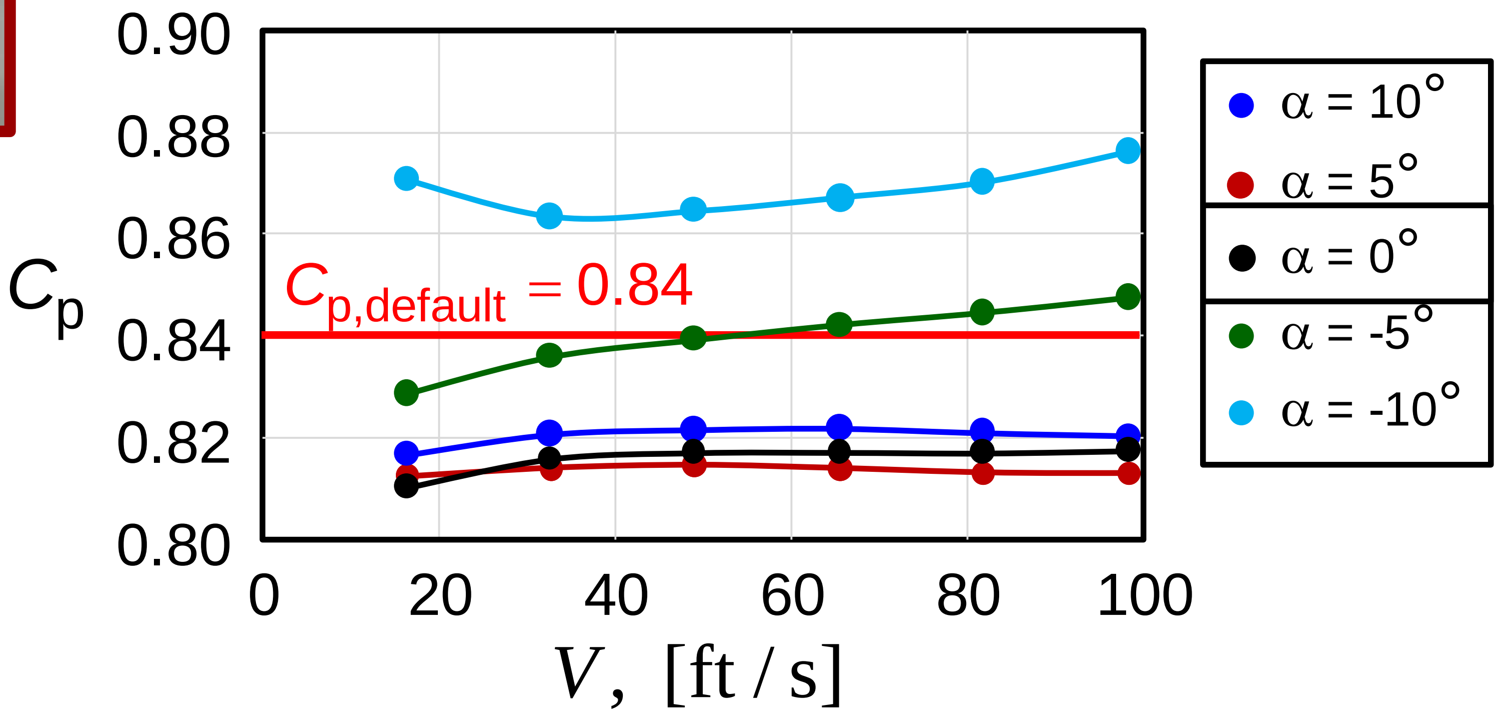
Probe Installation Inside of Wind Tunnel



S-probe Calibration

$$V = C_p \sqrt{\frac{\Delta P_{std}}{\rho}} \cos(\beta)$$

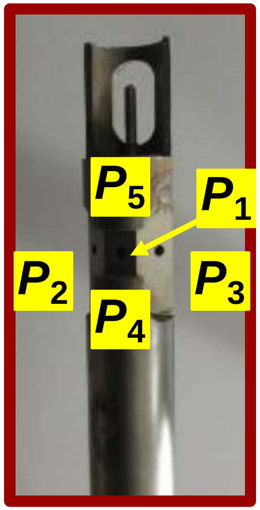
During Calibration ($\beta = 0$)



- S-probe calibration coefficient depends on velocity
- S-probe calibration coefficient depends on pitch (often neglected in S-probe calibrations)

Calibration Method for Prism (or Spherical) Probe

(EPA Method 2F)



Prism Probe

1) Set airspeed; $V_{NIST} = 16$ to 100 ft/s (16.5 ft/s steps)

2) Set probe pitch angles: $\alpha = -45^\circ$ to 45° (3° steps)

3) Rotate probe until $P_2 = P_3$ to determine Yaw Angle (β)

4) Measure **Pitch Calibration Factor (F_1)** at β

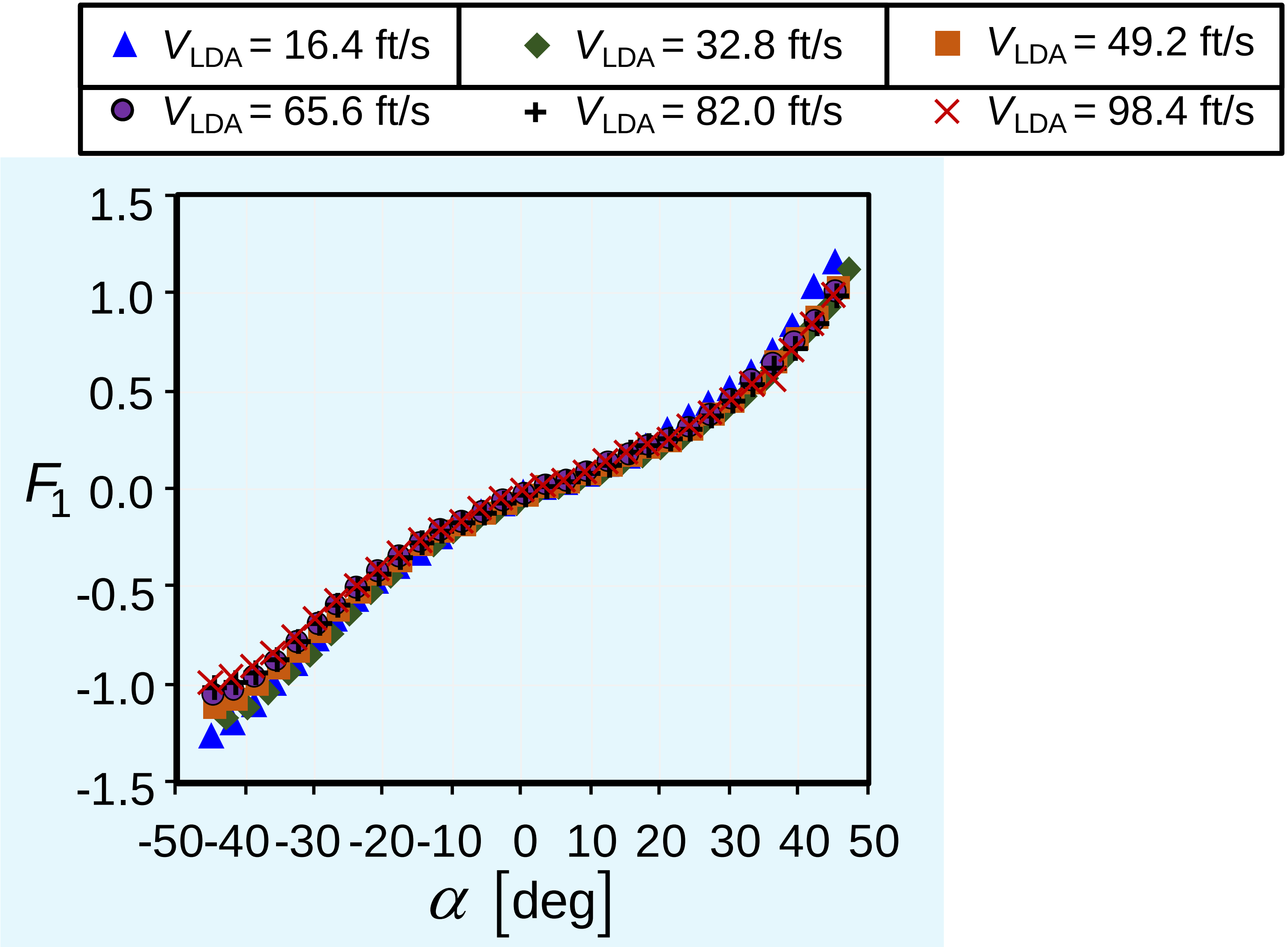
$$F_1 = \frac{P_4 - P_5}{P_1 - P_2}$$

5) Measure **Velocity Calibration Factor (F_2)** at β

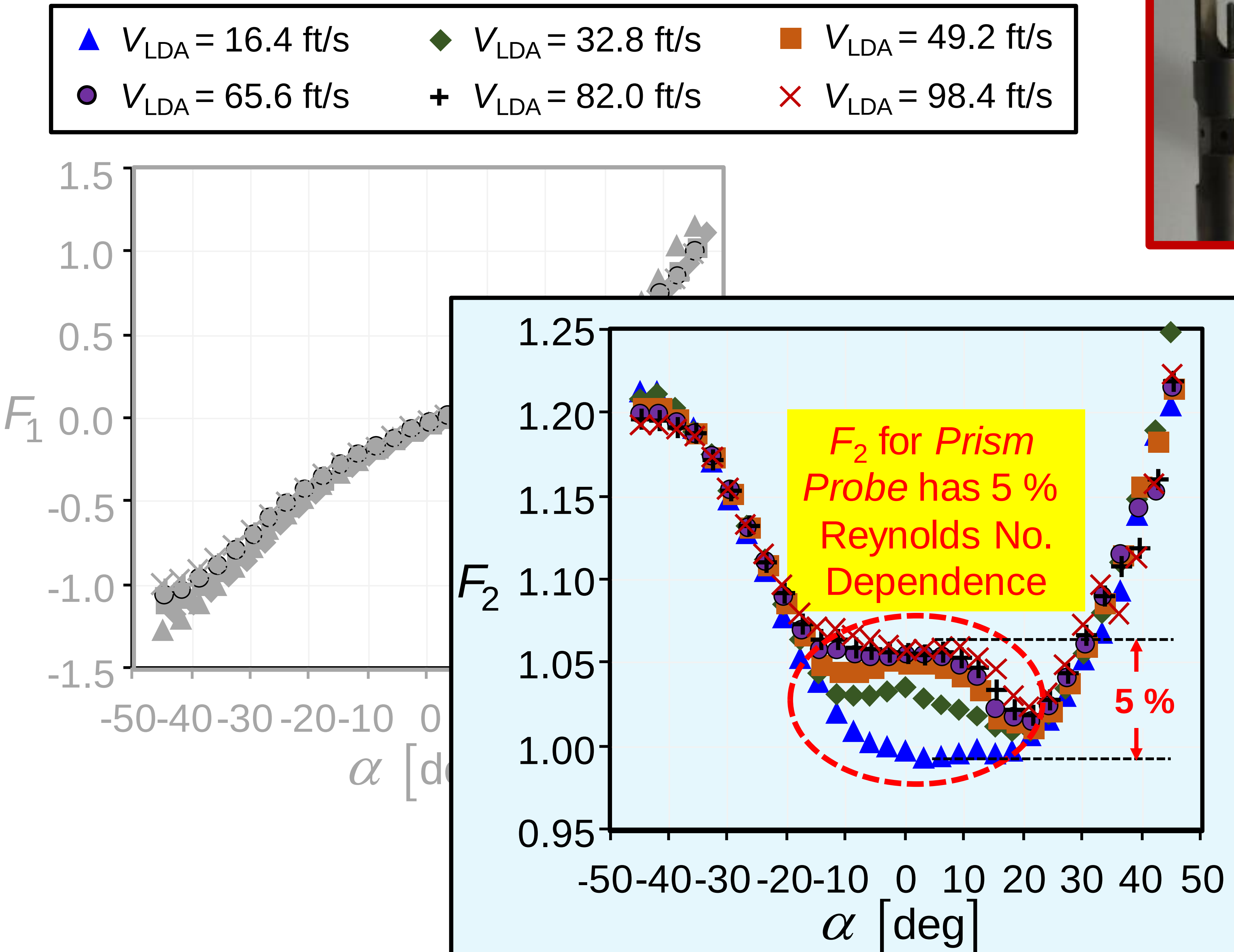
$$F_2 = \sqrt{\frac{\Delta P_{std}}{P_1 - P_2}} = V_{LDA}\sqrt{\frac{\rho}{2\left(P_1 - P_2\right)}}$$

$$\Delta P_{std} = \rho V_{LDA}^2 / 2$$

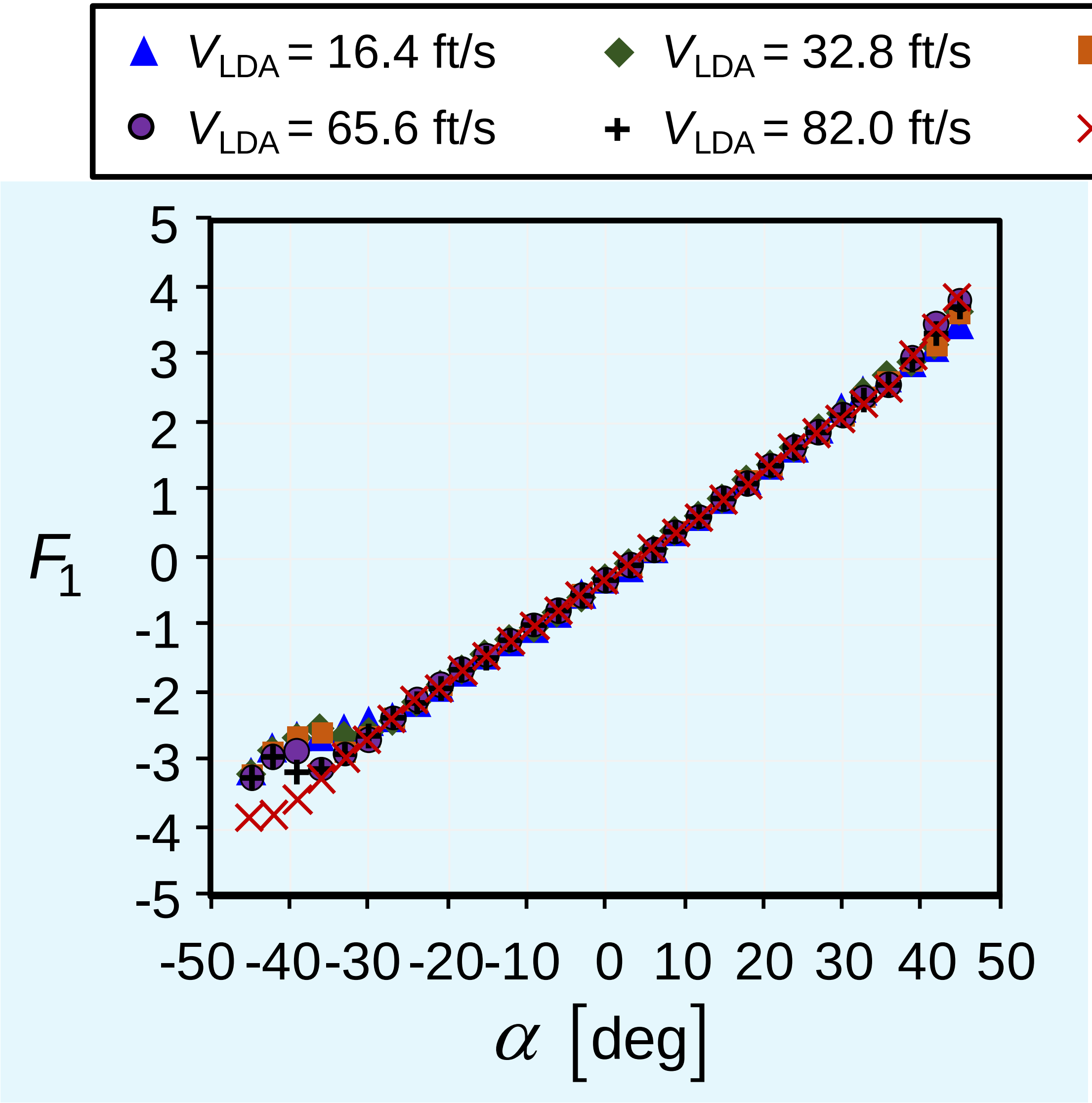
Prism Probe Calibration Results



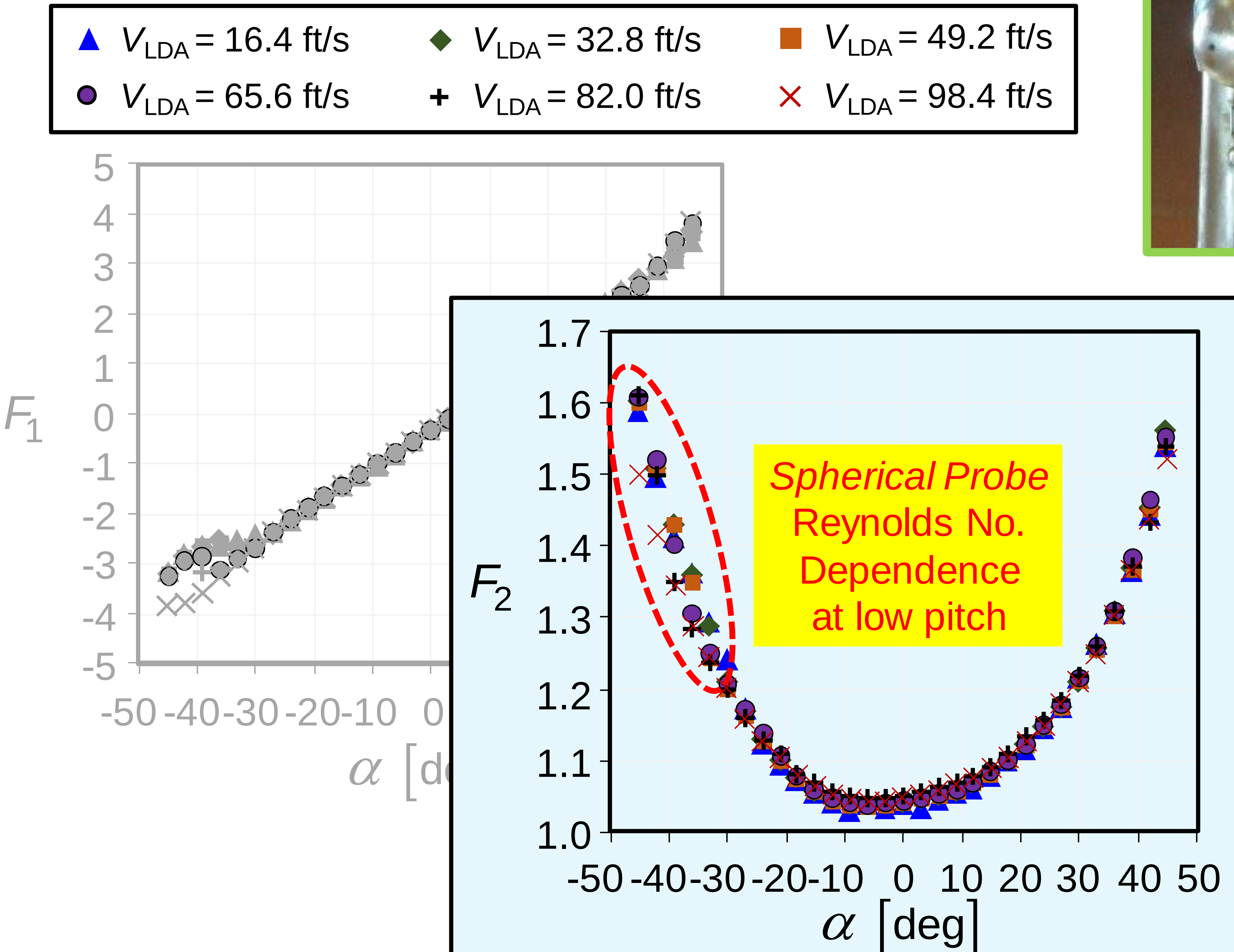
Prism Probe Calibration Results



Spherical Probe Calibration Results



Spherical Probe Calibration Results



Applying 3-D Probe Calibration during RATA

Calibration Parameters	EPA Method 2F	NIST Implementation of Method 2F
Pitch Calibration Factor (F_1)	$F_1 = F_1(\alpha)$	$F_1 = F_1(\alpha, Re, Tu)$
Velocity Calibration Factor (F_2)	$F_2 = F_2(\alpha)$	$F_2 = F_2(\alpha, Re, Tu)$

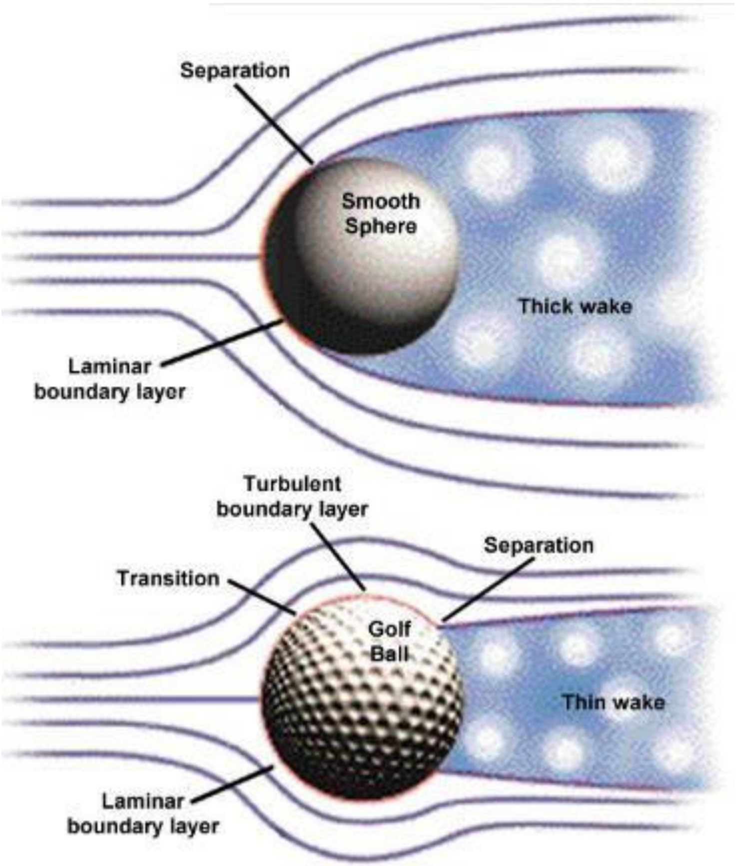
- ***EPA Method 2F;*** F_1 and F_2 are _only_ functions of the pitch angle (α)
- ***3-D probe calibration data showed the importance of accounting for*** *Reynolds number* (*Re*) dependence
- ***NIST Implementation of Method 2F;*** F_1 and F_2 account for *Reynolds number* (*Re*) and Turbulence (*Tu*) dependence
- **Field Measured probe velocity**

$$V_{\text{probe}} = F_2 \sqrt{(P_1 - P_2)} \cos\alpha \cos\beta \quad at\ P_2 - P_3 = 0$$

Why is Turbulence Important?

- Wind tunnel probe calibrations are often *performed in laminar flow* (*i.e.*, turbulence intensity is nearly zero)

- Probes are used *in stacks* where *flow is certainly turbulent*
  - ❖ Flow separation location and wake characteristics can vary significantly between laminar and turbulent flow
  - ❖ Pressure measurements located In laminar-wake behind probe will vary significantly from turbulent-wake
  - ❖ Turbulent velocity fluctuations induce an additional pressure at pressure ports. (This turbulent induced pressure is not present when the flow is laminar)



How do we Generate Turbulence?

Grid (12.5 cm spacing)

Flag

- Turbulence intensity up to 11 % for grid and up to 25 % for flag
- Turbulence intensity (*Tu*) is the rms of the velocity fluctuations divided by mean velocity

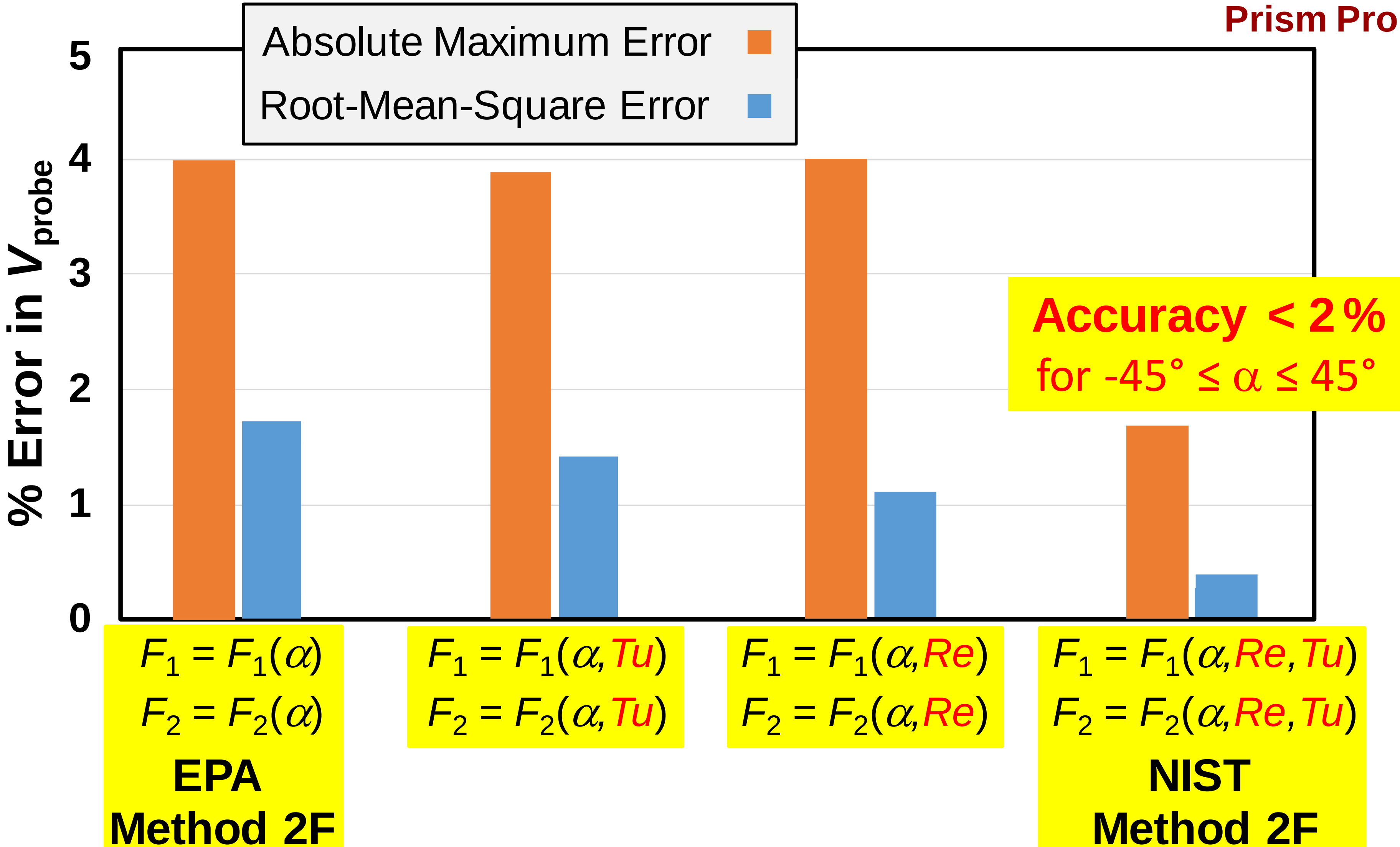
$$Tu = \frac{u_{\mathrm{RMS}}}{U} = \frac{\sqrt{(u'^2 + v'^2 + w'^2)/3}}{U}$$

- Magnitude controlled by downstream distance from grid or flag

Does Turbulence Really Impact Accuracy?

$$V_{\text{probe}} = F_2\sqrt{(P_1 - P_2)}\cos\alpha\cos\beta \quad at\ P_2 - P_3 = 0$$

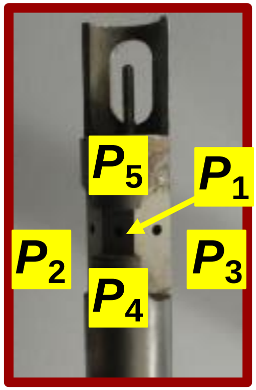
Prism Probe



3 Non-Nulling Correlations

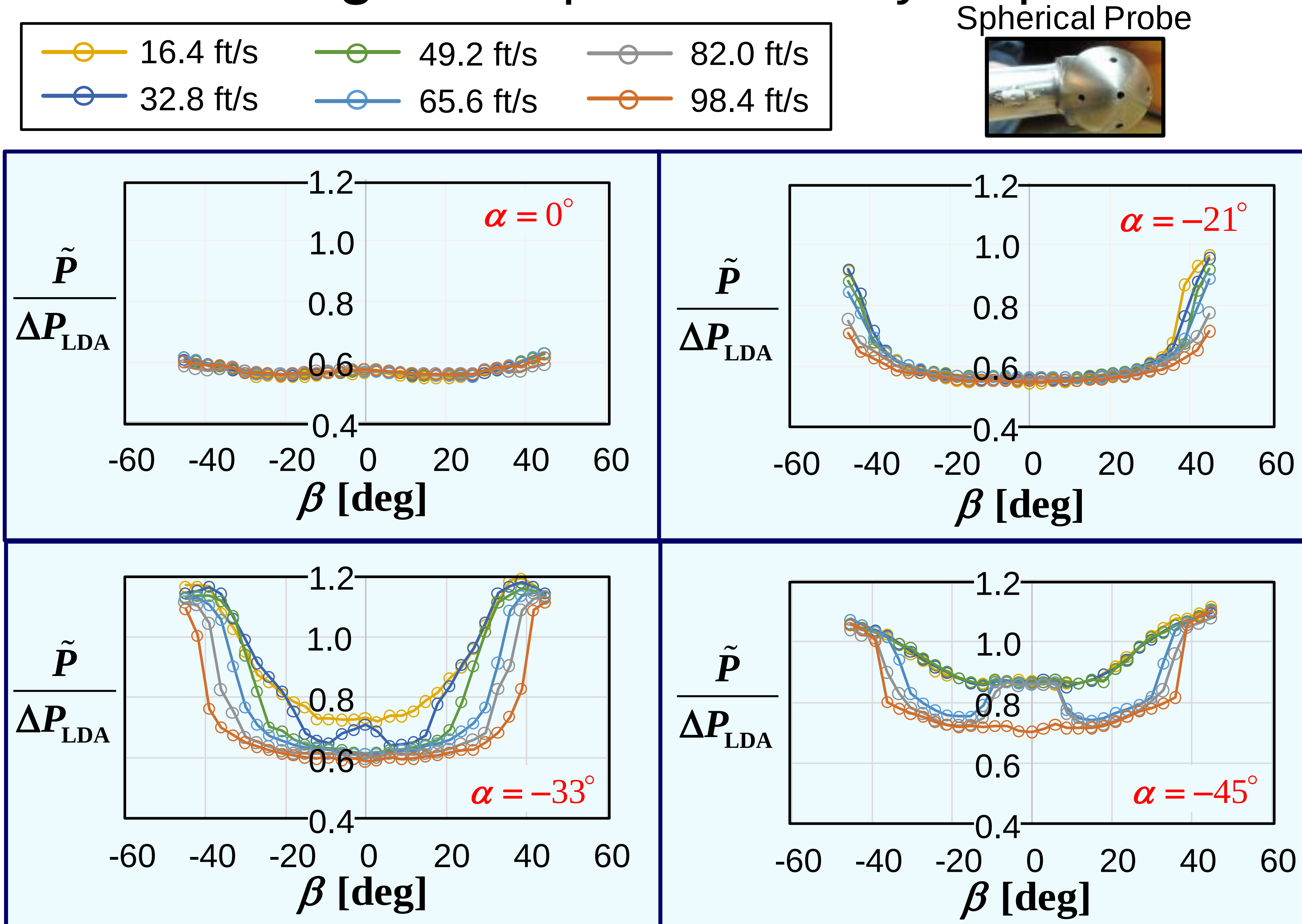
Measured Parameters	EPA Method 007	NIST Method 007
Normalized Pseudo Dynamic Pressure	$\frac{P_1 - P_t}{\widetilde{P}_{EPA}} = \widetilde{F}(\alpha, \beta)$	$\frac{\widetilde{P}_{NIST}}{\Delta P_{LDA}} = \widetilde{F}(\alpha, \beta, Re, Tu)$
Pitch Angle Function	$\frac{P_4 - P_5}{\widetilde{P}_{EPA}} = F_\alpha(\alpha, \beta)$	$\frac{P_4 - P_5}{\widetilde{P}_{NIST}} = F_\alpha(\alpha, \beta, Re, Tu)$
Yaw Angle *F*unction	$\frac{P_2 - P_3}{\widetilde{P}_{EPA}} = F_\beta(\alpha, \beta)$	$\frac{P_2 - P_3}{\widetilde{P}_{NIST}} = F_\beta(\alpha, \beta, Re, Tu)$

- Preliminary EPA Method 007 ***will not work for*** 3-D probes for which $\widetilde{P}_{EPA} = 0$
- NIST Method 007
  - accounts for Reynolds (Re) number and Turbulence (Tu) dependence
  - works well for several probes over wide range of pitch and yaw since ($\widetilde{P}_{NIST} > 0$)



Prism Probe

Non-Nulling: Example of Velocity Dependence



Custom Probe Shapes Designed at NIST

- NIST is researching various probe designs
- Probe performance is based on ***probe geometry*** and ***hole placement***
- Goal is to identify probes that are ***highly immune*** to Reynolds number effects and Turbulence over a wide range of pitch and yaw

Truncated (flat) Probe

Disk shape

Cylindrical Probe

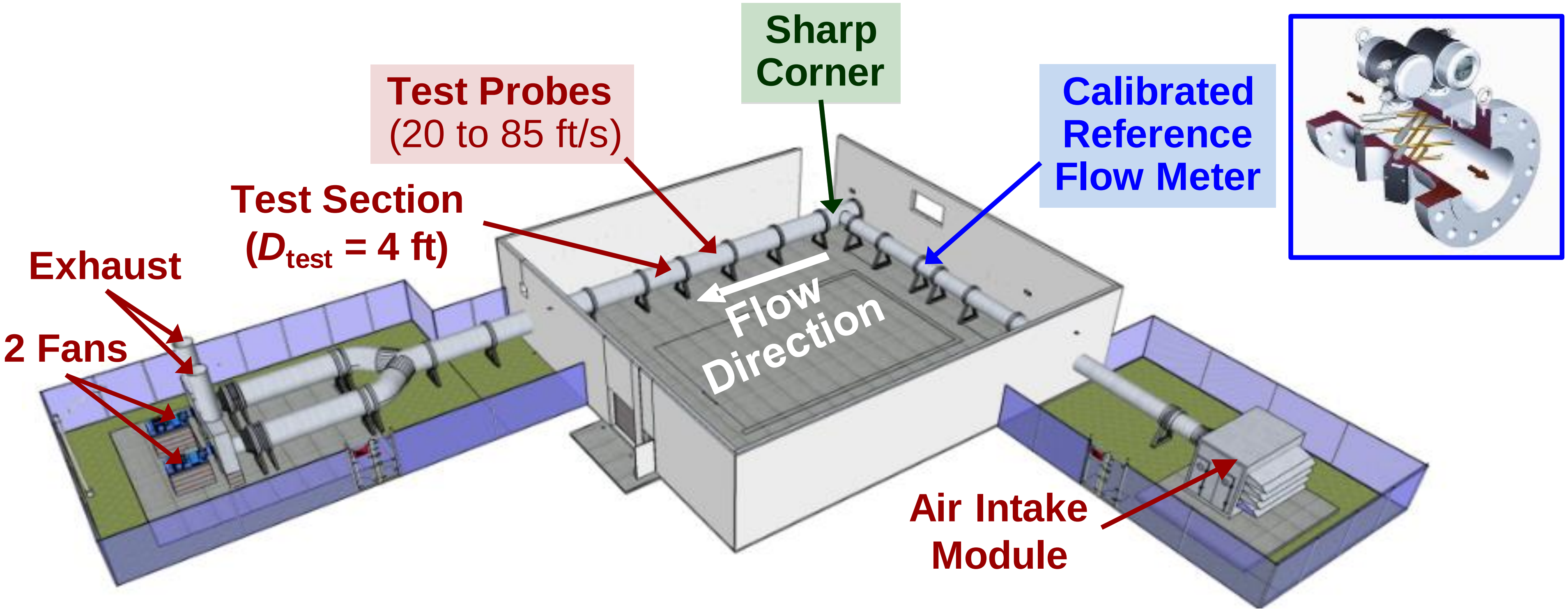
Modified Spherical Probe

Scale-Model Smokestack Simulator (SMSS)

- **A Facility Designed to Assess the Flow Measurement Accuracy of CEMS and RATA**

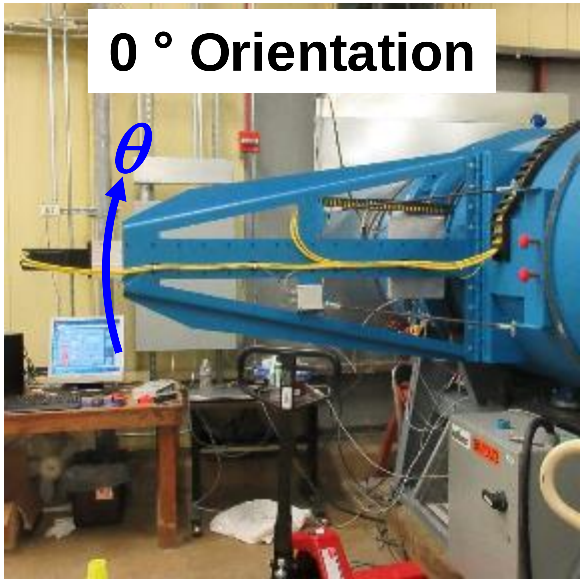
- **Three Design Criteria**
  1) Facility must have ***CEMS and RATA equipment*** commensurate to what is used in industry
  2) Facility must ***create smokestack-like flow conditions***
  3) Facility must ***establish NIST traceable velocities*** (V_{NIST}) to compare CEMS and RATA

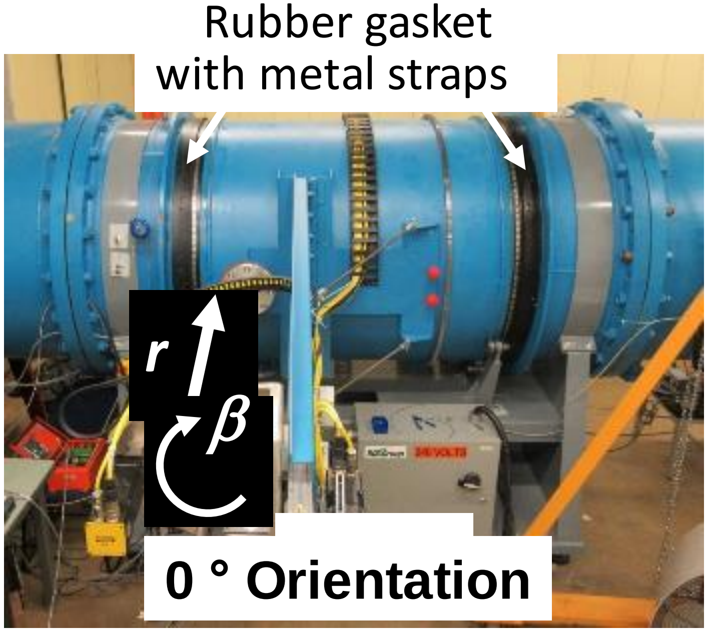
Scale-Model Smokestack Simulator (SMSS)



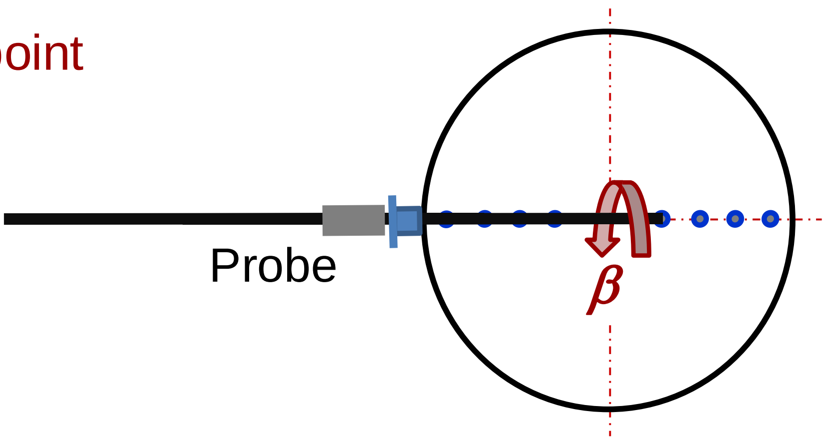
1) 8 path ultrasonic flow meter measures flow to better than 0.5 %
2) Stack flow conditions (high swirl and skewed velocity profile) realized by sharp corner section
3) RATA equipment installed in SMSS Test Section
   - RATA equipment – probes calibrated Wind Tunnel installed in the automated traverse system

RATA Performed using an Automated Pitot Traverse Unit Installed in 4ft Test Section





- Pitot probe can be positioned to any desired location in the cross section
  - Probe moves radially to a selected RATA point
  - Probe rotates to determine Yaw angle (β)



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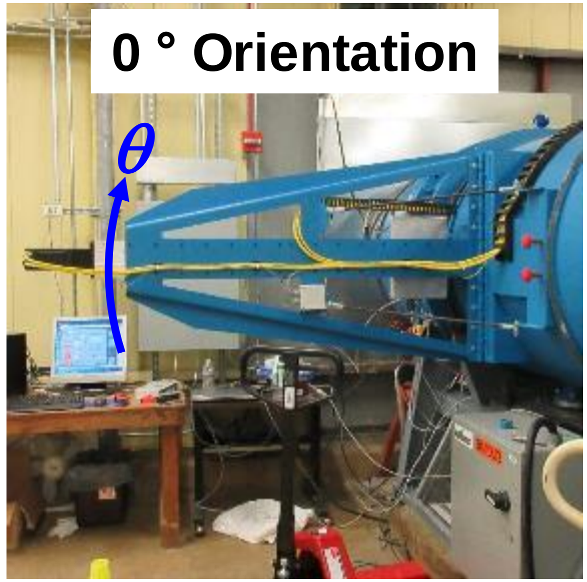
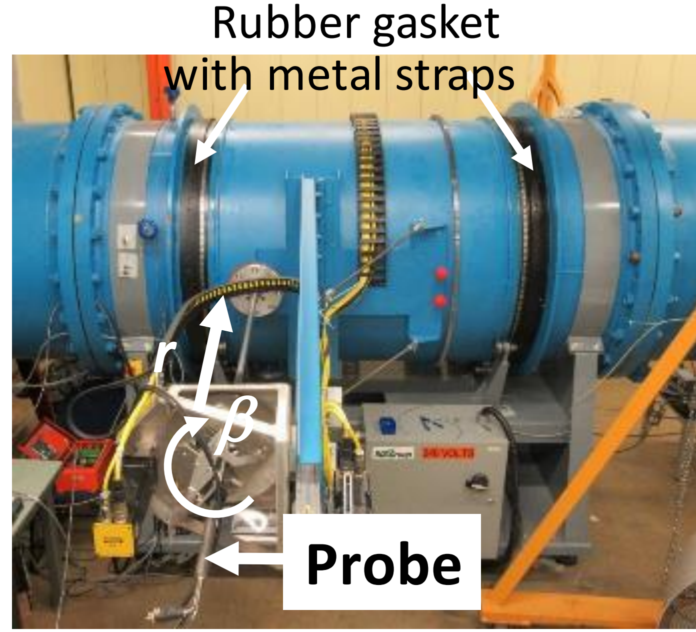
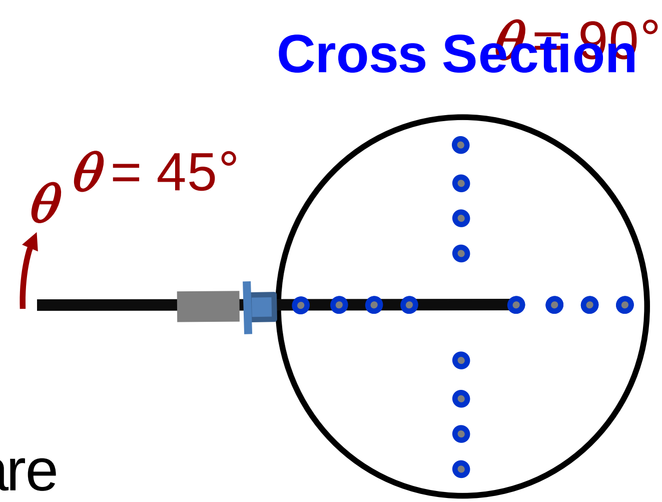
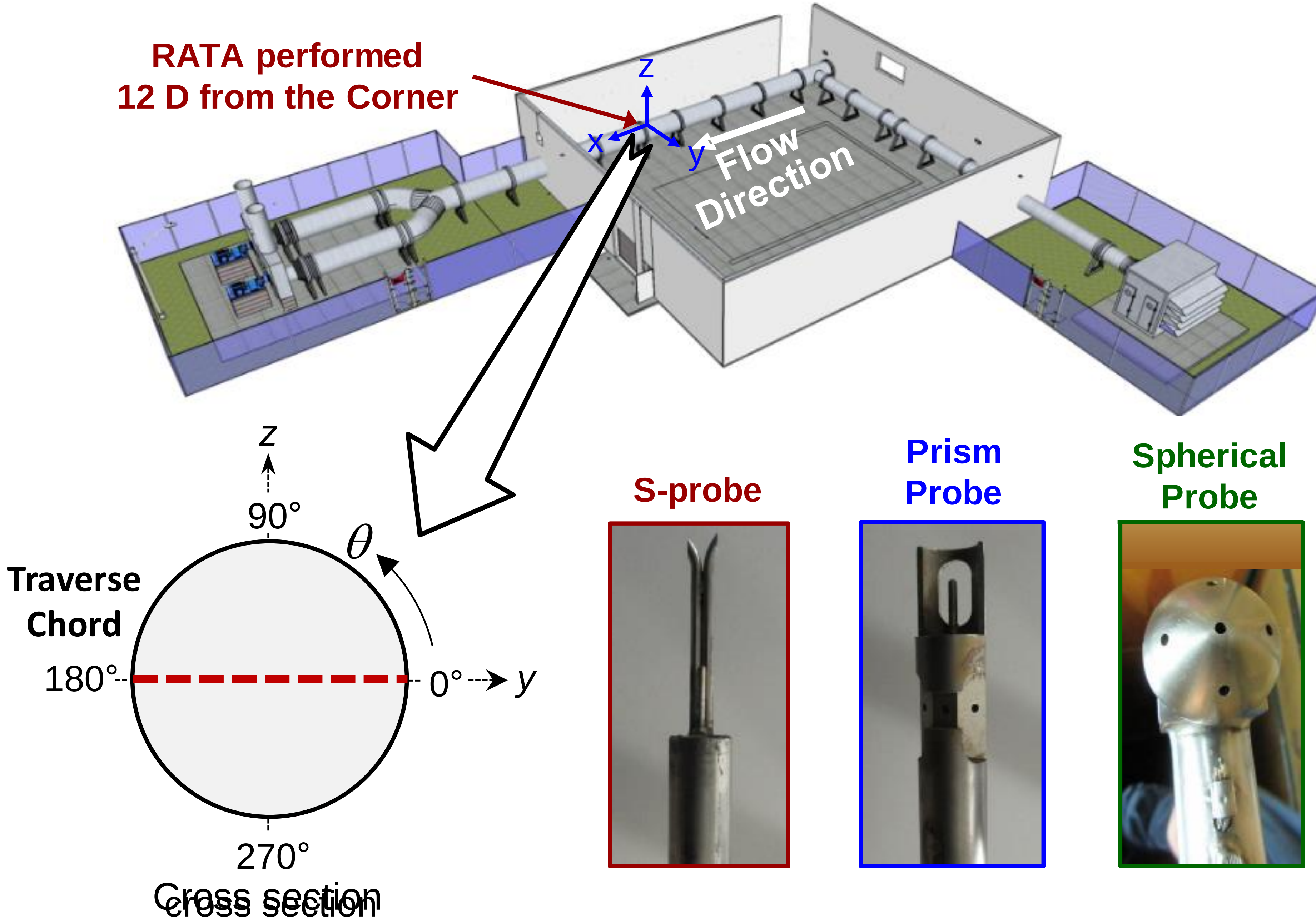




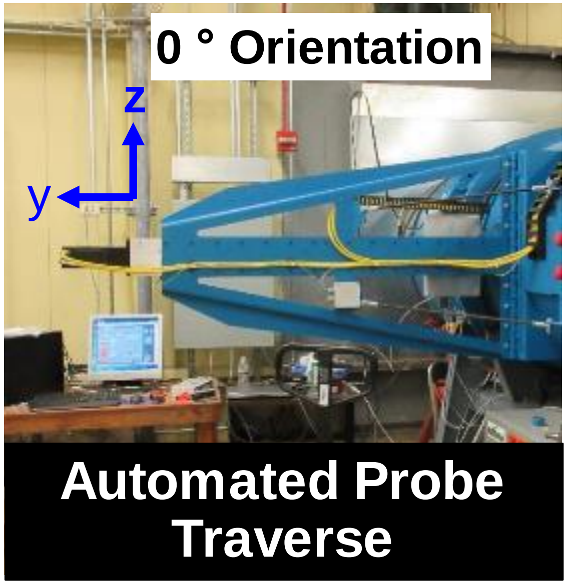
- ❖ Pitot probe can be positioned to any desired location in the cross section
  - Probe moves radially to a selected RATA point
  - Probe rotates to determine Yaw angle (β)
  - Traverse arm rotates to in θ-direction to measure RATA points on different chords
- ❖ Completely Automated via LabVIEW software

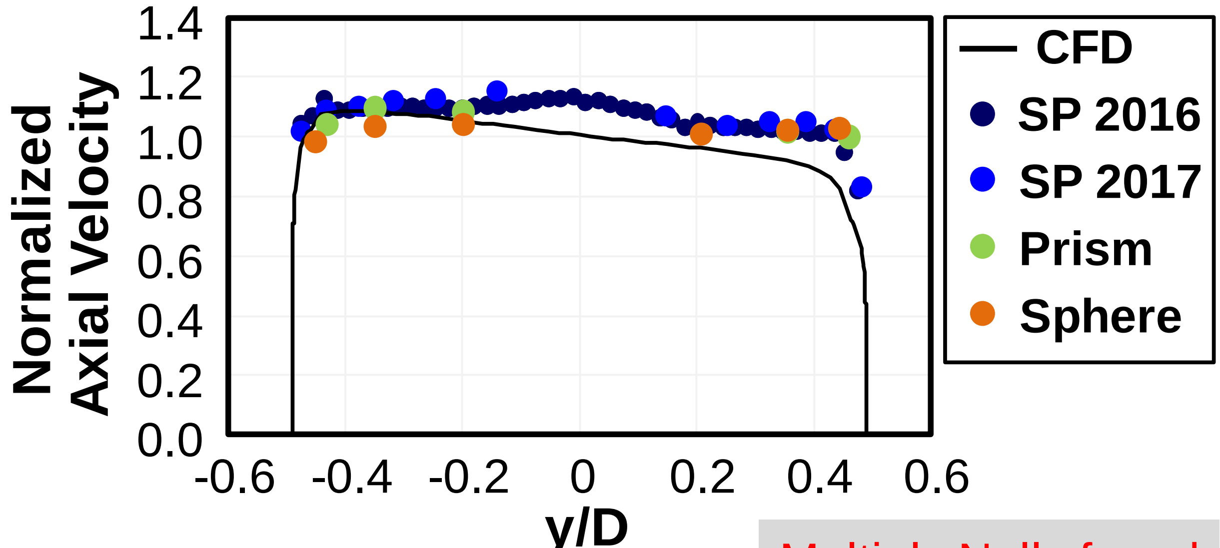


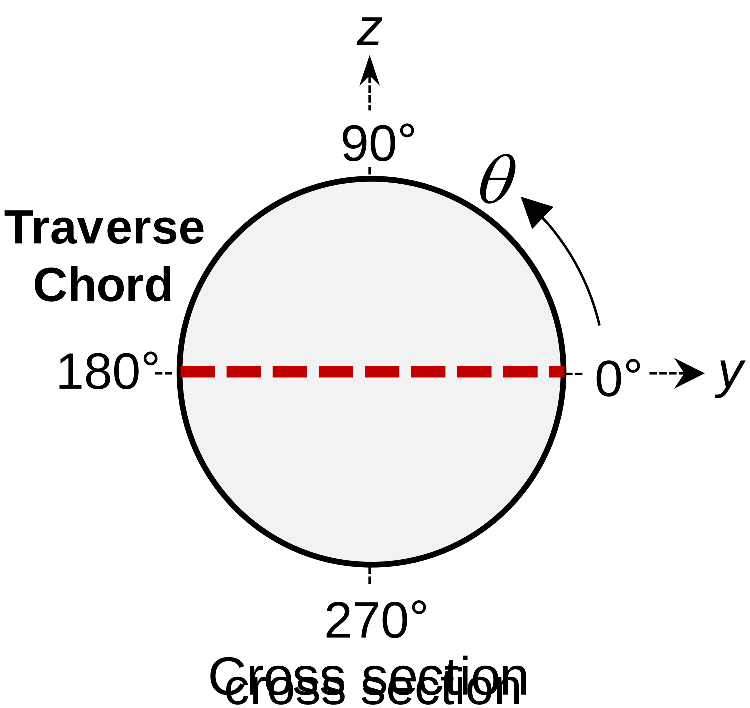
RATA Measurement Location

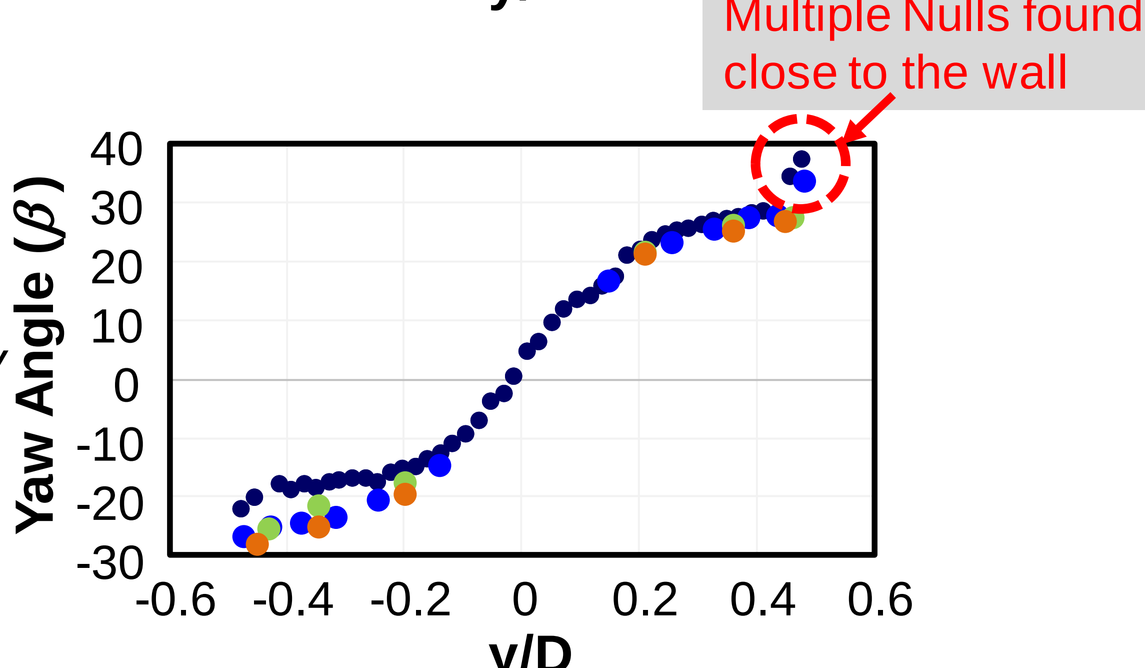


RATA: Velocity Profile, Yaw and Pitch Angles









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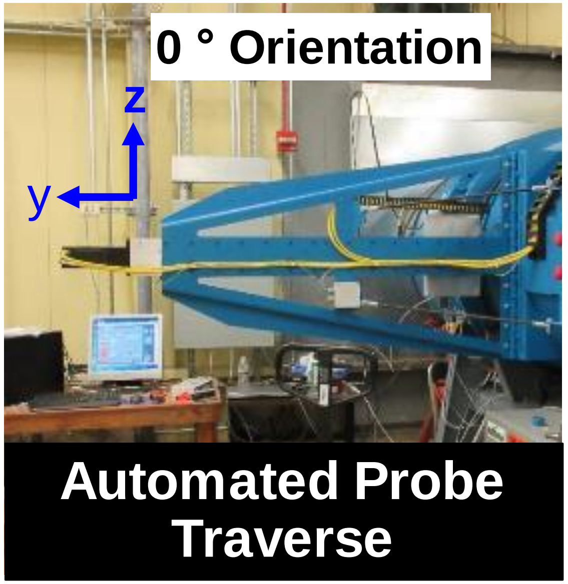

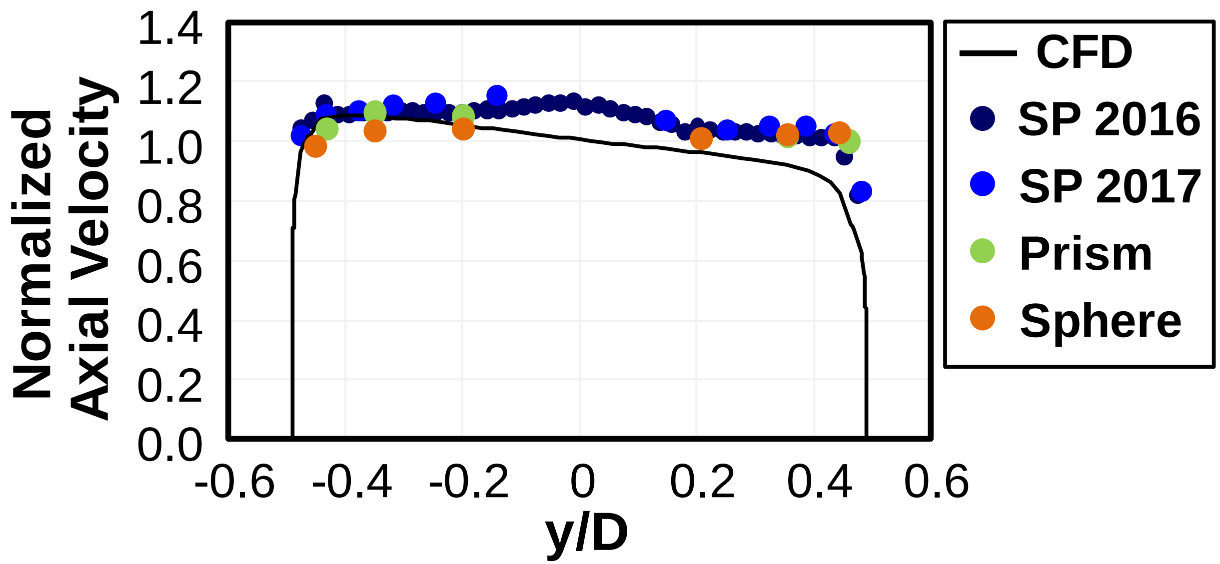

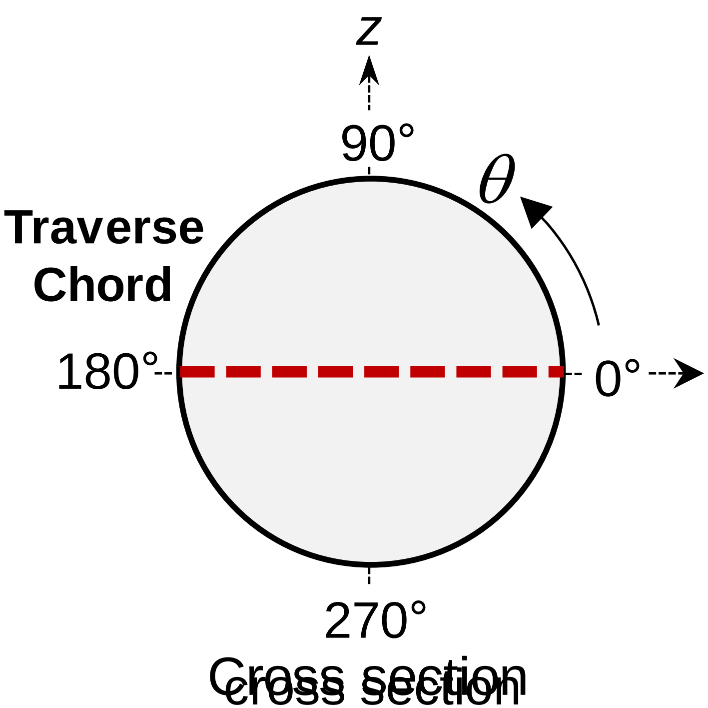

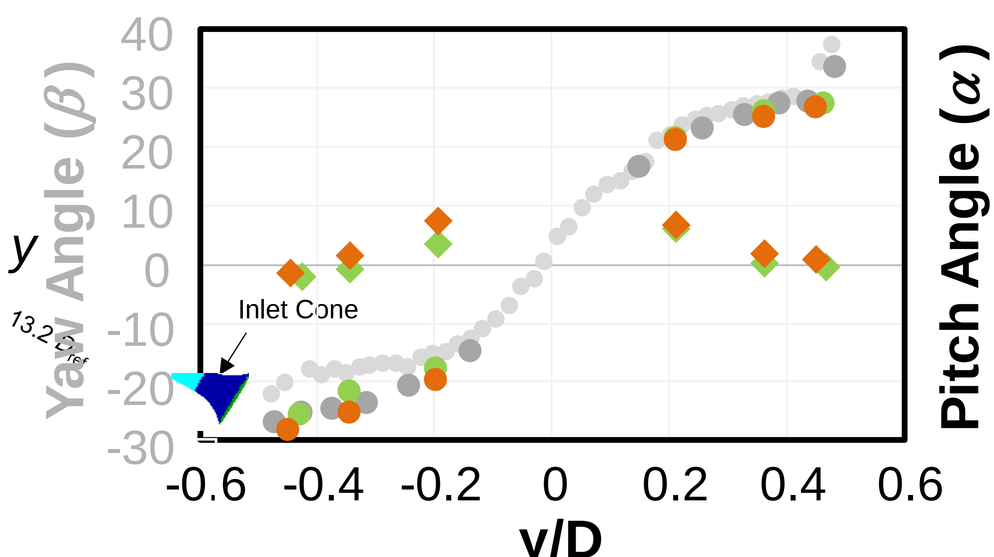

S-Probe RATA along 2 Diametric Chords

# of Points	V_{NIST}, [ft/s]	V_{Probe}, [ft/s]	% Difference
12	76.40	81.50	+ 6.7 %
24	76.40	81.37	+ 6.5 %
48	76.40	80.40	+ 5.2 %

- In all cases the ***S-probe over predicts*** the actual flow
- Slight increase in accuracy with more traverse points
- C_p = 0.84; **What is the accuracy if we use a calibrated S-probe?**

S-Probe RATA along 2 Diametric Chords

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12	76.40	81.50	**+ 6.7 %**
24	76.40	81.37	+ 6.5 %
48	76.40	80.40	+ 5.2 %
12	76.40	79.72	**+ 4.4 %**

$C_p = 0.84$ (first row, 12 points)

$C_p(Re, \alpha)$ (last row, 12 points)

- In all cases the ***S-probe over predicts*** the actual flow
- Slight increase in accuracy with more traverse points
- $C_p = 0.84$; **What is the accuracy if we use a calibrated S-probe?**
- **Calibration improves accuracy**

Prism Probe RATA along 2 Diametric Chords

# of Points	V_{NIST}, [ft/s]	V_{Probe}, [ft/s]	% Difference
12	67.64	70.10	+ 3.6 %

- The ***Prism probe over predicted*** the actual flow
- Better accuracy than calibrated S-probe (6.7 % uncalibrated)

Spherical Probe RATA along 2 Diametric Chords

# of Points	V_{NIST}, [ft/s]	V_{Probe}, [ft/s]	% Difference
12	67.63	68.52	+ 1.3 %

- The ***Spherical probe over predicted*** the actual flow
- Better accuracy than S-probe (6.7 %) and the Prism probe (3.4 %)

Non-Nulling Method Works Well!

- NIST has developed a ***robust, high accuracy non-nulling method***
  - Improvement over Method 007 (*i.e.*, more accurate fit over wide range of pitch and yaw)
  - Accounts for turbulence (*Tu*) and Reynolds number (*Re*) dependence

- Recap Spherical Probe RATA Results
  - Measured $\boldsymbol{V}_{\mathbf{RATA}}$ and $\boldsymbol{V}_{\mathbf{NIST}}$
  - Accuracy evaluated by $\%\,Diff = 100\left(V_{RATA}/V_{NIST} - 1\right)$

# Points	% Diff	Method	*Tu* (During Cal.)	*Tu* (During Use)
12	+ 1.3 %	2F	0 %	10 %
12	**- 0.8 %**	Non-Null	10 %	10 %

- Results are preliminary pending field test

Summary

1) Wind Tunnel Probe Calibrations

- **S-probe** has a large pitch dependence (10 % effect) that cannot be accounted for via calibration.
- **3-D Probes** highly accuracy if Reynolds dependence and Turbulence characterized
- Robust non-nulling techniques have been developed and work well!
- New probe designs less sensitive to turbulence and Reynolds number are being developed

2) SMSS Facility Results

- RATA Testing
  - Spherical probe exhibited best accuracy (± 1 %)
  - prism probe (~ +3 %)
  - S-probe (~ + 6 %)
- SMSS Facility has large yaw angle ~35° near the wall
- Accuracy of Non-nulling method is the same as yaw-nulling method (within 1 %)

Questions?