Non-Nulling Measurements of Flue Gas Flows in a Coal-Fired Power Plant Stack

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Work sponsored by NIST & EPRI (Electric Power Research Institute)

Outline

1) Background and Motivation

2) How are stack emissions measured? What makes stack measurements difficult?

3) What is the Non-Nulling Method? How does it work?

4) Results of Field Test at a Coal-Fired Power Plant

5) Conclusions

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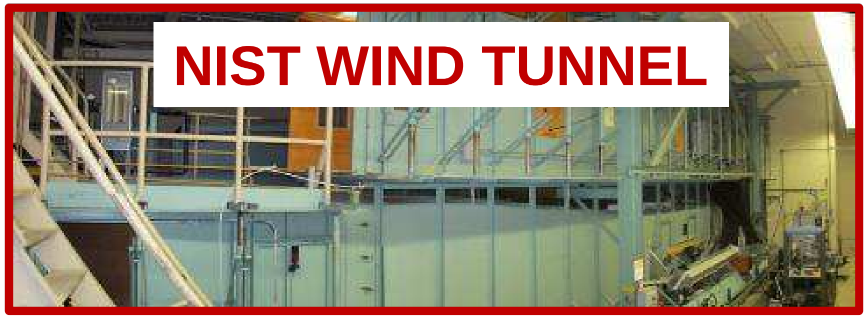
Background

3 Tier Approach to Improve Stack Flow Measurements

1) **Study different probe types in NIST Wind Tunnel**
   - S-Probe
   - 3-D Probes (*e.g.*, Prism & Spherical Probes)
   - *NIST Custom Probes*
   - Nulling and Non-nulling Methods



2) **Evaluate the Capabilities of Various Stack Flow Measurement Technologies in NIST Scale Model Smokestack Simulator (SMSS)**
   - Facility generates complex flows typical of stacks
   - Facility uncertainty < 1% (k =2)
   - Only has a 1.2 m test section & uses ambient air

3) **Collaborate with EPRI to apply NIST results to Coal-Fired Smokestacks**

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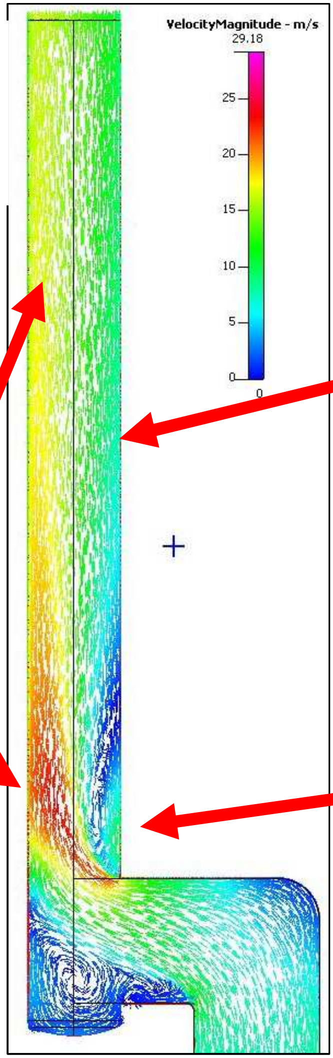
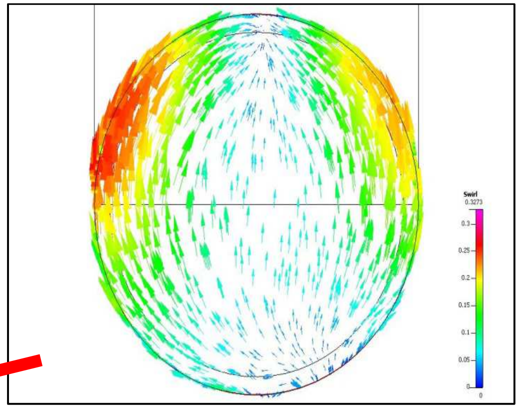
What makes Stack Flow Measurements Difficult?

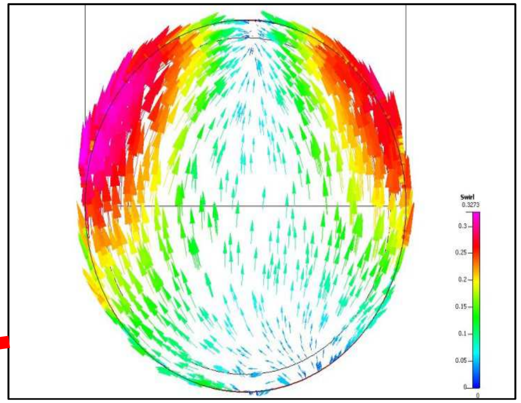
(Stack flows are complex and have significant "installation effects" on flow meters)

Numerically Computed Velocity Field





Swirl persist as flow travels up the stack



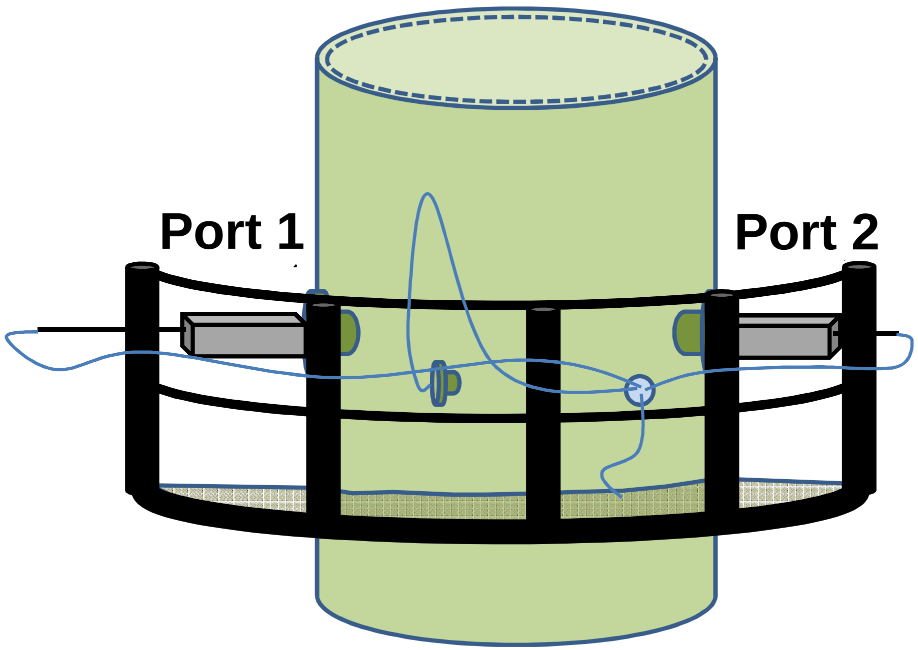
Strong swirl (*i.e.*, cross flow velocity) at the base of the stack

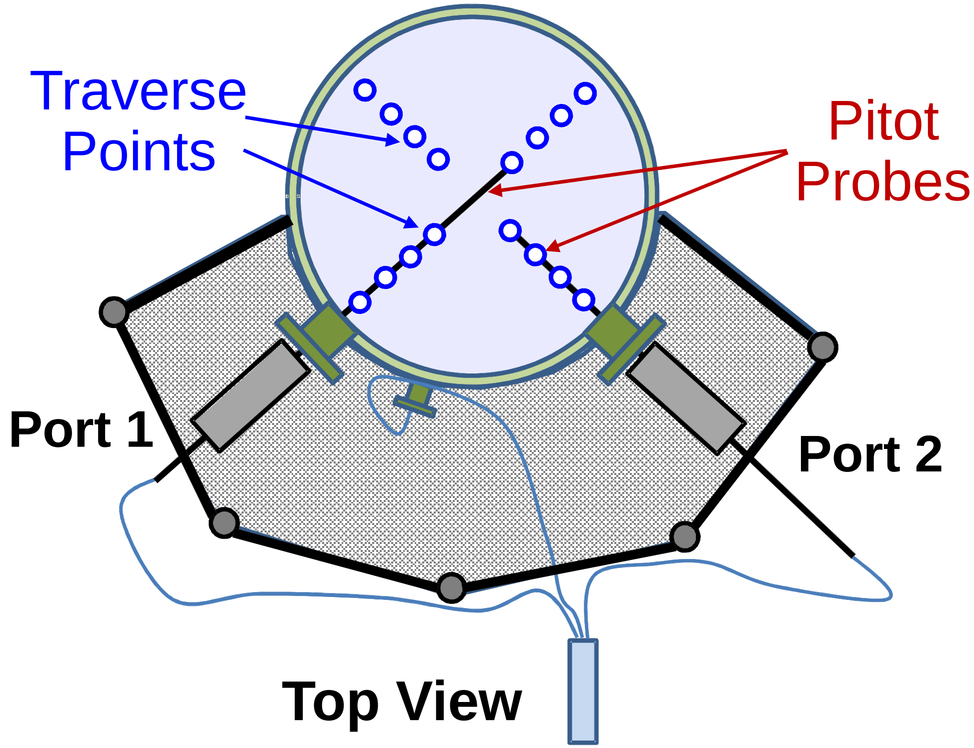
Asymmetric Flow Profile

Flow distortions are primarily a function of Stack Geometry (*i.e.*, elbows, fans, upstream plumbing)

Dickerson Power Plant Stack: Simulation performed by Betsy Moore

How are stack emissions measured?



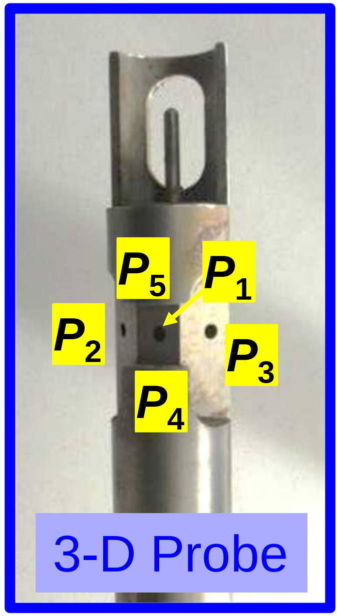


- **Pitot Probe traversed along two orthogonal diameters** in stack cross section
- **Velocity determined at discrete points** based on differential pressure measurements across pitot probe ports
- **Flow determined by integrating point velocity measurements**

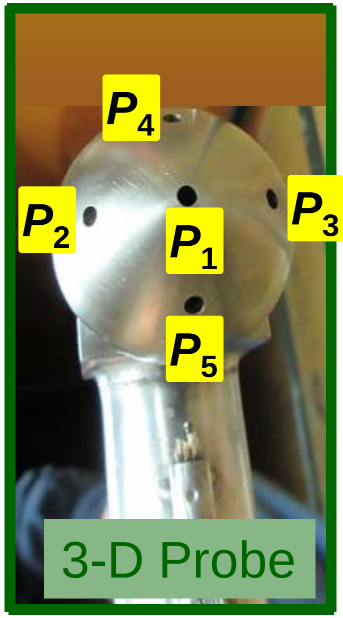
3 EPA Approved Pitot Probes

S-probe

Prism Probe



Spherical Probe



- **S-probe** (Most Commonly Used Probe)
  - o Robust
  - o Performance degrades in high pitch stack flows (2-D probe)
- **Prism & Spherical Probes** (Rarely Used)
  - o Requires calibration but measures 3-D velocity vector

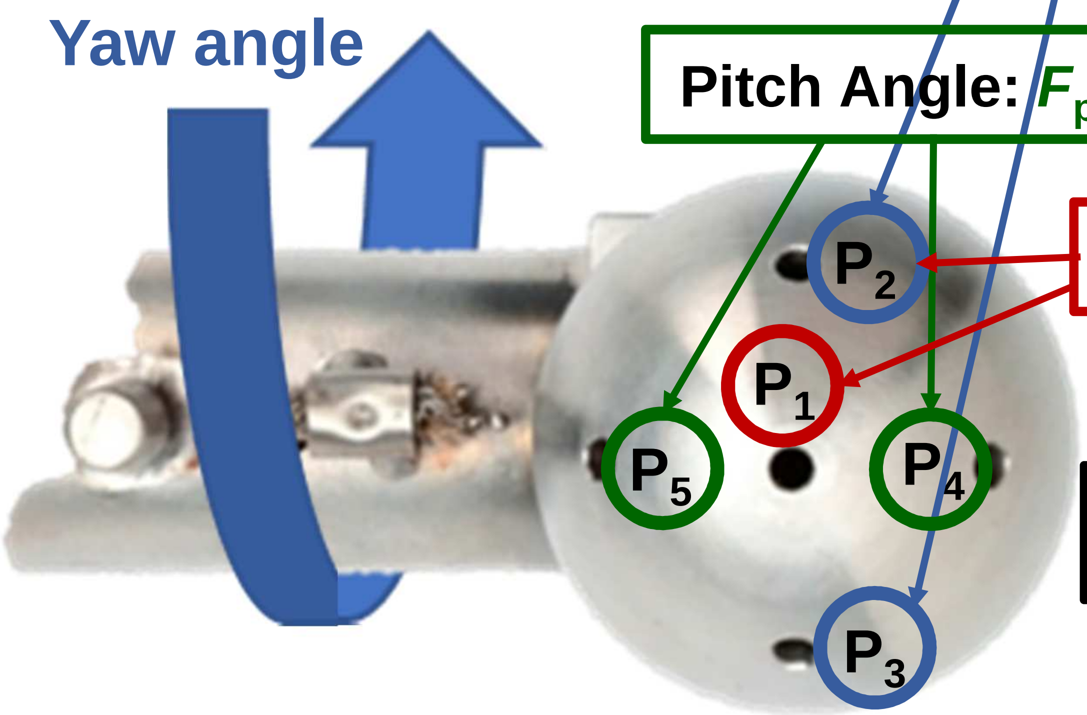
ALL PROBES CURRENTLY USE *NULLING* PROCEDURE TO FIND YAW ANGLE

What is the *Nulling Method* for 3D Probes (EPA Method 2F)?

Yaw Angle: Rotate about axis until $P_2 - P_3 = 0$

"Nulling the Probe"

Pitch Angle: $F_{pitch} \propto (P_4 - P_5)$



Dynamic Pressure: $F_{dyn} \propto (P_1 - P_2)$

Velocity Along Stack Axis

$$V_{axis} = \sqrt{2P_{dyn}/\rho}\cos(Yaw)\cos(Pitch)$$

- ***Nulling the Probe*** **is time intensive and increases measurement time**
- **In practice nulling a probe can require several iterations**
- **Velocity errors increase as ratio $(P_2 - P_3)/P_{dyn}$ departs from zero**

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Non-Nulling Method

1) NIST developed a non-nulling method for 3-D probes (no need to “null” probe)

Benefits

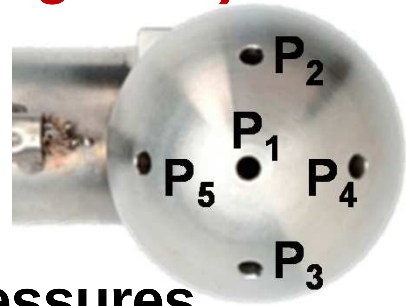
- Potential improved accuracy over S-probe
- Less human errors
- Potential improved accuracy over Nulling Method used for 3-D probes
- Reduced the overall measurement time

2) Non-Nulling Method needs to be **validated in industrial smokestacks stacks**

3) EPRI organized a field test at a coal-fired stack

How is the Non-Nulling Method Implemented & How does it Work?

- **Measurements are made with P1 aligned with stack axis (Yaw angle = 0)**
  (No need to rotate probe to find $P_2 - P_3 = 0$ at each traverse point)



$$V_{\text{axis}} = \sqrt{2\boldsymbol{P}_{\textbf{dyn}}/\rho}\cos(\boldsymbol{Yaw})\cos(\boldsymbol{Pitch})$$

- **Dynamic Pressure, Yaw and Pitch are curve fits to differential pressures**

Non-Nulling 4 Pressures (NN4P)

$$\boldsymbol{P}_{\textbf{dyn}} = P_{\text{dyn}}\left(P_{12}, P_{13}, P_{14}, P_{15}\right)$$

$$\boldsymbol{Yaw} = Yaw\left(P_{12}, P_{13}, P_{14}, P_{15}\right)$$

$$\boldsymbol{Pitch} = Pitch\left(P_{12}, P_{13}, P_{14}, P_{15}\right)$$

- **Each probe is calibrated in NIST Wind Tunnel**
  - non-nulling curve fit is based on 3000 wind tunnel measurements
  - **Fitted Range:** V_{axis} = 5 m/s to 30 m/s, Yaw = ± 42 deg, and Pitch = ± 20 deg

NIST Custom Probes

Five Hole Hemispherical Probe

5-hole Conical Probe

NIST developed two custom 5-hole probes

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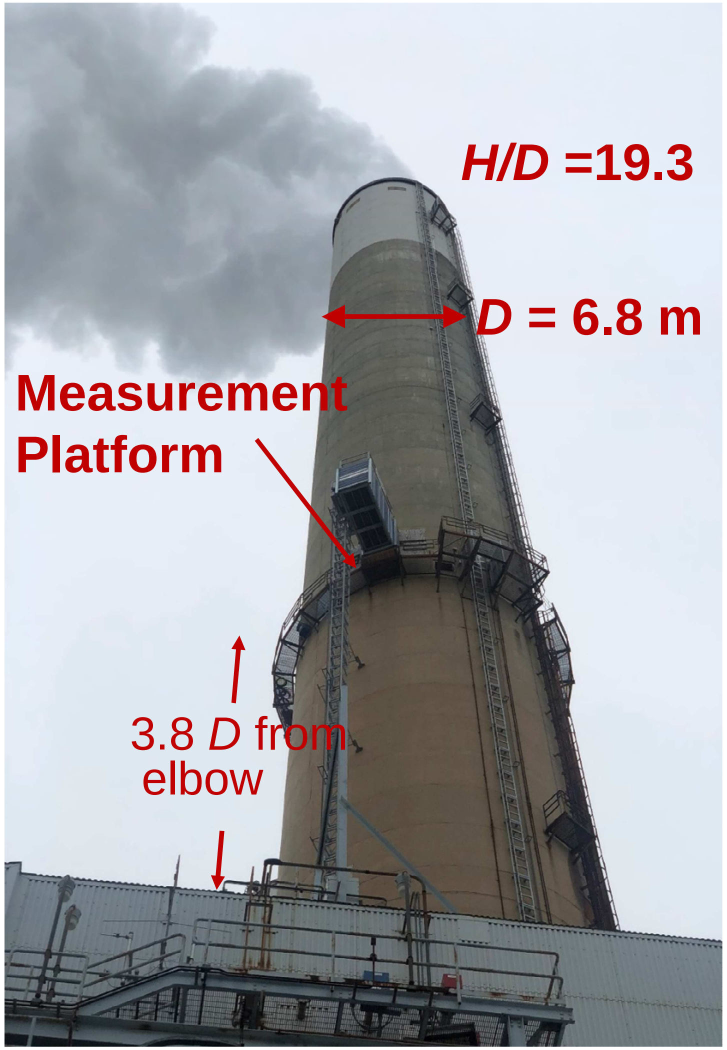
Field Test at a Coal-Fired Power Plant (500 MW)



Test Protocol

- Test probes at full load (17 m/s) and low load (6 m/s)
- Flow from stack flow monitor (CEMS) used to normalize velocity data (CEMS was calibrated by S-probe by prior to our testing)

Probes Tested

- Spherical probes
- NIST custom probes (hemispherical and conical)

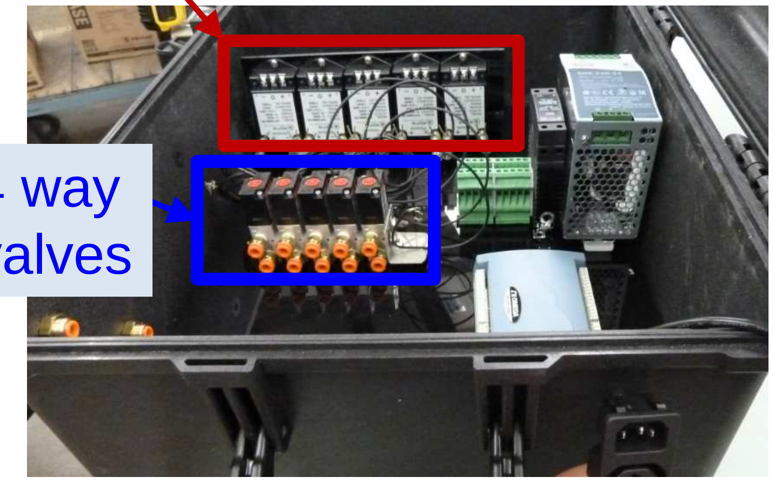
Objectives

- Compare Non-Nulling vs. Nulling (EPA Method 2F)
- Compare Spherical vs. NIST custom probes

Developed Rugged Data Acquisition System for Field Test

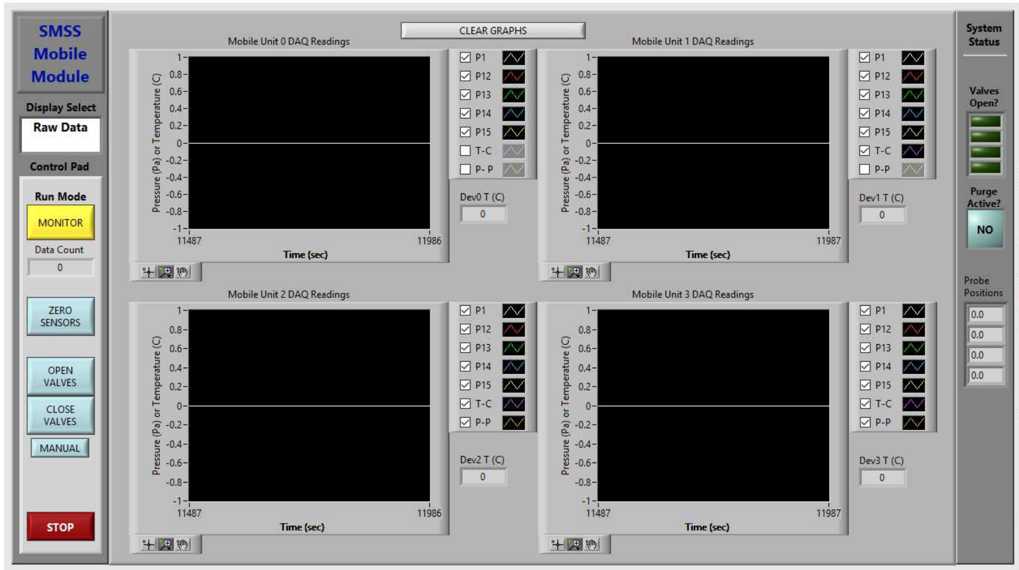
DP transducers

4 way valves



Toughbook

- **Equipment housed in a water-proof box**
- **Key Features**
  - Industrial grade differential pressures
  - 4-way valves
  - Weather-proof Laptop
  - LabVIEW data acquisition program (Sample rate 10Hz)

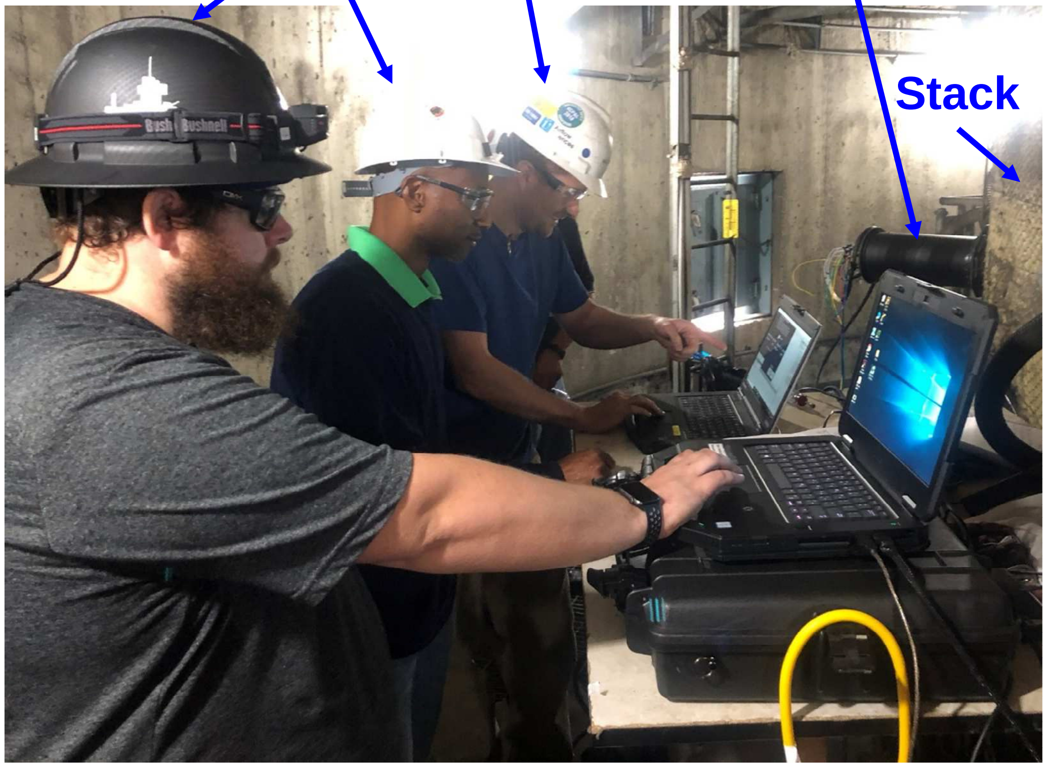


Measurement Equipment Installed in Annulus Between Stack and Outside

Joey and Myself

Probe Tester

Pitot Probe Traverse Unit



Pitot Probe Support

dP signals from probe plumbed to NIST Box

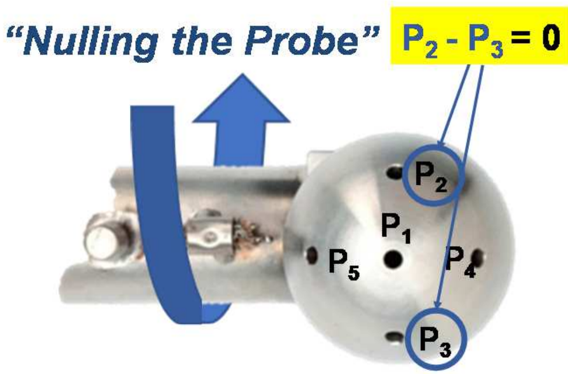
What are the Challenges of Field Conditions?

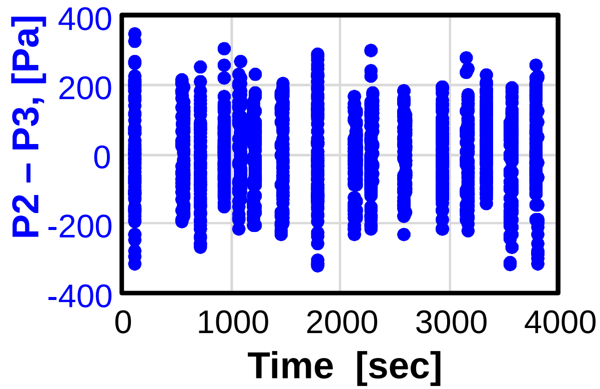
1) **Asymmetric swirling flow**

2) **Plugging due to water droplets/particulates**
   - Power plant equip with wet scrubber
   - Purges necessary to clear probe ports of water droplets & particulates

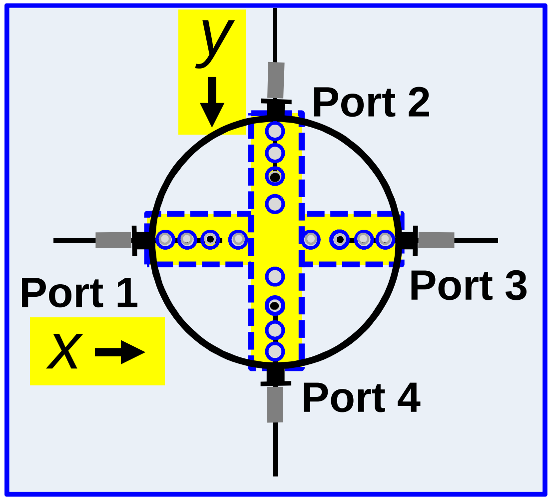
3) **Flow fluctuations (Unsteady)**

4) **Noisy pressure signals & short measurement times (10 sec)**

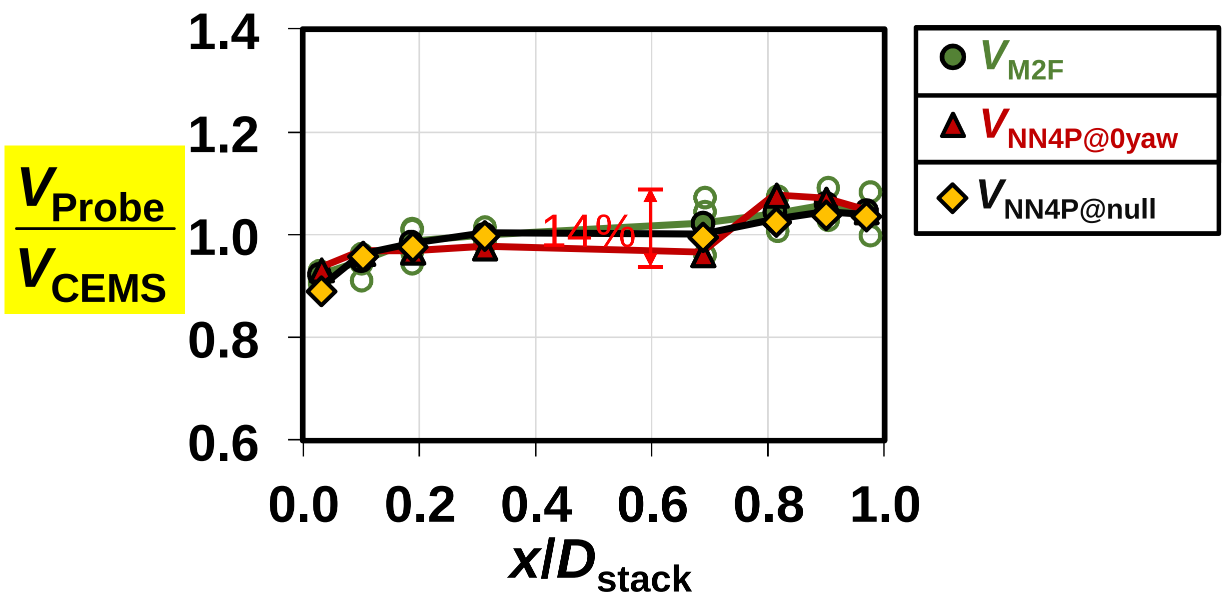


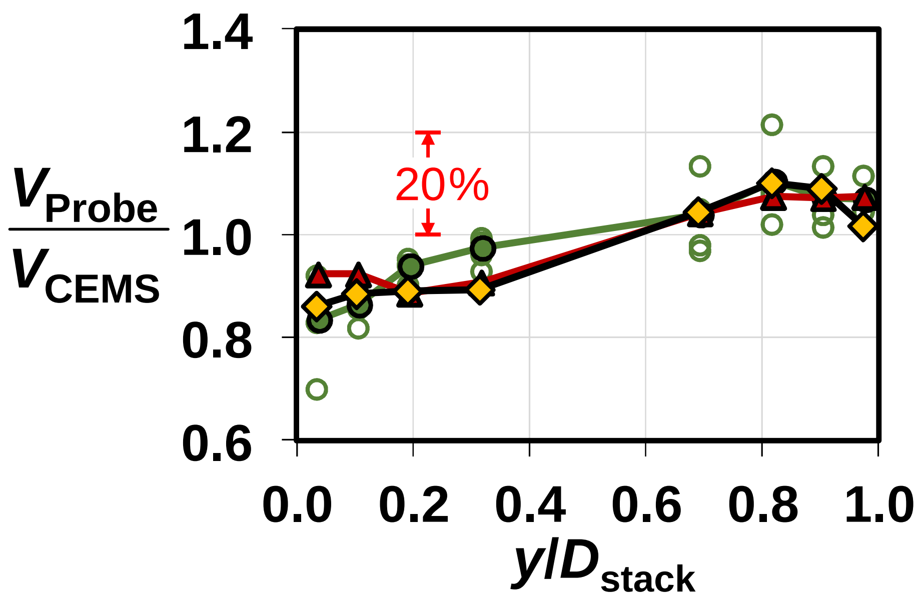


Axial Velocity for Spherical Probes at High Load, 17 m/s



V_{Probe}/V_{CEMS}	Nulling M2F	Non-Nulling NN4P@0yaw	Non-Nulling NN4P@null
Average	0.994	0.994	0.984
% Stdev 4 runs	1.6 %	0.2 %	0.8 %
% Deviation from CEMS	**-0.6 %**	**-0.6 %**	**-1.6 %**





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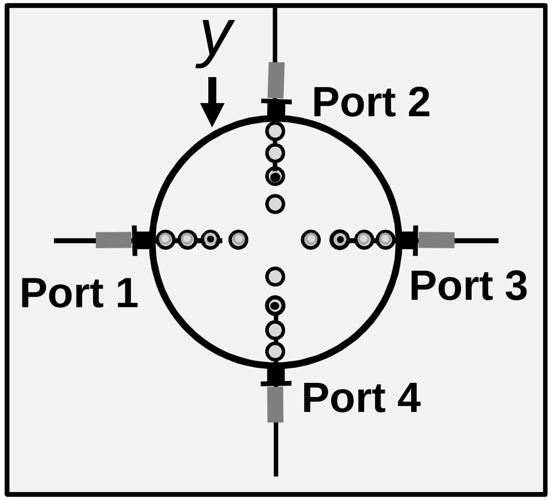

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- **Normalized axial velocity profiles were similar**
  - for **low load Sphere**: Nulling (Method 2F) and Non-Nulling
  - for **NIST Probes at low and high flows**: Nulling and Non-Nulling
- **Velocity differed for NIST probes determined using Method 2F (Nulling)** at high and low loads

Summary of Results

(% Deviation of Average Flow from CEMS)

Probe Type	Flow Load	Nulling M2F	Non-Nulling N4Pv@0yaw	NN4Pv@null
Spherical Probes	17 m/s	-0.6 %	-0.6 %	-1.6 %
Spherical Probes	6 m/s	1.9 %	2.8 %	-1.5 %
NIST Probes	17 m/s	5.3 %	- 0.8 %	-1.5 %
NIST Probes	6 m/s	10.5 %	- 0.6 %	-3 %

- **In all cases Non Nulling results are in good agreement with stack flow monitor (CEMS)**

- **Nulling (Method 2F)**
  - o Good agreement of M2Fnist and Non-Nulling for spherical probes
  - o Poor Nulling of NIST Probes (P23 ≠ 0) likely cause of bias

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Conclusions

1) **Non-Nulling Method performed well for all flows and all probes**
   - Minimum 16 point traverse was performed
   - Better accuracy could potentially be realized if more traverses points are used (especially more points close to the wall to account for the boundary layer)

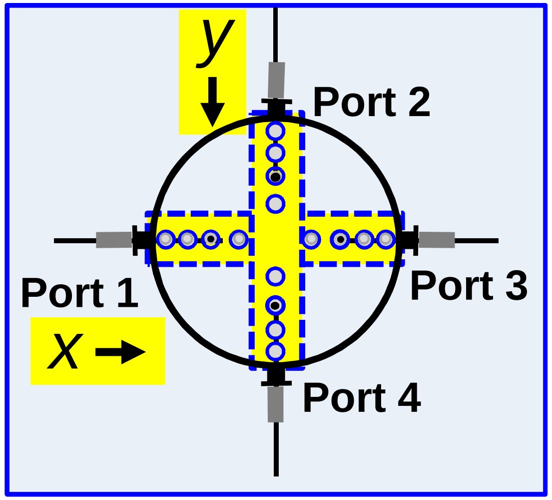
2) **Non-Nulling results are similar to those found in NIST Stack simulator** suggesting that flow results found in SMSS facility translate to the field

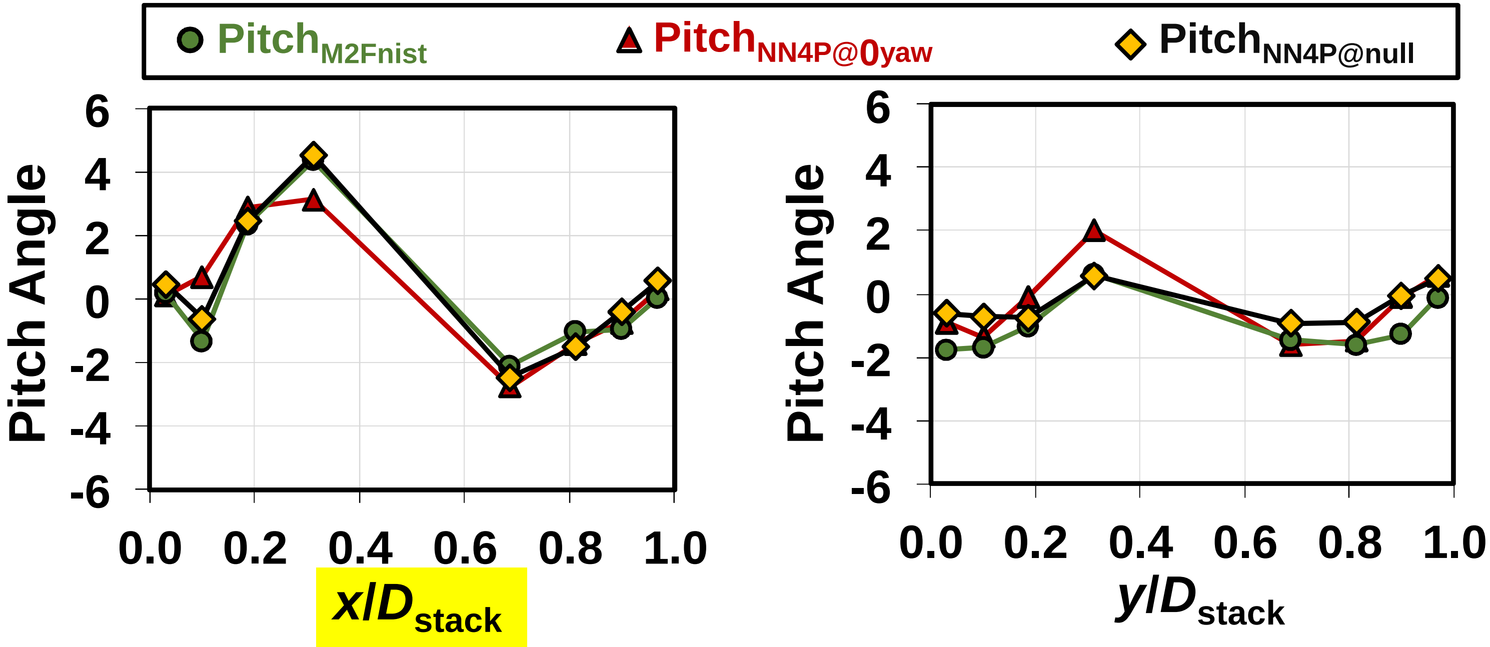
3) **Nulling (Method 2F) vs. Non-Nulling Results**
   - Good agreement for Spherical probes
   - Poor agreement for NIST probes likely due to imperfect nulling ($P23 \neq 0$)

4) **CEMS flow monitor** (calibrated by an Sprobe) **likely does a reasonable job because the measured pitch angle in the stack was small**

Questions?

Pitch Angle for Spherical Probes at High Load, 17 m/s





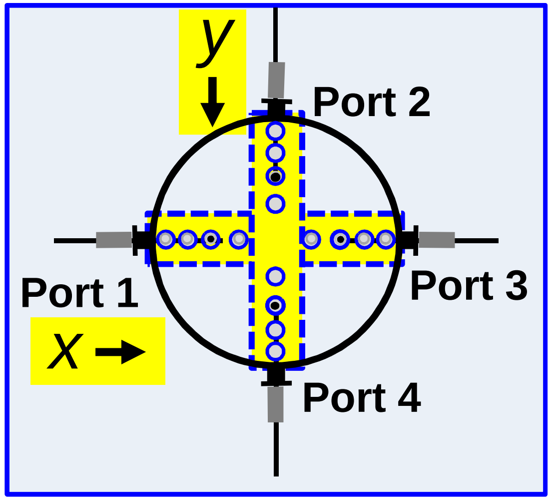
1) **Non-Nulling and Method 2F in good agreement** on both chords

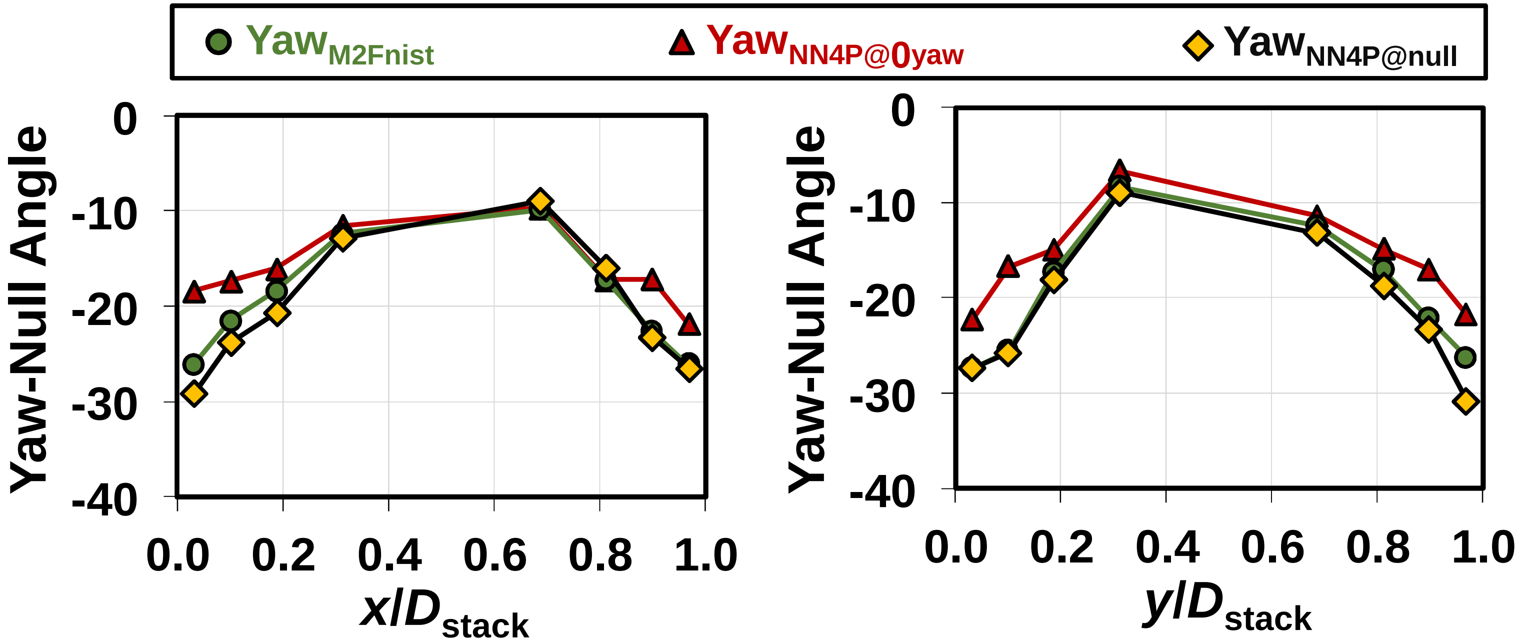
2) **Magnitudes of pitch angle are relatively small** (maximum value of 5^{O})

3) S-probe calibrated **CEMS likely gives reasonable flow results**

4) **NIST probes exhibited similar trends** at high and low loads, nulling and non-nulling

Yaw-Null Angle for Spherical Probes at High Load, 17 m/s





1) Non-Nulling and Method 2F profiles are similar with extremum values near stack wall (~ -30°)

2) Differences between Method 2F and Non-Nulling at yaw=0 are small near stack axis and grow to as much 7° near wall

3) NIST probes gave similar results at high and low loads

RATA Testers and Probe Traversing

- **All testing was performed by Air Flow Science**
- The **M**ultiple **A**utomated **P**robe (MAP) was employed to perform probe traverses
- **NIST and Air Flow Science used separate data acquisition systems**

Multiple Automated Probe (MAP)

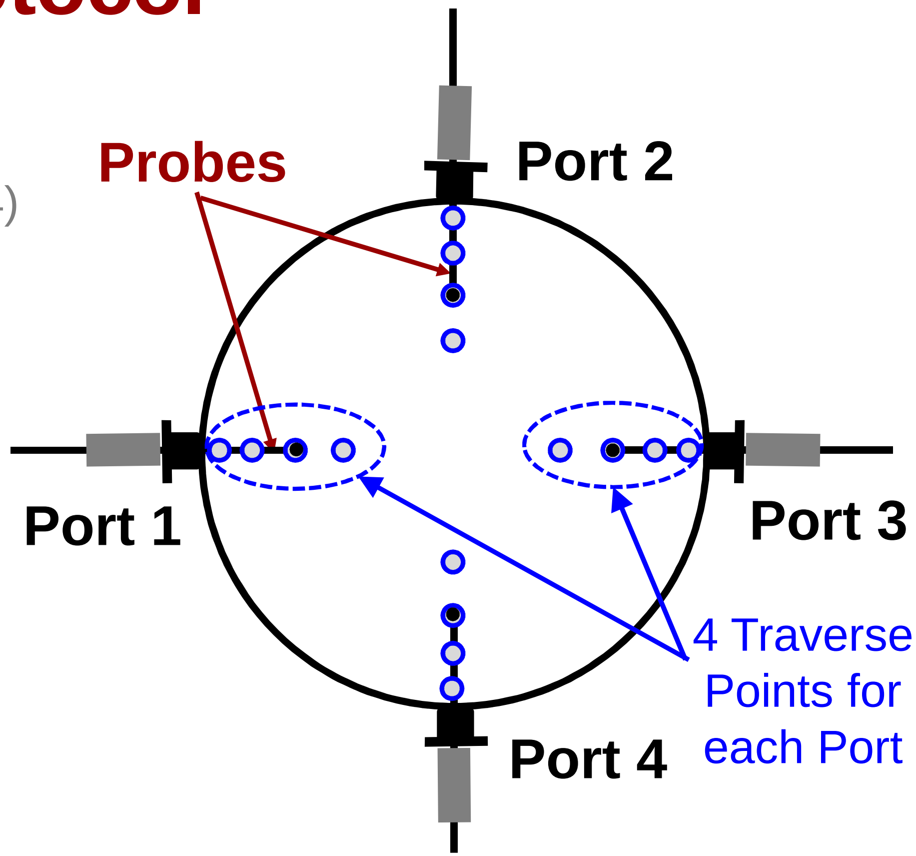
- **Manually time synchronized data acquisition systems at the start of testing**
- **MAP system output DC voltages to NIST system to indicate traverse point**

Stack Test Protocol

- **A single probe installed in each of the 4 Ports**
  - o Spherical Probes in all Ports
  - o NIST Probes (Hemisphere in Ports 1 & 3 and Conical in 2 & 4)

- **8 Traverse points along two diametric chords**

- **Traverse unit moves probe to specified point**
  - o Traverse unit rotates probe to a zero yaw angle
  - o Stack velocity measured via Non-Nulling (**NN4Pv@0yaw**)
  - o Traverse unit "*nulls the probe*" (yaw angle where $P_2 - P_3 = 0$)
  - o Stack velocity determined via Method 2F (**M2Fnist**)
  - o Simultaneously stack velocity determined via Non-Nulling (**NN4Pv@null**)



- **Procedure repeated at each traverse point: 3 velocities are measured at each point**
  - o 3 measured velocities: $V_{NN4Pv@0yaw}$, $V_{M2Fnist}$, and $V_{NN4Pv@null}$

- **Probe velocities are normalized by CEMS (V_{CEMS}) to help account for unsteady flow**