Data Quality Improvements Using Measurement Uncertainty Analysis

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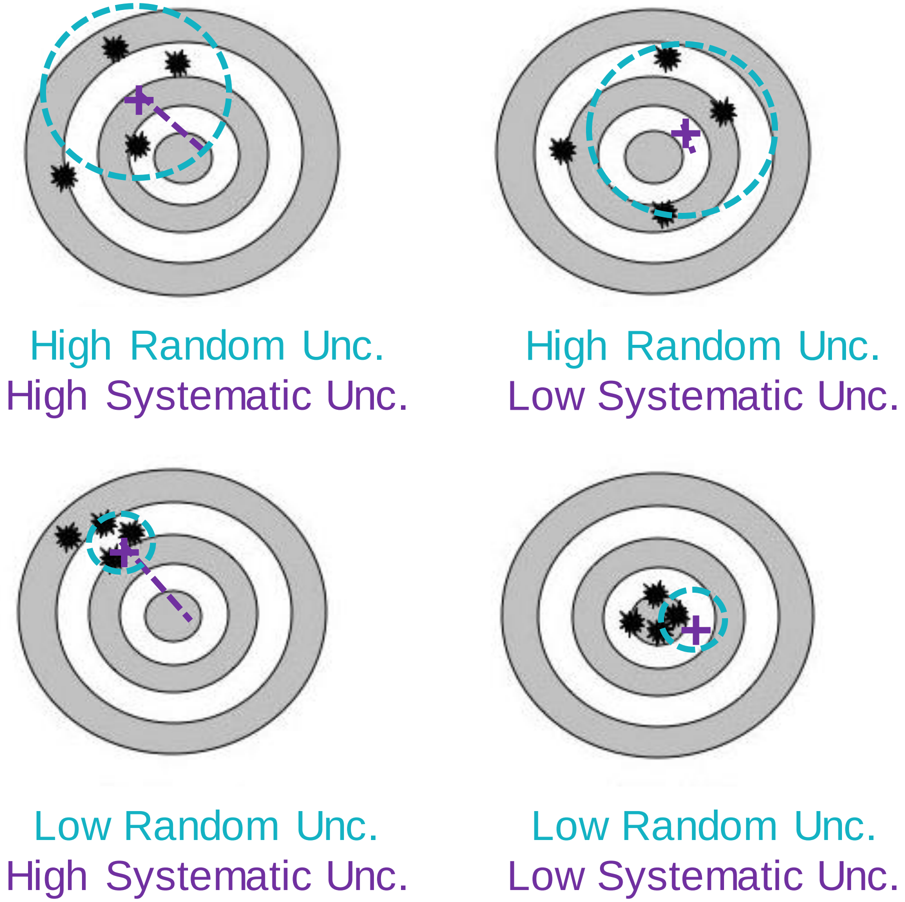
DATA QUALITY WORKING GROUP FACE TO FACE MEETING

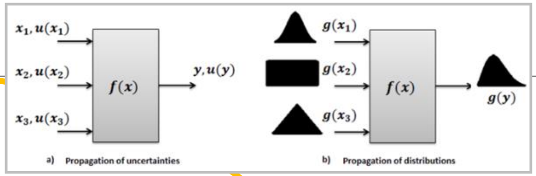
DAYTON, OHIO
8/13/24 - 8/15/24

Random vs Systematic Uncertainty

- Random Uncertainty (s_x)
  - Scatter of the results
  - Repeatability
  - Estimated via replicate data points
- Systematic Uncertainty (b_x)
  - Bias
  - Standard offset
  - From instrumentation, installation effects, and regression fitting

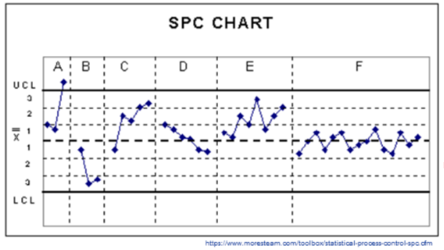


MUA Vision at GRC



Statistical Process Control/Monitoring

✓ *Quantify repeatability of measurement systems, facilities, and processes*



Ground-Up Uncertainty Propagation

✓ *Quantify systematic uncertainties and target meaningful improvements*

Early problem detection and validation

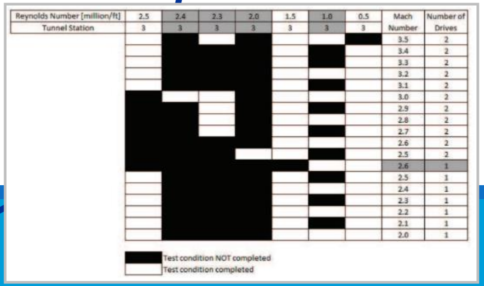
High Quality MUA

Design tests based on uncertainty goals

Pre-test instrument and data reduction analysis

Test Planning

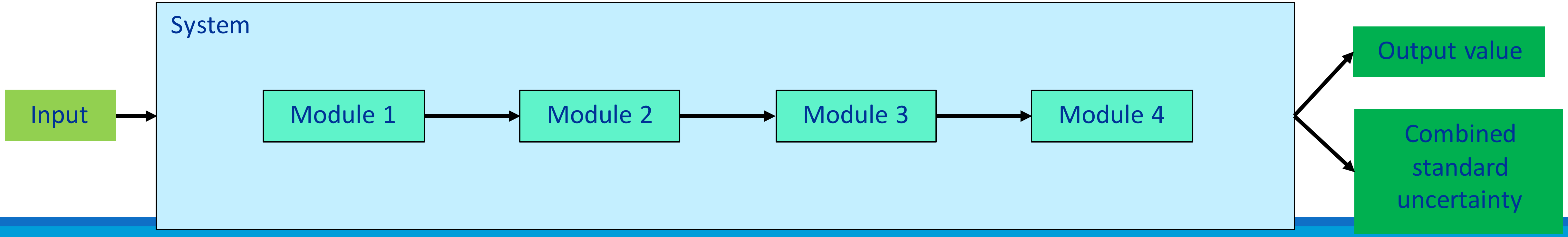
✓ *Optimize uncertainty-cost relationship*



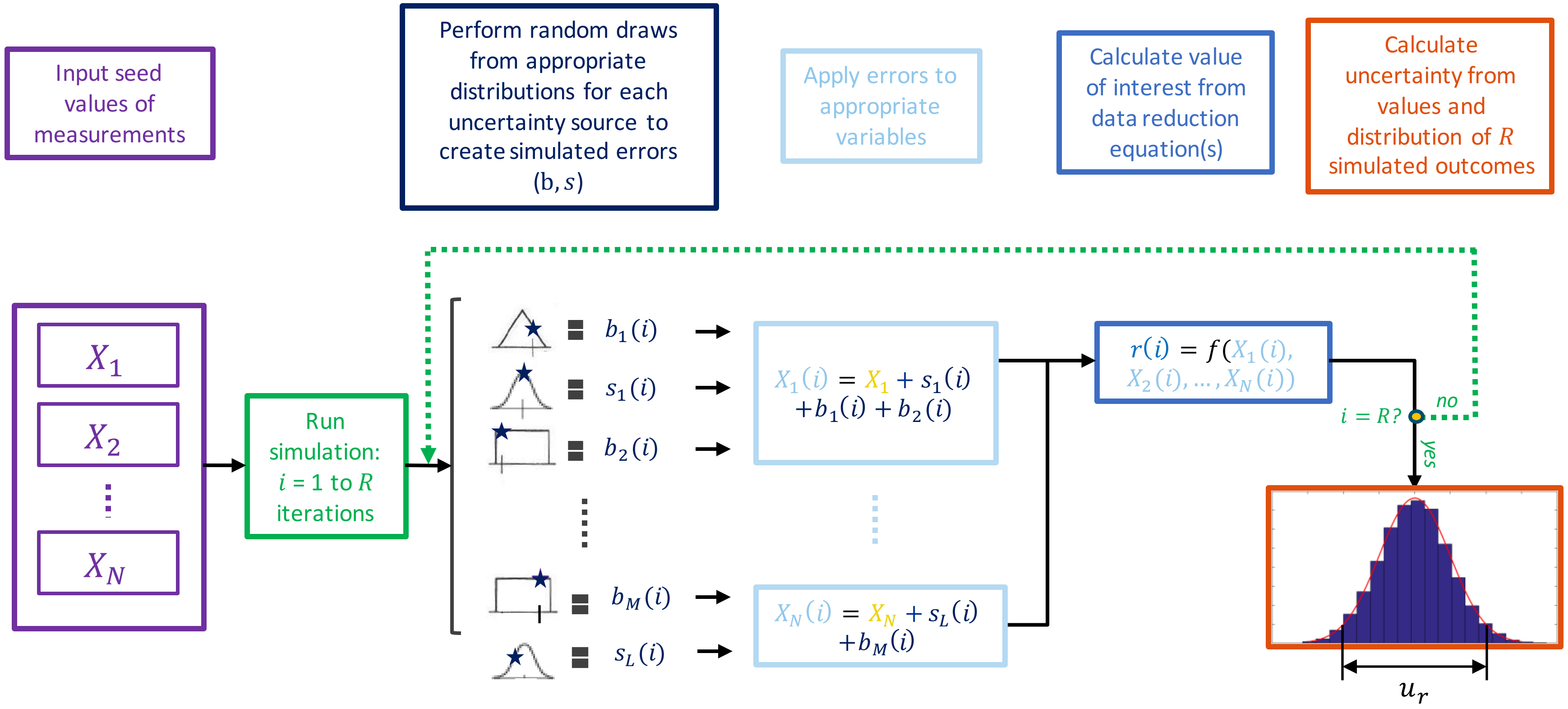
MUA Tools at GRC

Measurement ANalysis Tool for Uncertainty in Systems (MANTUS)

- A modular approach at modeling measurement systems.
- Each block represents a single piece of instrumentation in the signal measurement channel.
- The scope of the tool is to model and analyze a single, representative measurement channel such as one transducer or thermocouple connected to a data system.



Monte Carlo Process

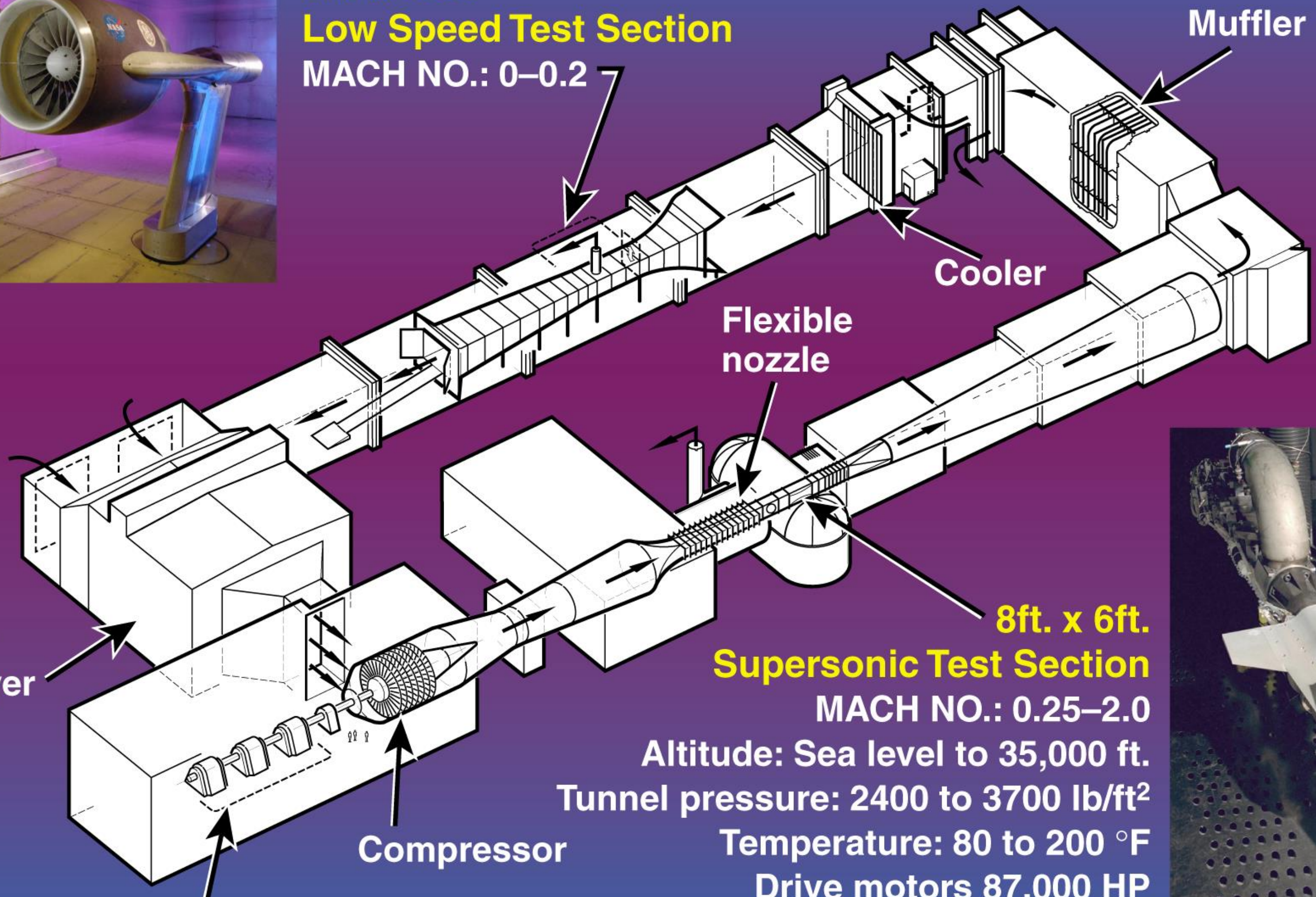


Applied MUA, 8x6 Example

- Identify variables of interest
  - For 8x6, primarily calibrated Mach and temperature conditions in test section
- Identify uncertainty sources
  - Generate elemental uncertainty estimates for sources. (MAnTUS)
- Use MATLAB to employ the Monte Carlo Method (MCM) to propagate elemental uncertainty estimates through the data reduction sequences.
  - Simulate tens of thousands of synthetic realizations of the sequence of characterization and customer tests
    - Static pressure characterization
    - Total pressure characterization
    - Total temperature characterization
    - Facility baseline

Glenn Research Center
Cleveland, Ohio

8x6 SWT/9x15 LSWT Wind Tunnel Complex



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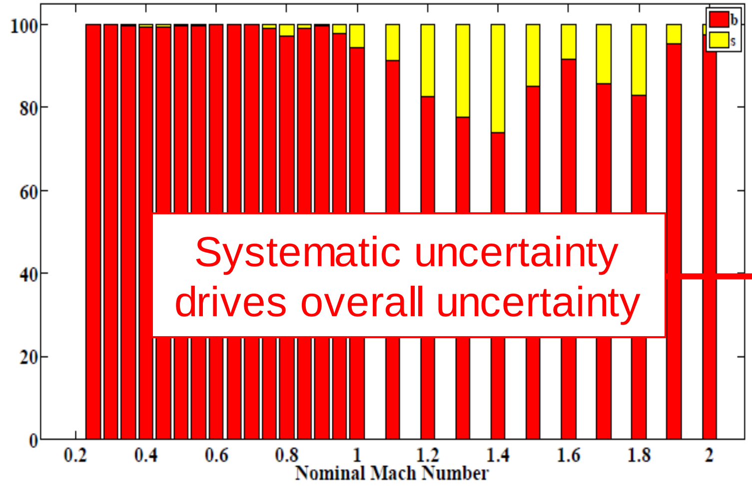
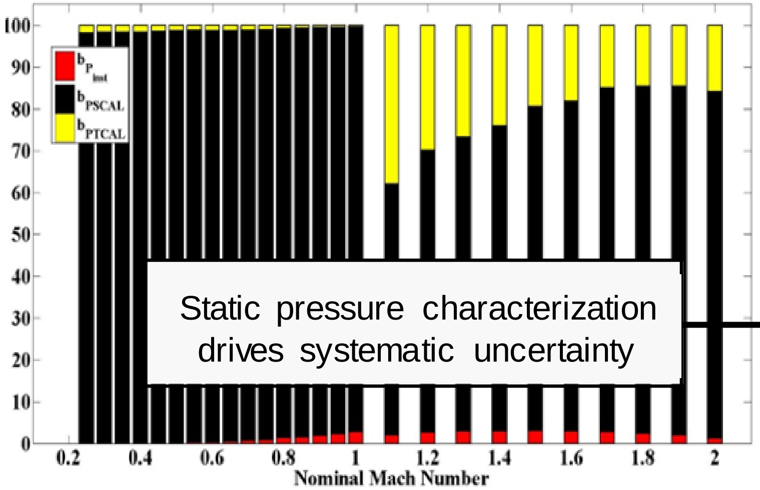
Uncertainty Estimates

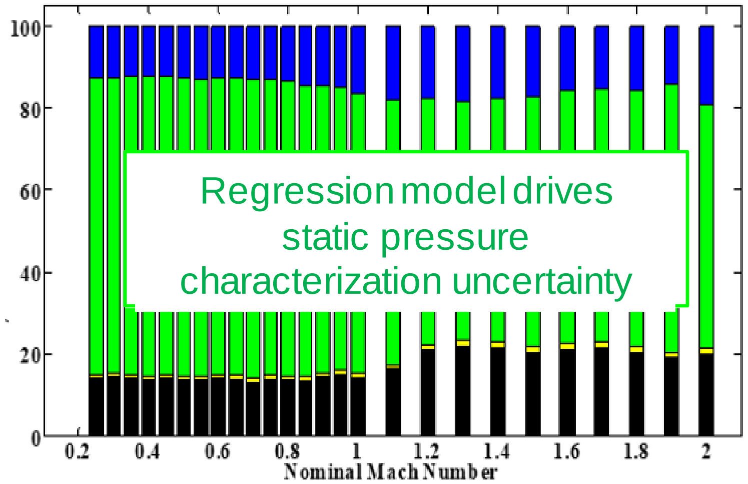
- Original 8x6 uncertainty analysis (2016) gave us the drill-down to the source of greatest uncertainty in Mach number: the static pressure characterization model
- Reducing this allows for most significant reduction to Mach number uncertainty



Systematic Uncertainty



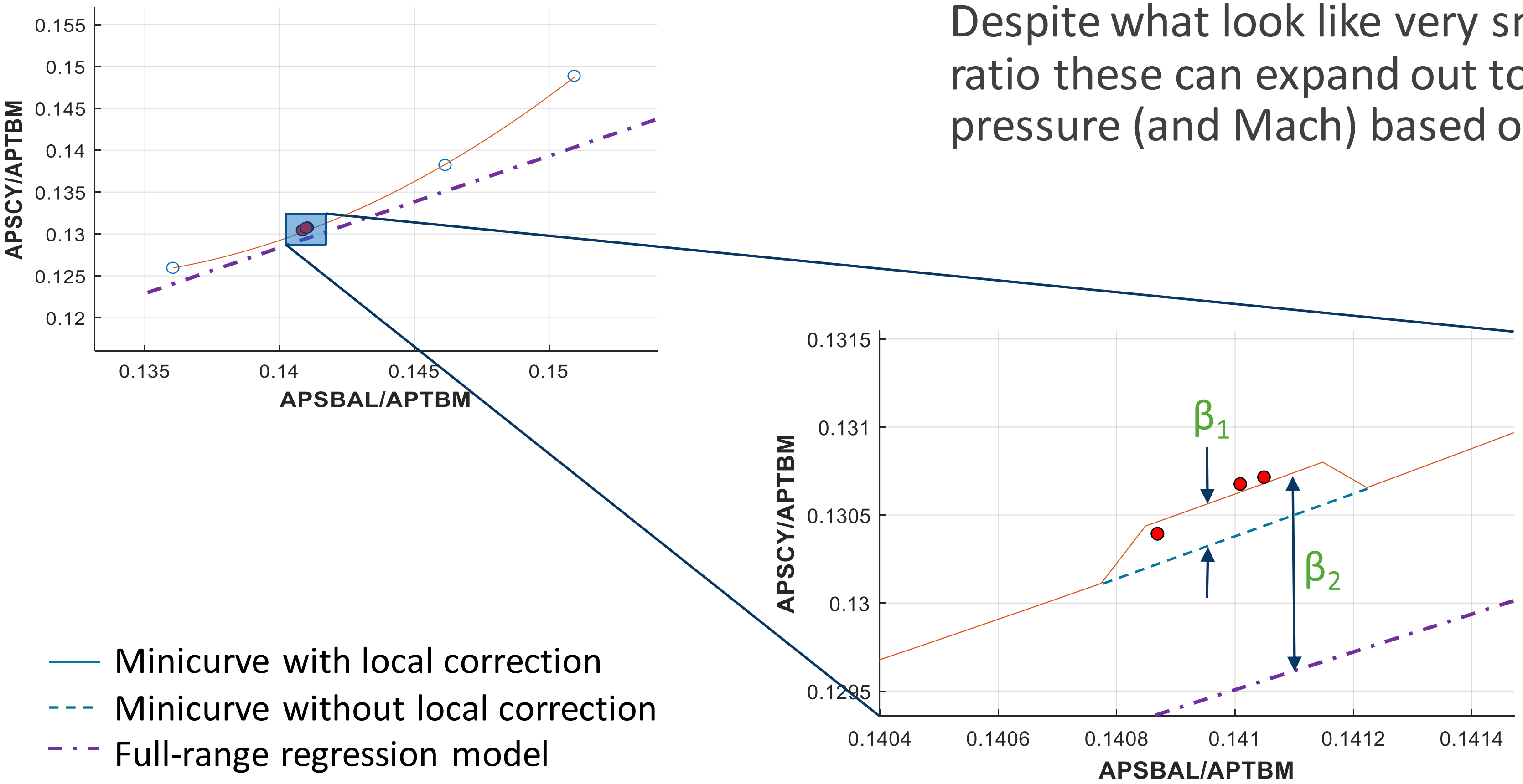
Static Pressure Characterization Uncertainty



Static and Total Pressure Characterization

- Original regression models were generalized over entire facility range.
- Noticed that repeatability at each set point condition was tight, but the group of replicates was offset from the generalized curve. This indicated a systematic bias was introduced by the regression model.
- MUA team worked with characterization team on a method to reduce this uncertainty source.
    - Each flexwall setting was treated as a unique test section configuration.
    - Static and total pressure models were generated for each configuration.
    - Chose to “over-speed” and “under-speed” the transonic test section using balance chamber pressure at each flexwall setting.
    - 3 replicates acquired at each nominal supersonic setting
    - Small correction factors generated for nominal supersonic settings from the 3 replicates to locally shift/correct the cal curve
    - Used when facility conditions are sufficiently “dialed in”
    - A regression model was also generated to bridge the gaps between flexwall settings to ensure continuity of data being displayed and characterize off-nominal conditions

Updated Approach, cont'd



Despite what look like very small deltas, since the y-axis is a ratio these can expand out to significant biases in static pressure (and Mach) based on the fit vs. repeats

$\beta_1 \approx 0.006$ psi
($\Delta M \approx 0.0012$)

$\beta_2 \approx 0.03$ psi
($\Delta M \approx 0.0042$)

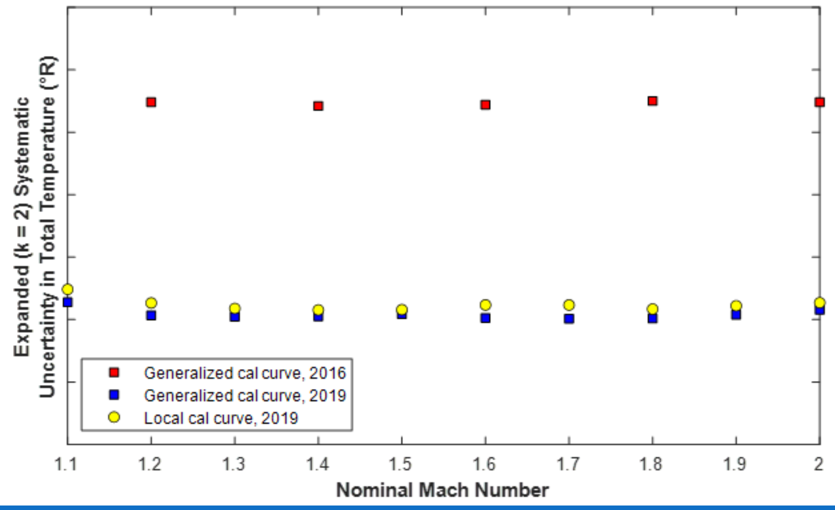
Total Temperature Calibration

- Transonic Array TC's are now Type E special limit of error "home-run" length wires to Kaye Ice-points
- Split calibration curve by flow regime, as well
- Modified form of curve fit:
  - TTTS = TTBM*f(PSBAL/PTBM)
- Chose to adopt the local supersonic calibration curve method used with static and total pressure curves

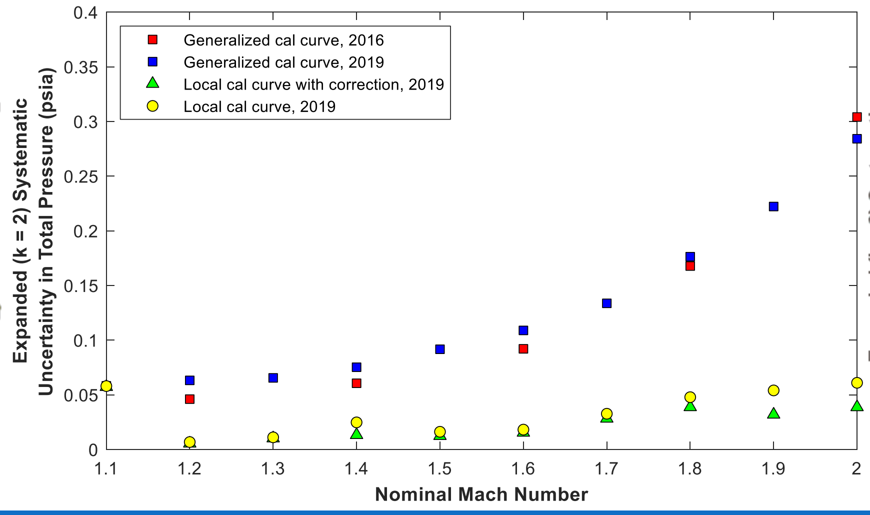
Example of MUA Improving Data Quality

- 8x6 SWT uncertainty estimates
  - Using What-If scenarios and working together with other disciplines
  - Areas for improvement were identified and actions were taken
    - Special-limit-of-error Type E (EEE) wire replaced both reference temperature and Transonic Array thermocouples
    - Improved regression models used for test section values of interest

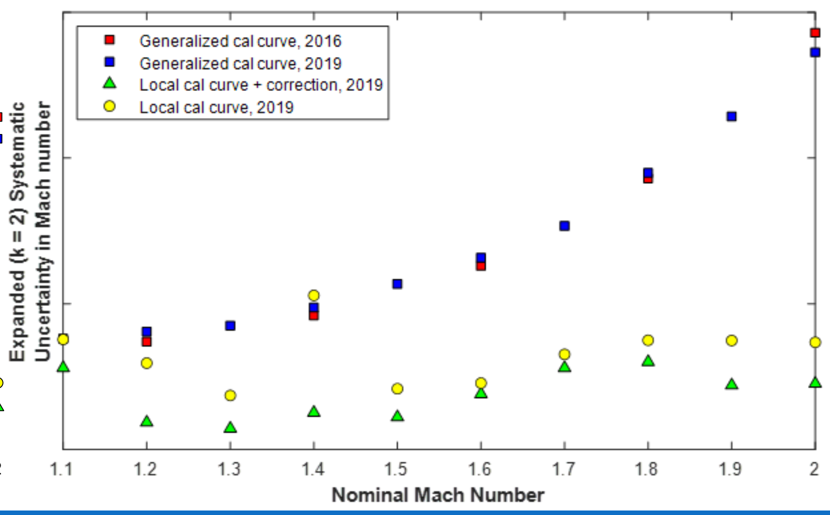
Total Temperature



Static Pressure



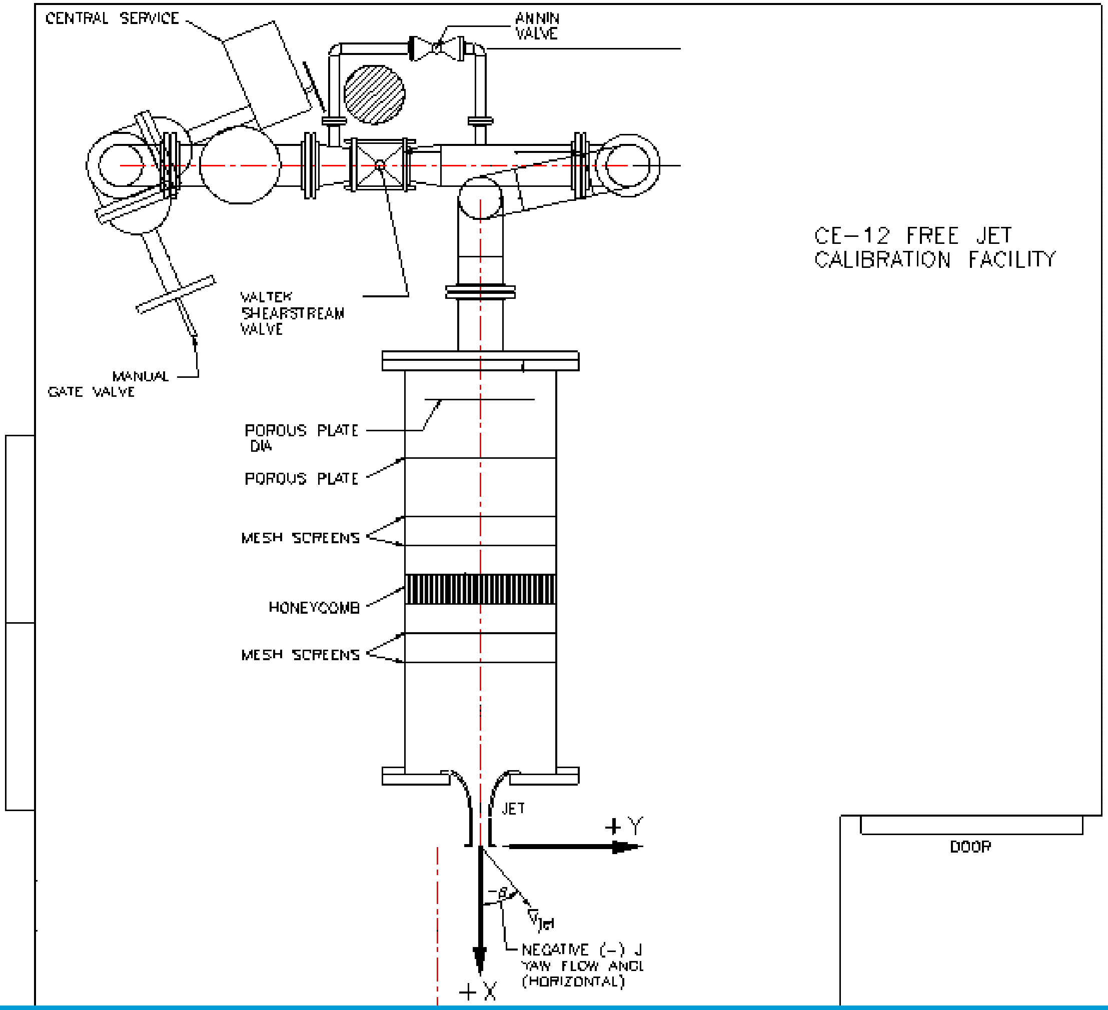
Mach Number

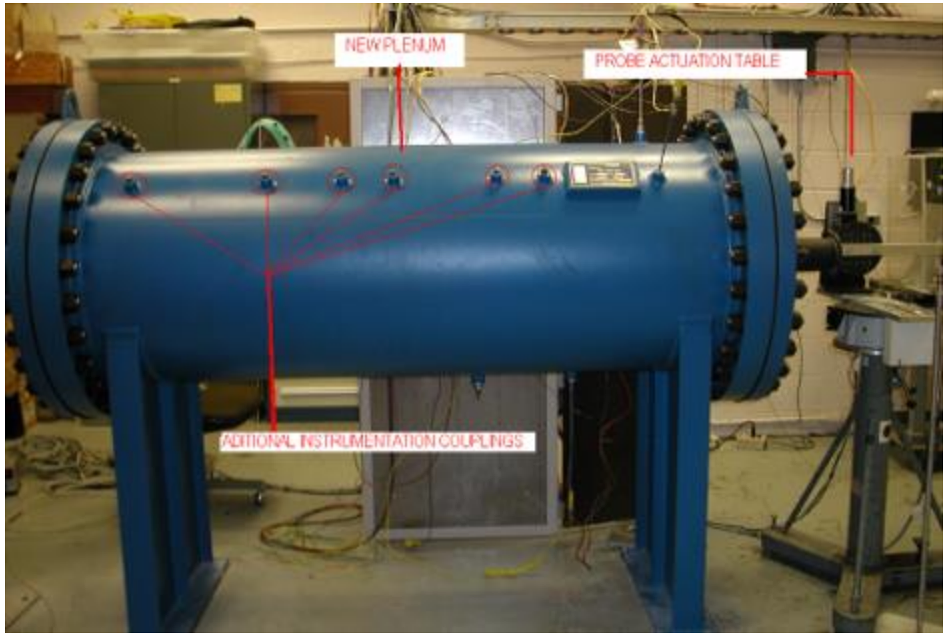


Applied MUA, CE-12 Example

- Customer interested in very low speed probe calibration
  - Current facility uncertainty levels don't meet requirements
- Investigate possible methods for lowering uncertainty to meet requirements
  - Improve instrumentation
    - Generate elemental uncertainty estimates for higher accuracy sources. (MAnTUS)
  - Change pressure measurement methods and data reduction associated with those methods
    - Use MATLAB to employ MCM to propagate elemental uncertainty estimates through possible changes to data reduction sequences

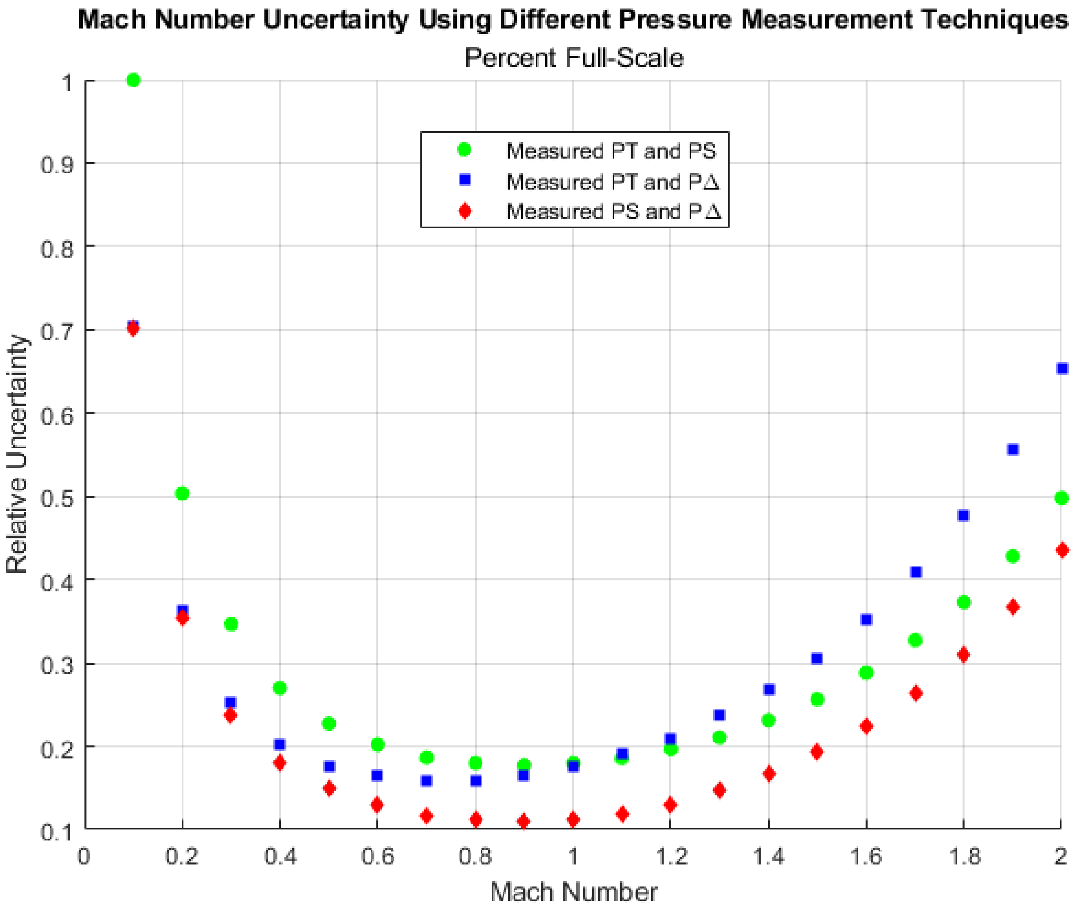
CE-12 Free Jet Facility





Changes to pressure measurements and data reduction

- Look at the Data Reduction Equation (DRE) for Mach Number
  - Measure P_T and P_S
    - $M = \sqrt{5\left(\left(\frac{P_T}{P_S}\right)^{2/7} - 1\right)}$
  - Measure P_T and P_Δ
    - $P_S = P_T - P_\Delta$
    - $M = \sqrt{5\left(\left(\frac{P_T}{P_T - P_\Delta}\right)^{2/7} - 1\right)}$
  - Measure P_S and P_Δ
    - $P_T = P_S + P_\Delta$
    - $M = \sqrt{5\left(\left(\frac{P_S + P_\Delta}{P_S}\right)^{2/7} - 1\right)}$



Changes to pressure measurements and data reduction

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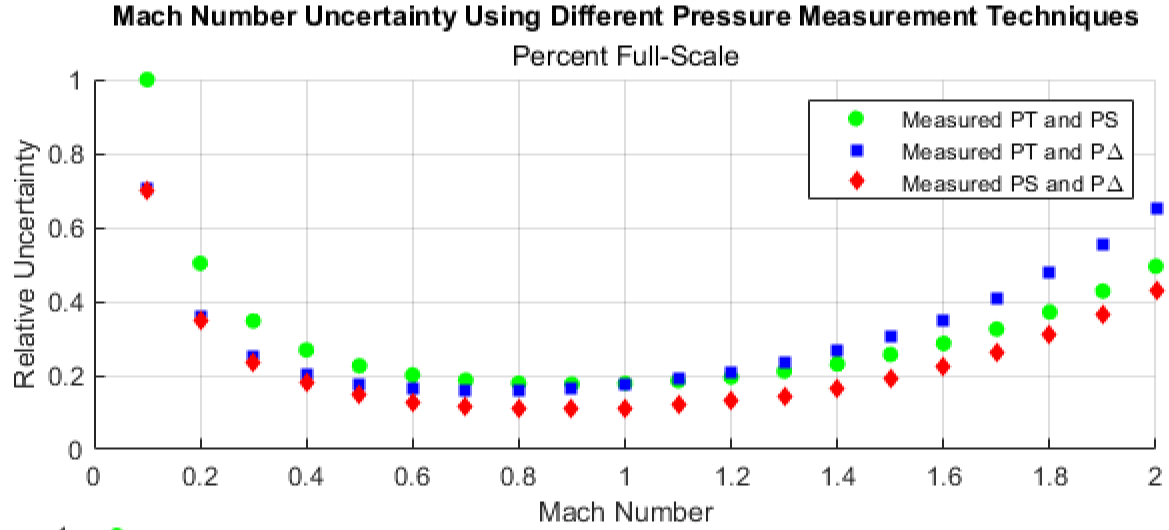
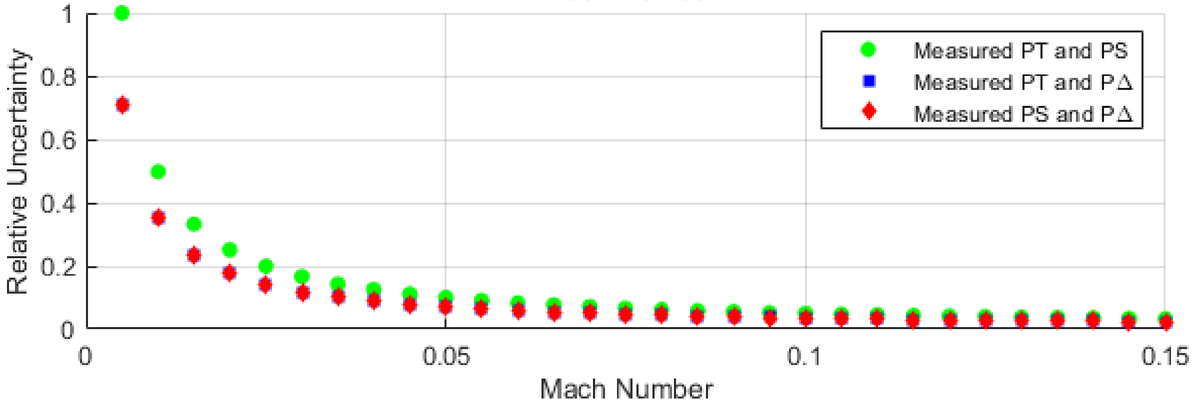




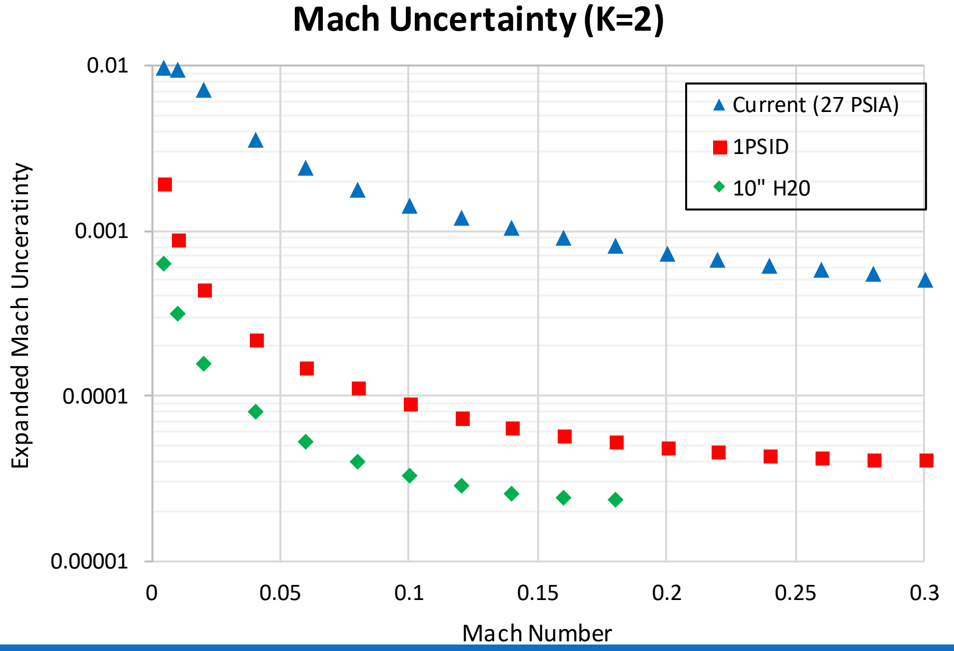
Investigated Instrumentation Changes

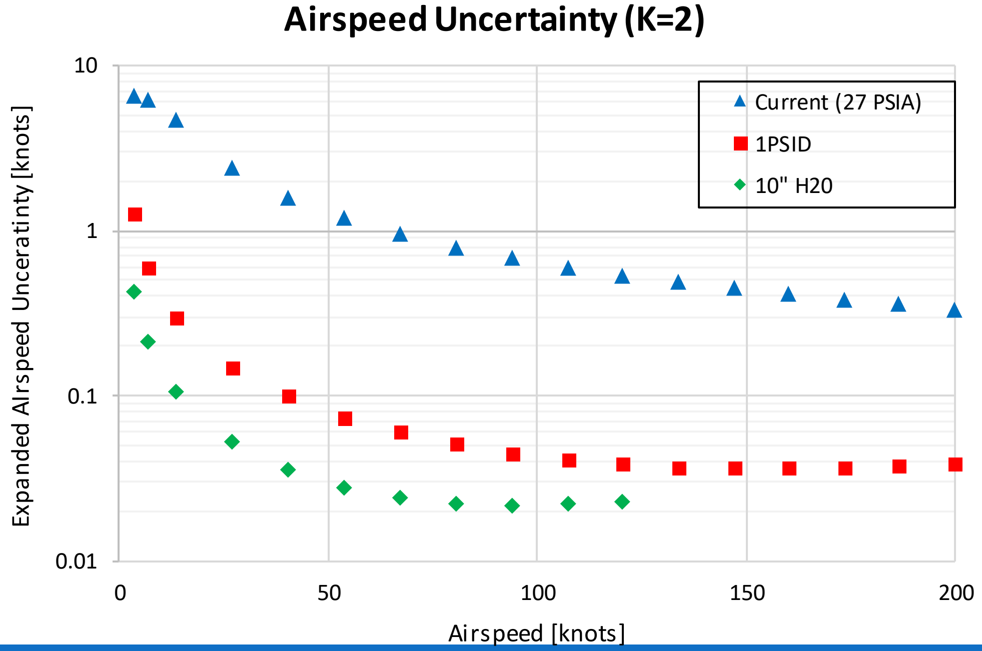
- Change Static Pressure measurements into Differential Pressure measurements
- Use MAnTUS to estimate new elemental uncertainties
- Use MATLAB to employ MCM to propagate new elemental uncertainty estimates through changes to data reduction sequences

Measurement	Instrument	Uncertainty Estimate [PSI]
P_T (Current)	27 PSIA Mensor	1.21×10^{-3}
P_S (Current)	27 PSIA Mensor	1.21×10^{-3}
P_Δ	±1 PSID Mensor	8.94×10^{-5}
P_Δ	±10” H2O Mensor	3.23×10^{-5}

Uncertainty Results

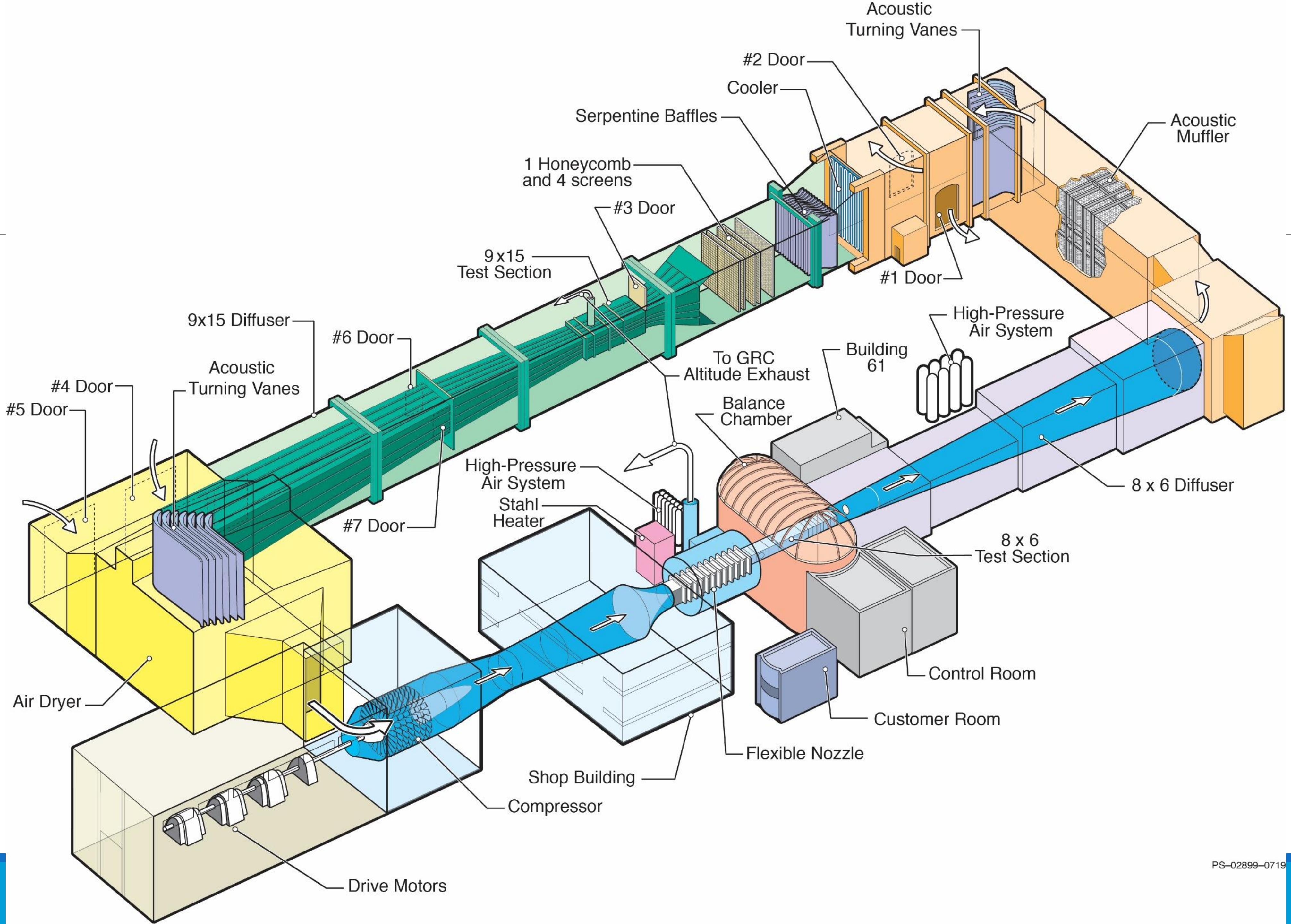
- Using uncertainty tools
  - Areas for improvement we identified
    - Changes in pressure measurement methods
    - Elementary estimates for potential new instrumentation
- Updated uncertainty estimates helped improve data quality for customer





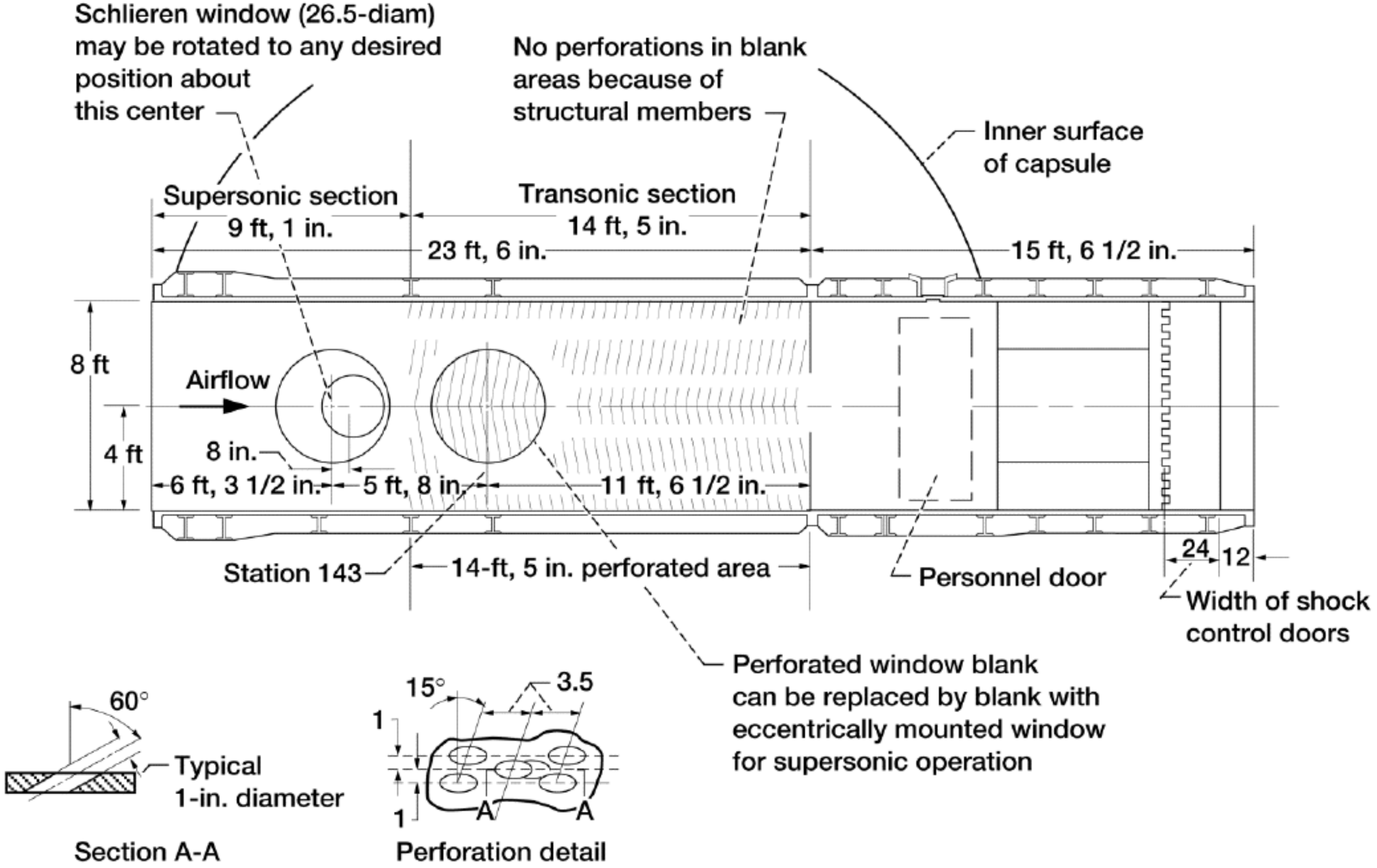
Questions?

Backups


Acoustic
Turning Vanes
#2 Door
Cooler
Serpentine Baffles
Acoustic
Muffler
1 Honeycomb
and 4 screens
#3 Door
9 x15
Test Section
#1 Door
High-Pressure
Air System
9x15 Diffuser
#6 Door
To GRC
Altitude Exhaust
Building
61
Acoustic
Turning Vanes
#4 Door
#5 Door
Balance
Chamber
High-Pressure
Air System
8 x 6 Diffuser
Stahl
Heater
#7 Door
8 x 6
Test Section
Control Room
Air Dryer
Customer Room
Flexible Nozzle
Shop Building
Compressor
Drive Motors
PS–02899–0719

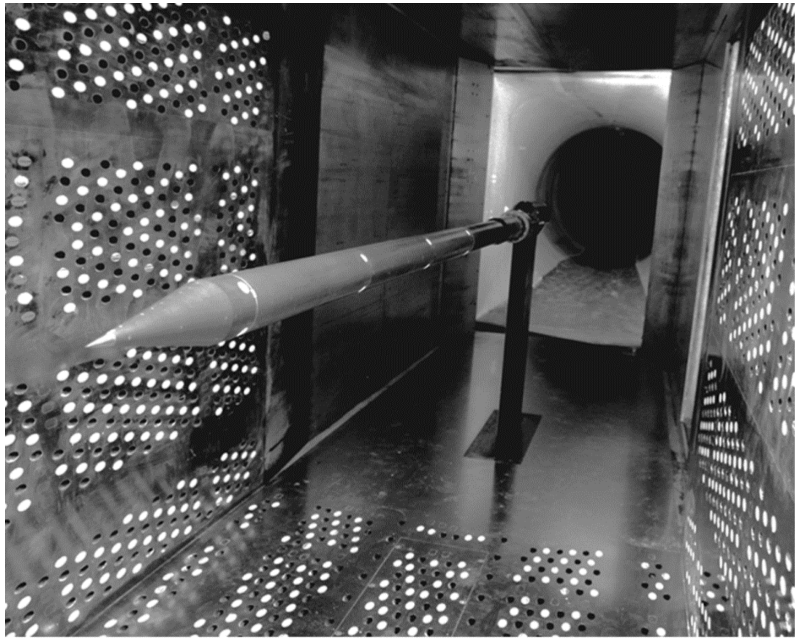
8x6 Test Section

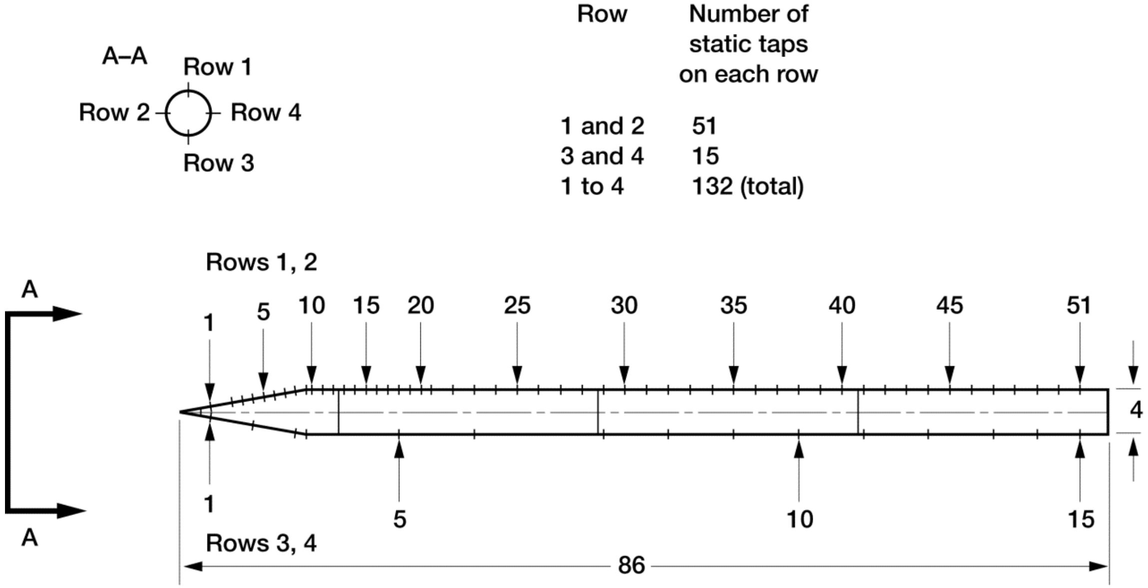
- Test section porosity configuration of interest is 14-ft 5.8% porosity (TSCFG 1)



8x6 SWT Characterization Hardware

4-inch Cone Cylinder is primary static pressure calibration tool



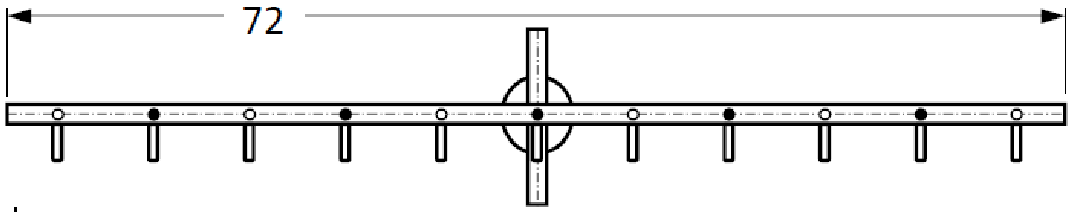


8-, 12-, 16-, and 20-inch cone cylinders

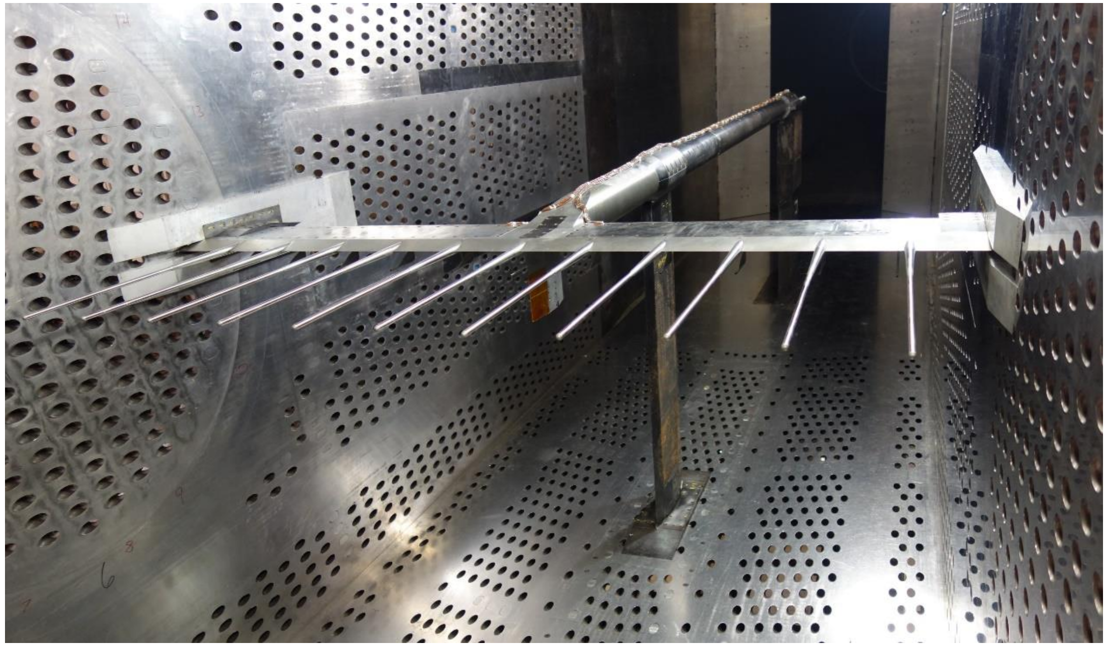
used for blockage studies

8x6 SWT Characterization Hardware

Transonic Array used for total pressure and temperature calibration



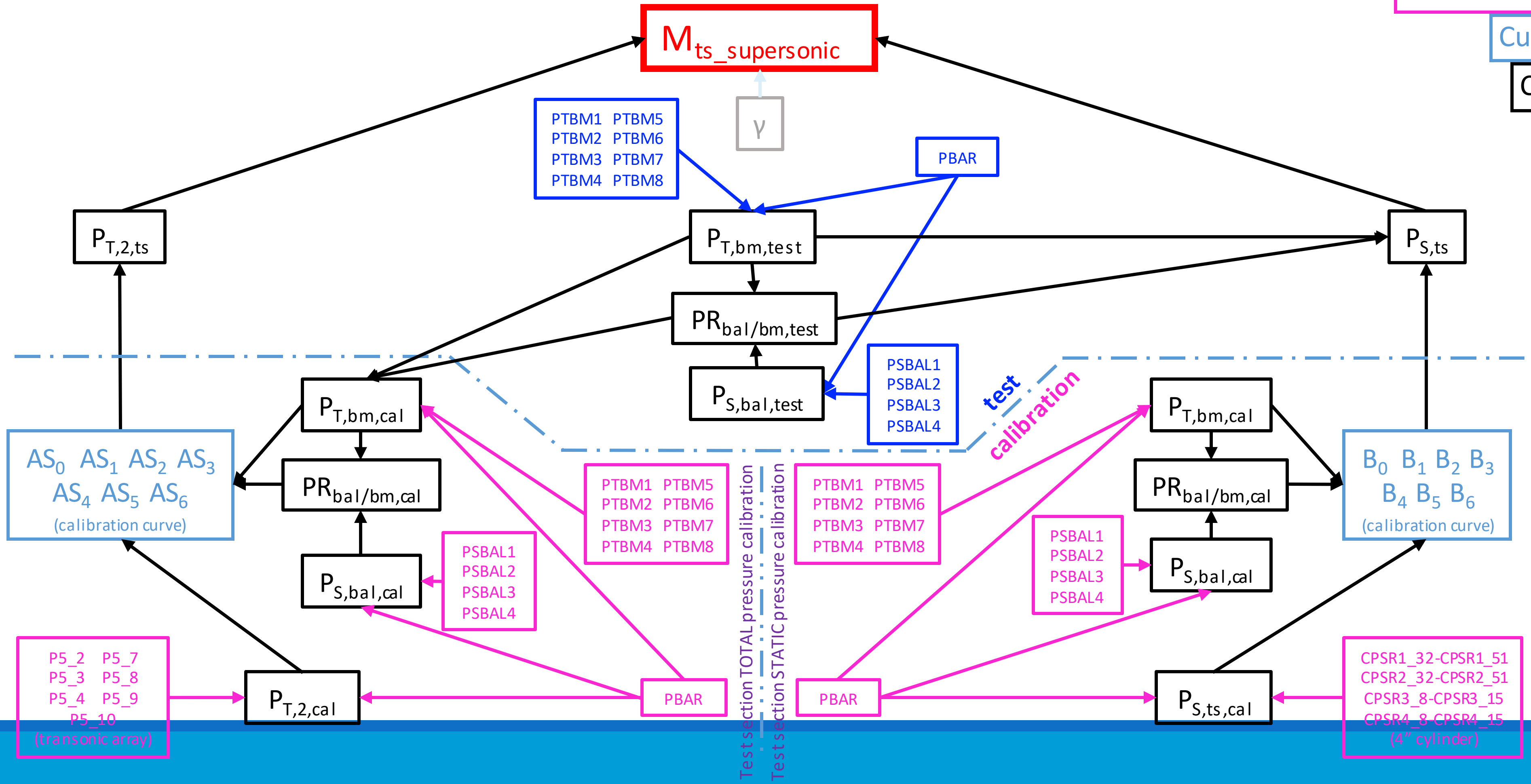
● Flow angle		1		2		3		4		5	
○ Pitot-static pressure	1		2		3		4		5		6
▯ Thermocouple	1	2	3	4	5	6	7	8	9	10	11
Distance from center of rake, inches	30	24	18	12	6	0	6	12	18	24	30



MUA at GRC Continued

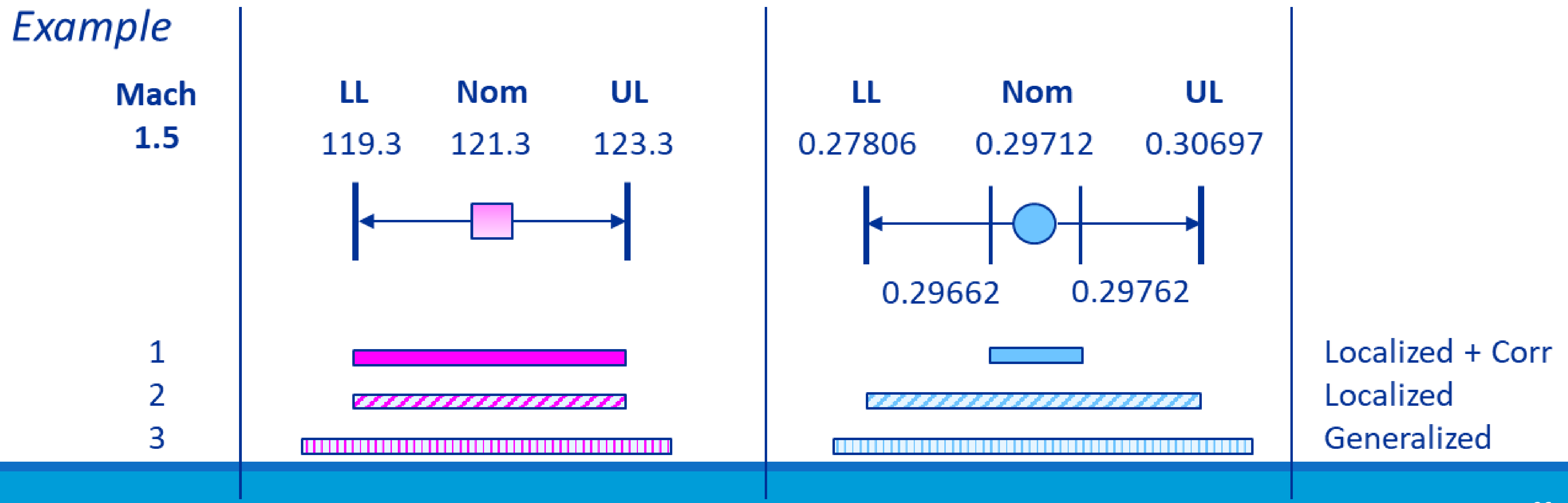
Value of interest
Direct Measurements (Test)
Direct Measurements (Calibration)
Curve-fit constants
Calculated data
Constants

Data Flow chart: Mach Number in 8x6

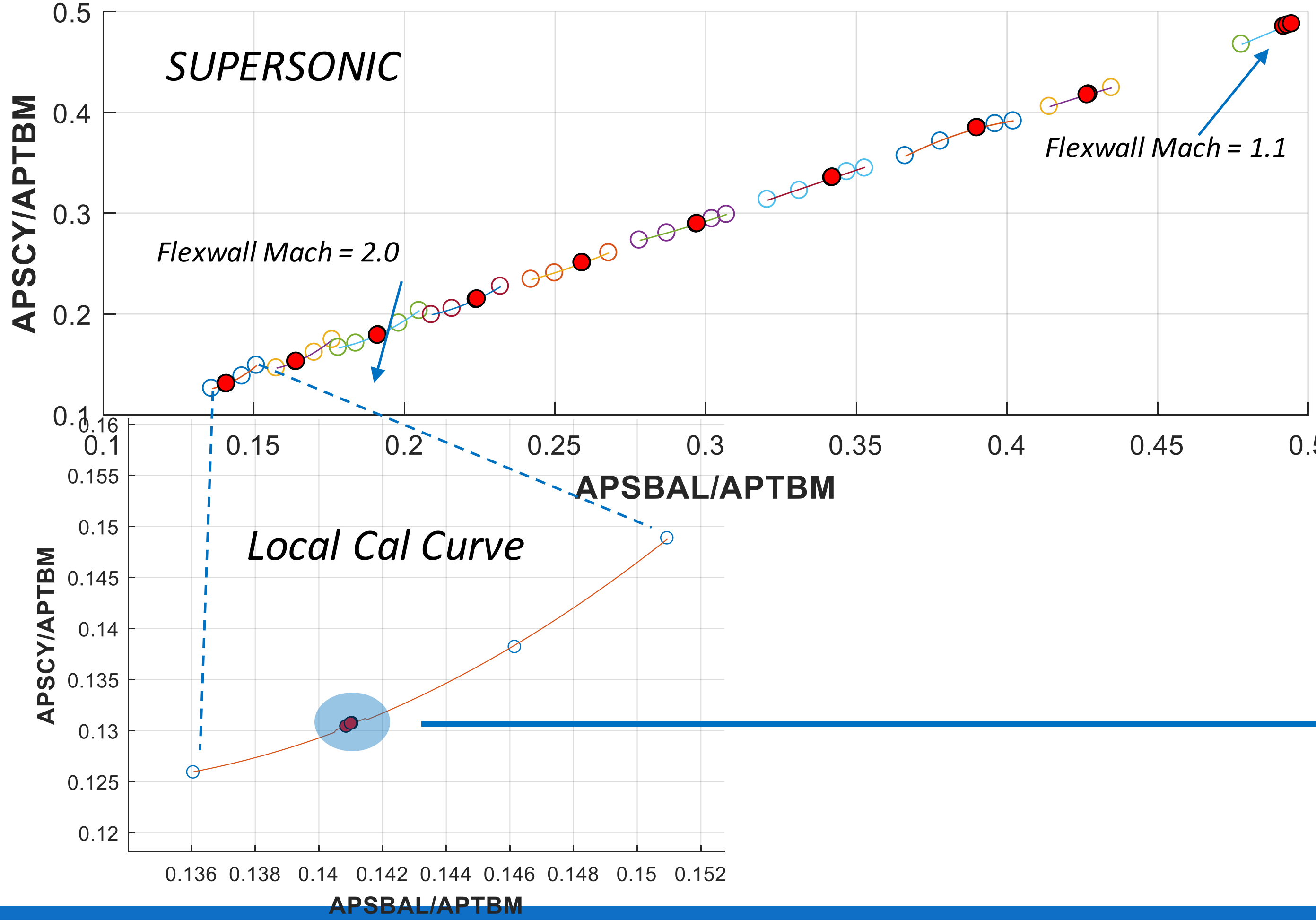


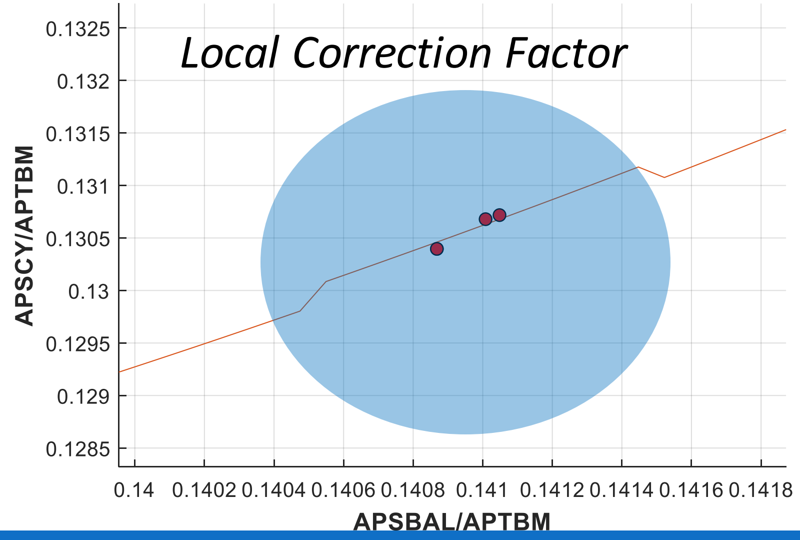
2019 characterization test unique test section scenarios

Scenario	Flexwall Position	$R_{S,bal,bm}$	Prediction model
1	within ±2 deg of nominal setpoint	within ±0.0005 of nominal setpoint	Localized + Corr
2	within ±2 deg of nominal setpoint	within nominal setpoint boundaries	Localized
3	outside nominal setpoint boundaries	outside nominal setpoint boundaries	Generalized



Static Pressure Characterization, Updated

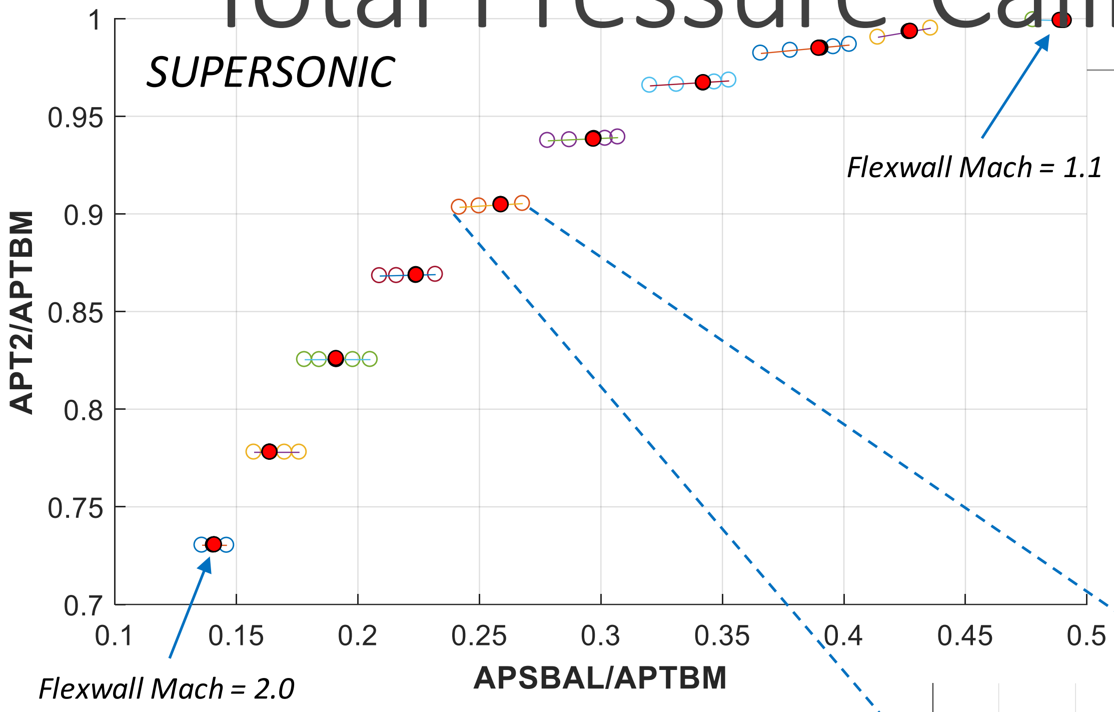


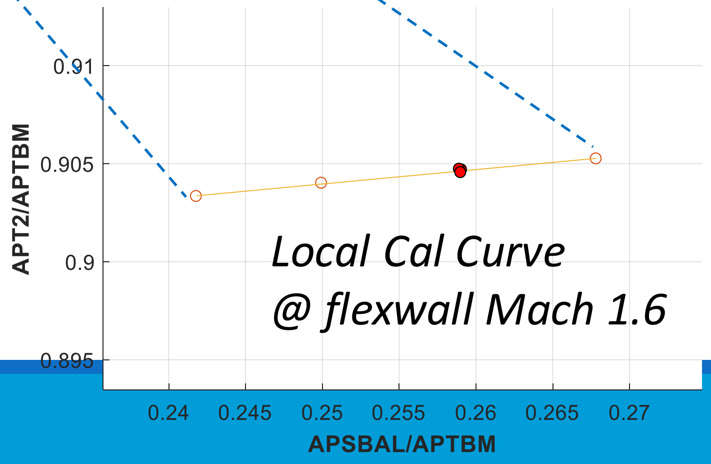


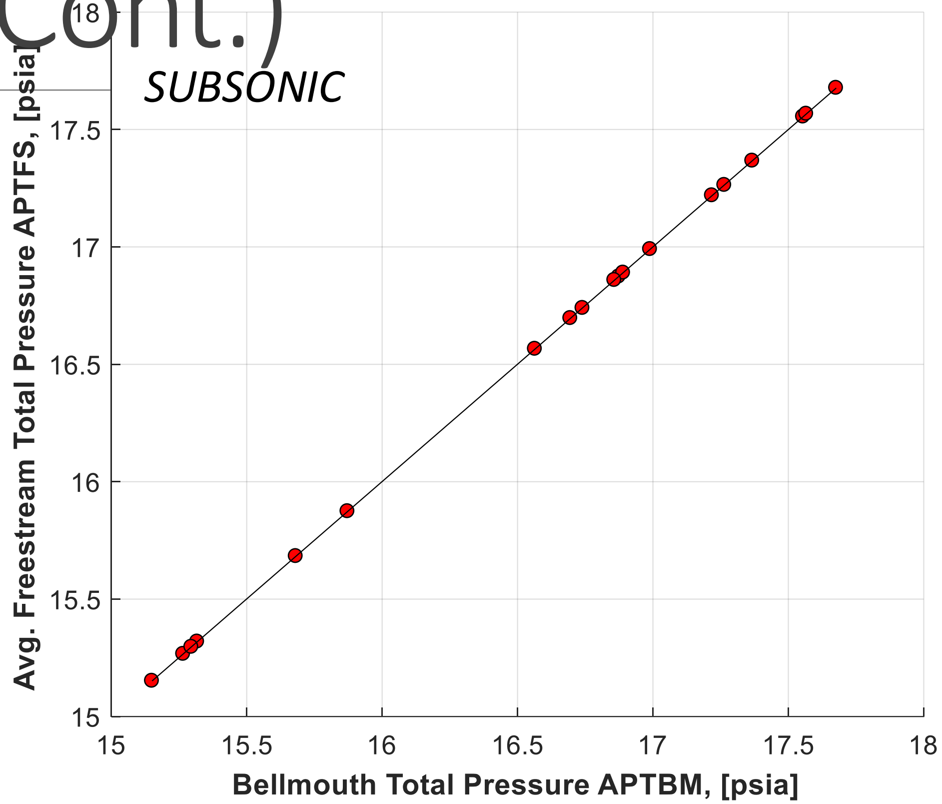
Total Pressure Calibration

- Chose to adopt local supersonic calibration curve method used with static pressure curves
- Split the total pressure calibration curve by flow regime, as well
- Small correction factors were determined but their values were insignificant and left out of the calibration routine

Total Pressure Calibration (Cont.)

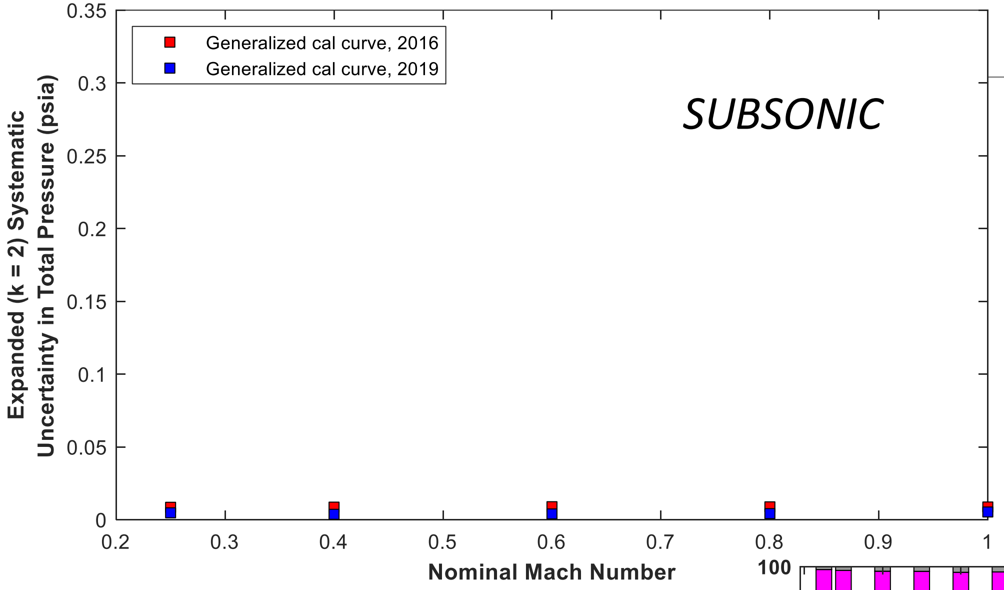


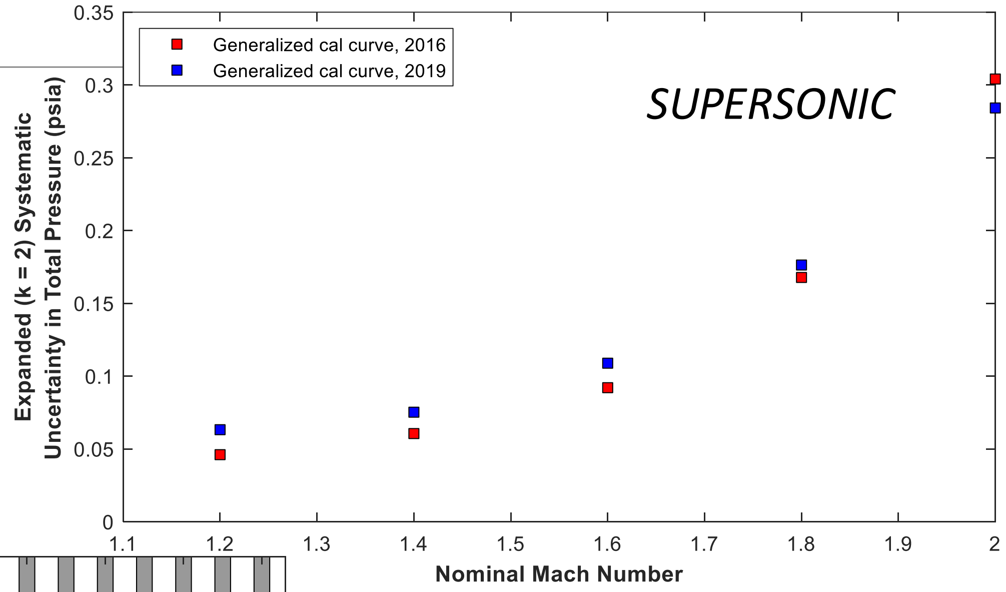


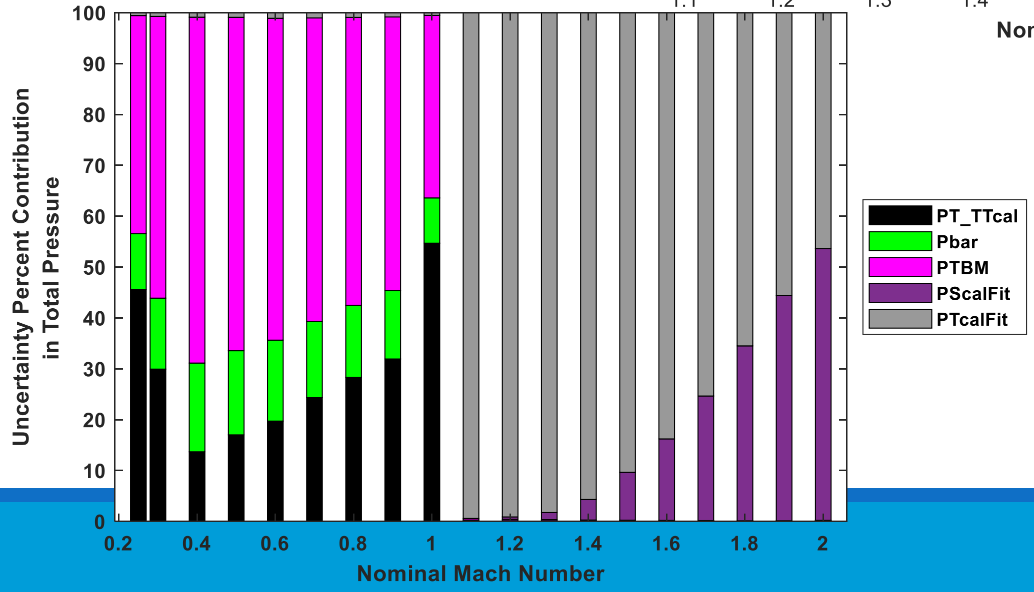


Not shown:
- Supersonic total pressure cal curve made from only “nominal” Mach number data

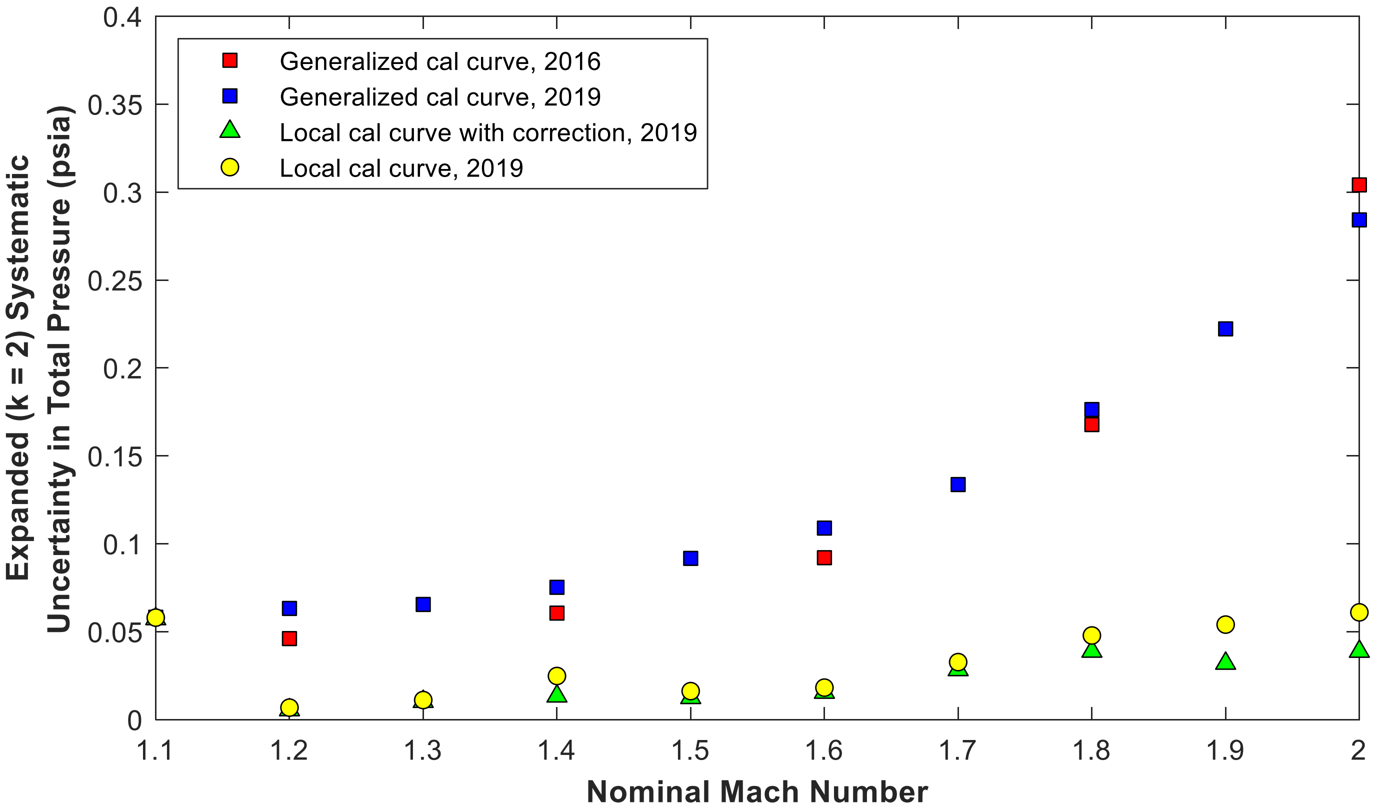
Uncertainty results for $P_{T,ts}$ (generalized curve fit model)

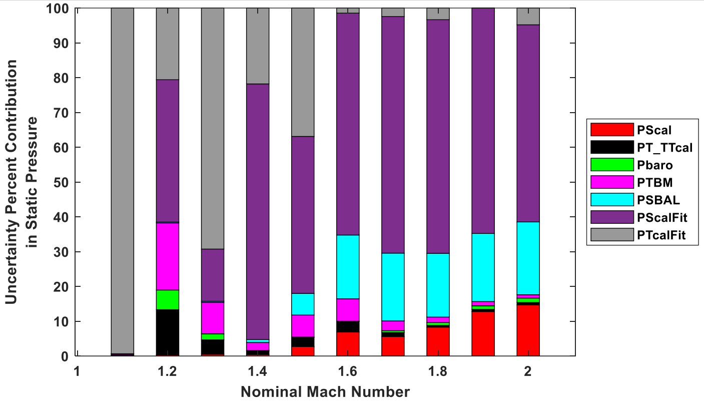




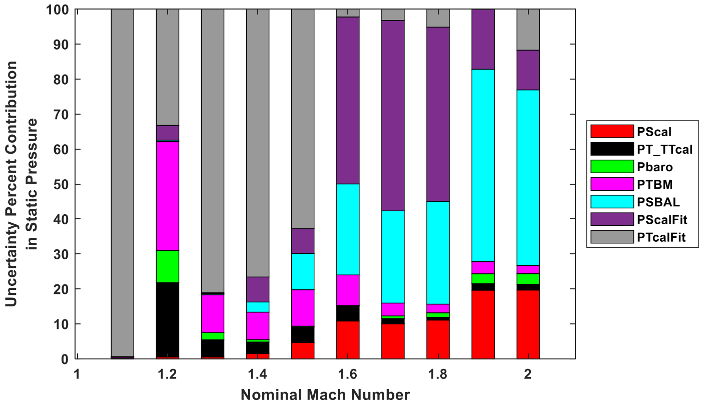


Comparison of uncertainty in $P_{T,ts}$ (generalized, local, and local + correction curve fit models)



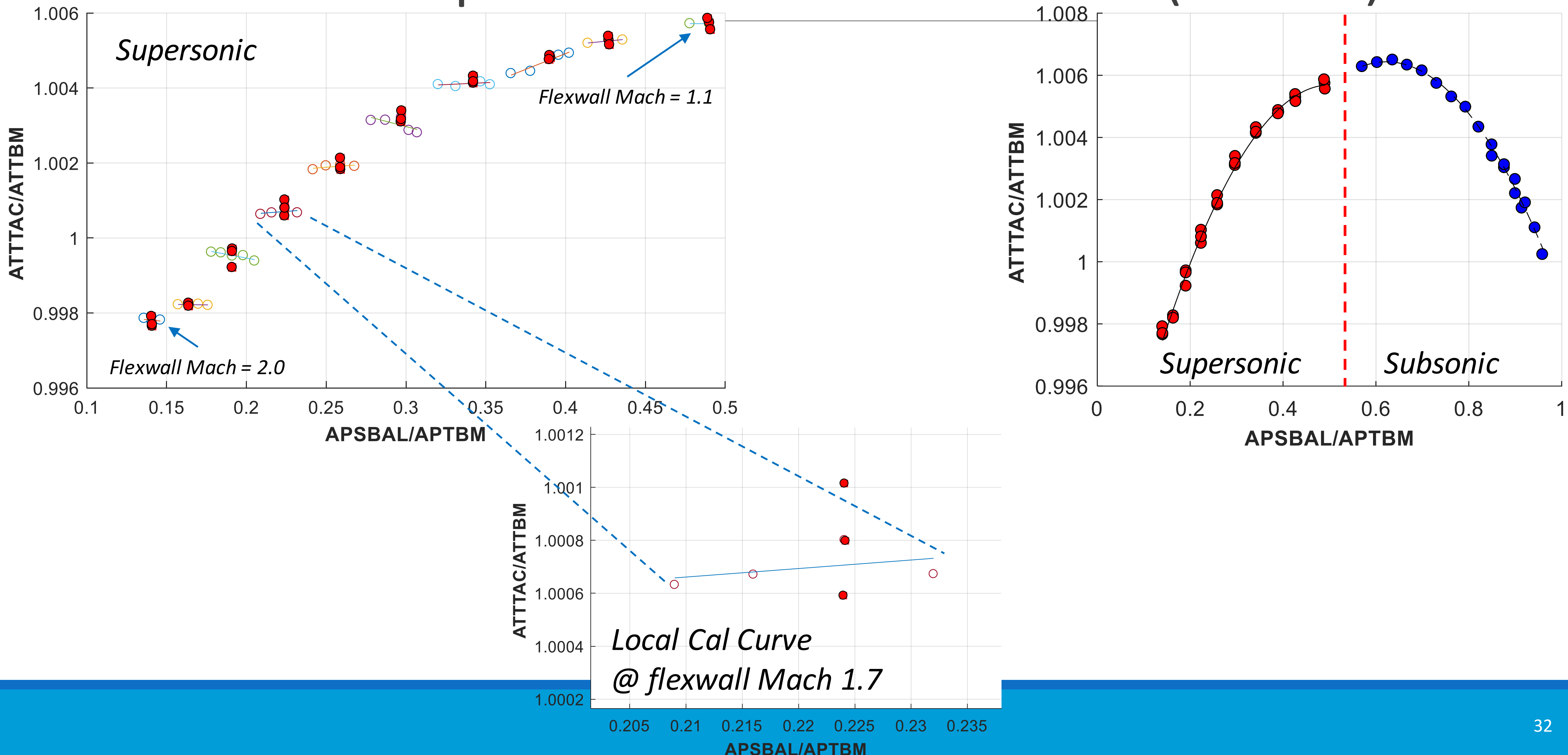


UPC, local curve fit model

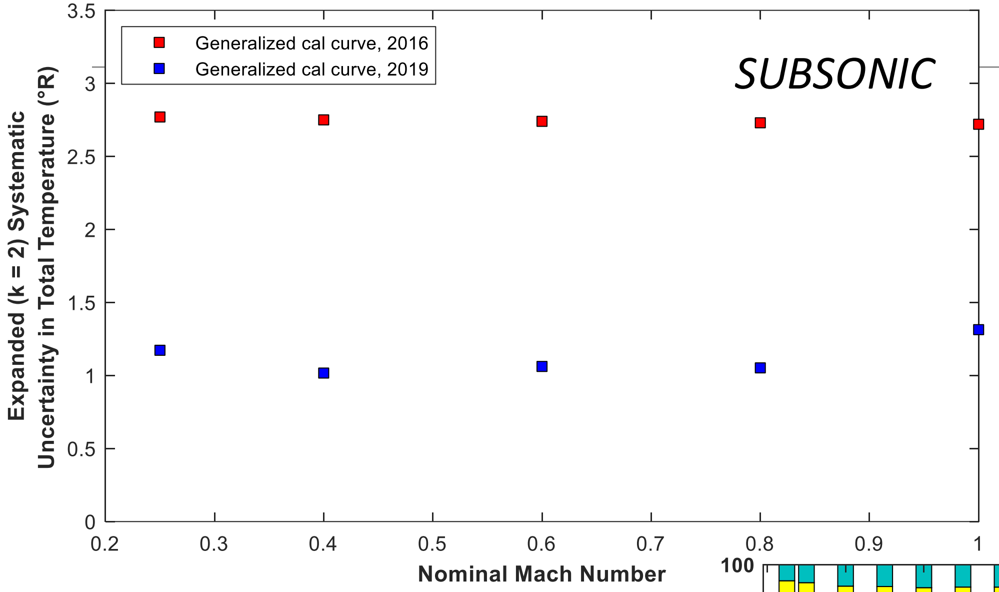


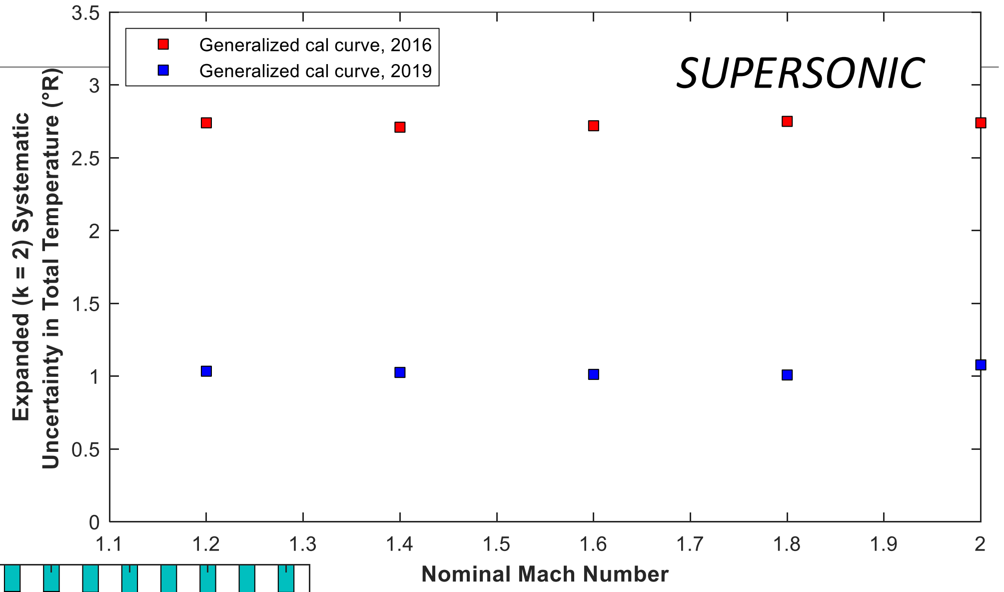
UPC, local + correction curve fit model

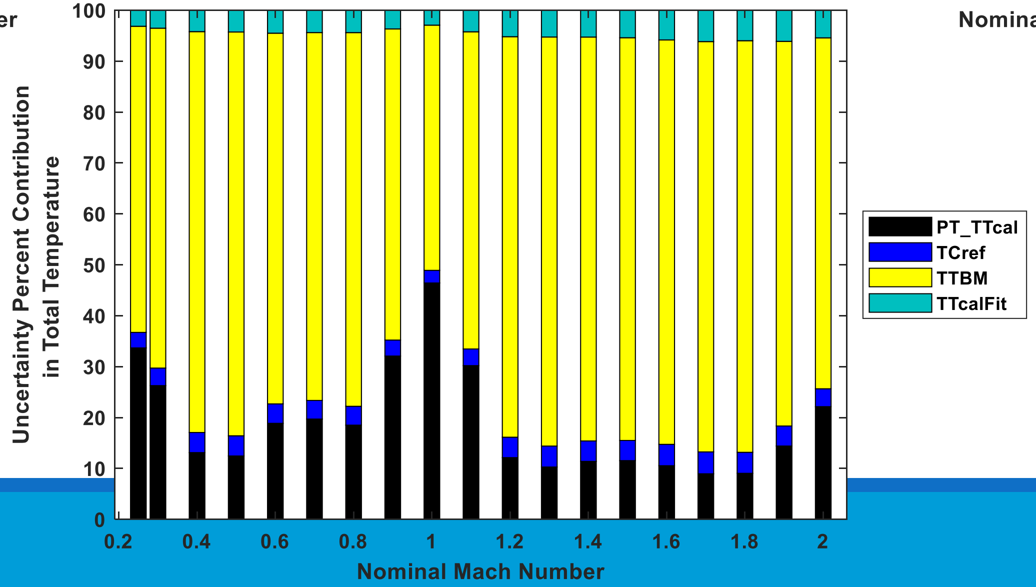
Total Temperature Calibration (Cont.)



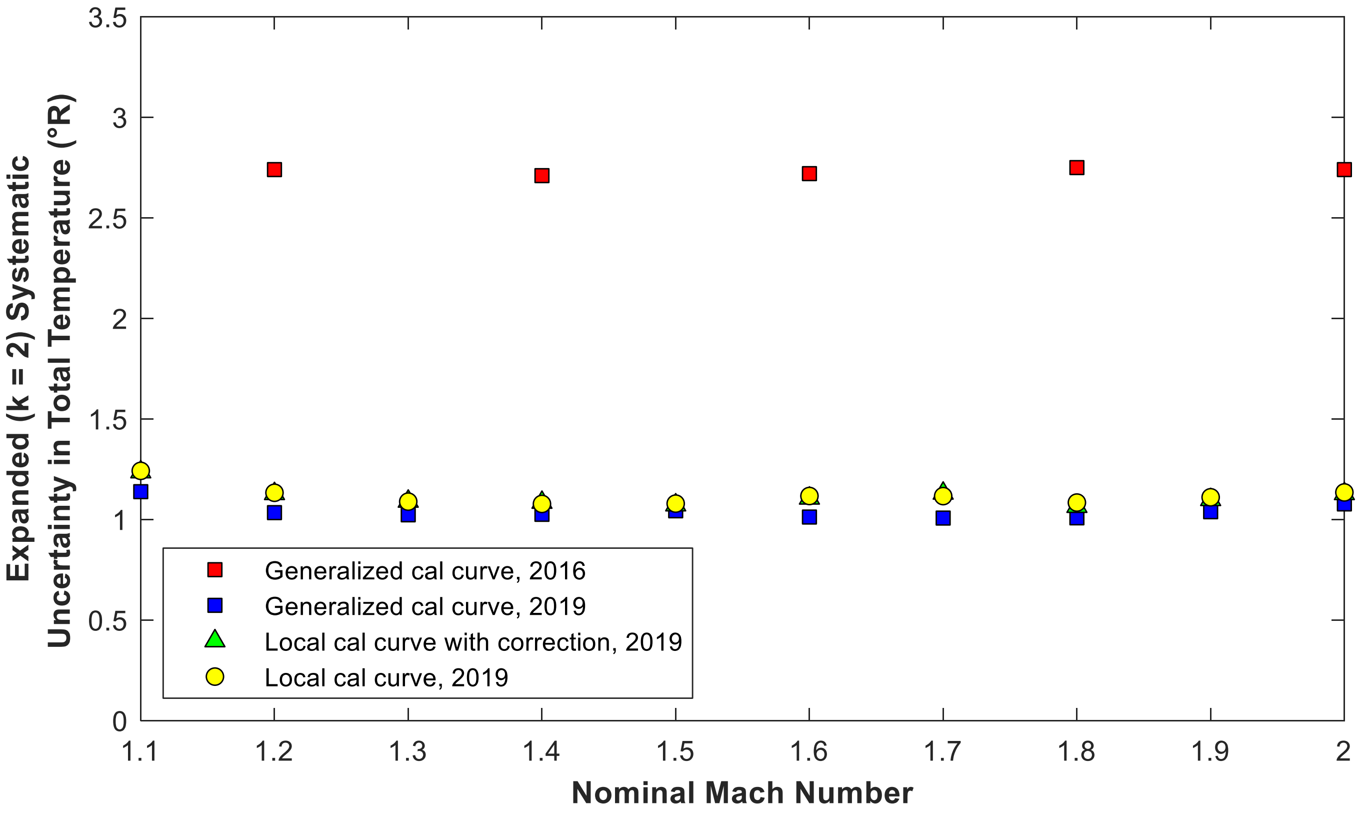
Uncertainty results for $T_{T,ts}$ (generalized curve fit model)

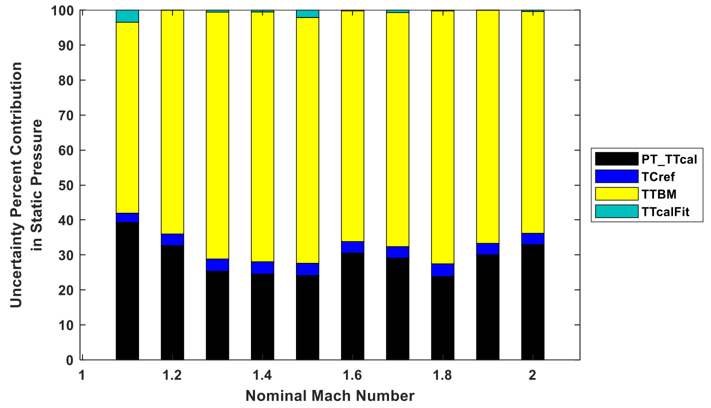




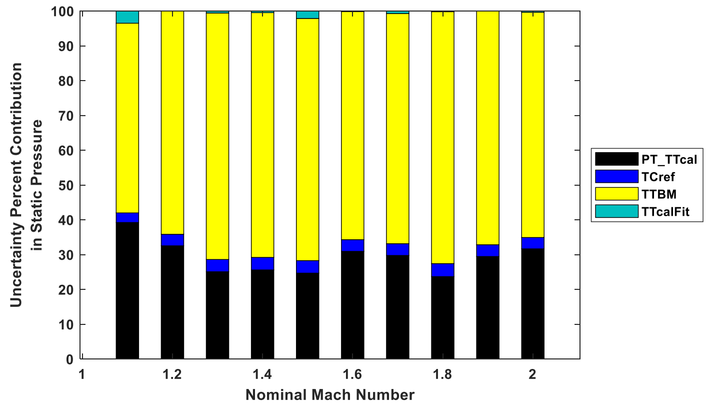


Comparison of uncertainty in $T_{T,ts}$ (generalized, local, and local + correction curve fit models)



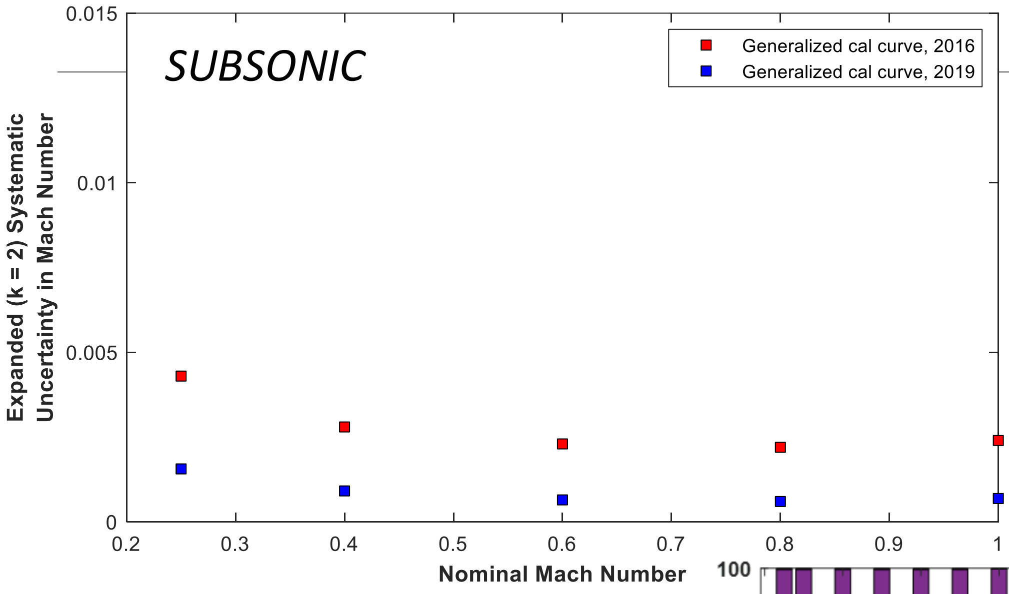


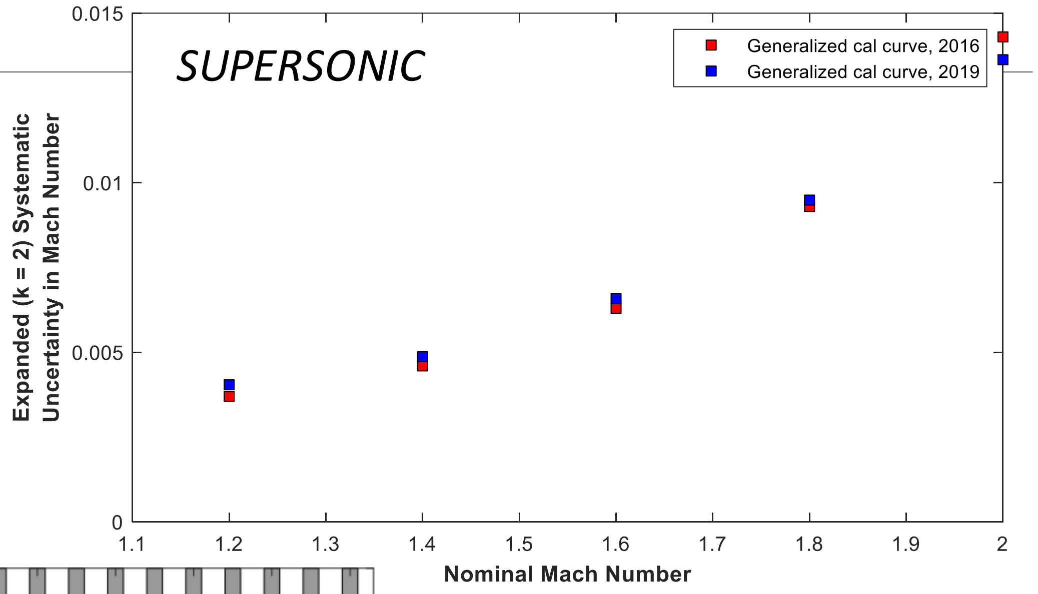
UPC, local curve fit model

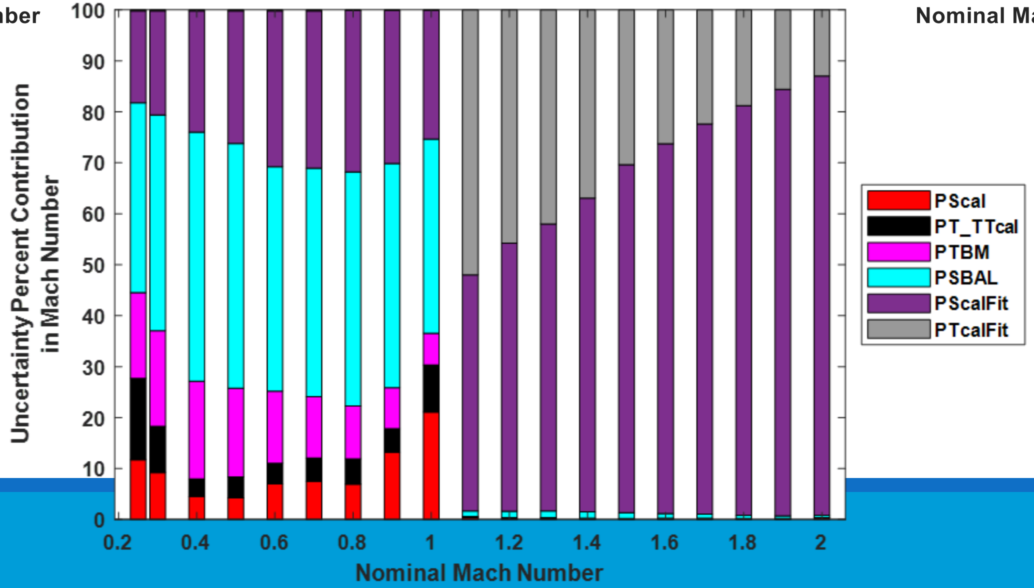


UPC, local + correction curve fit model

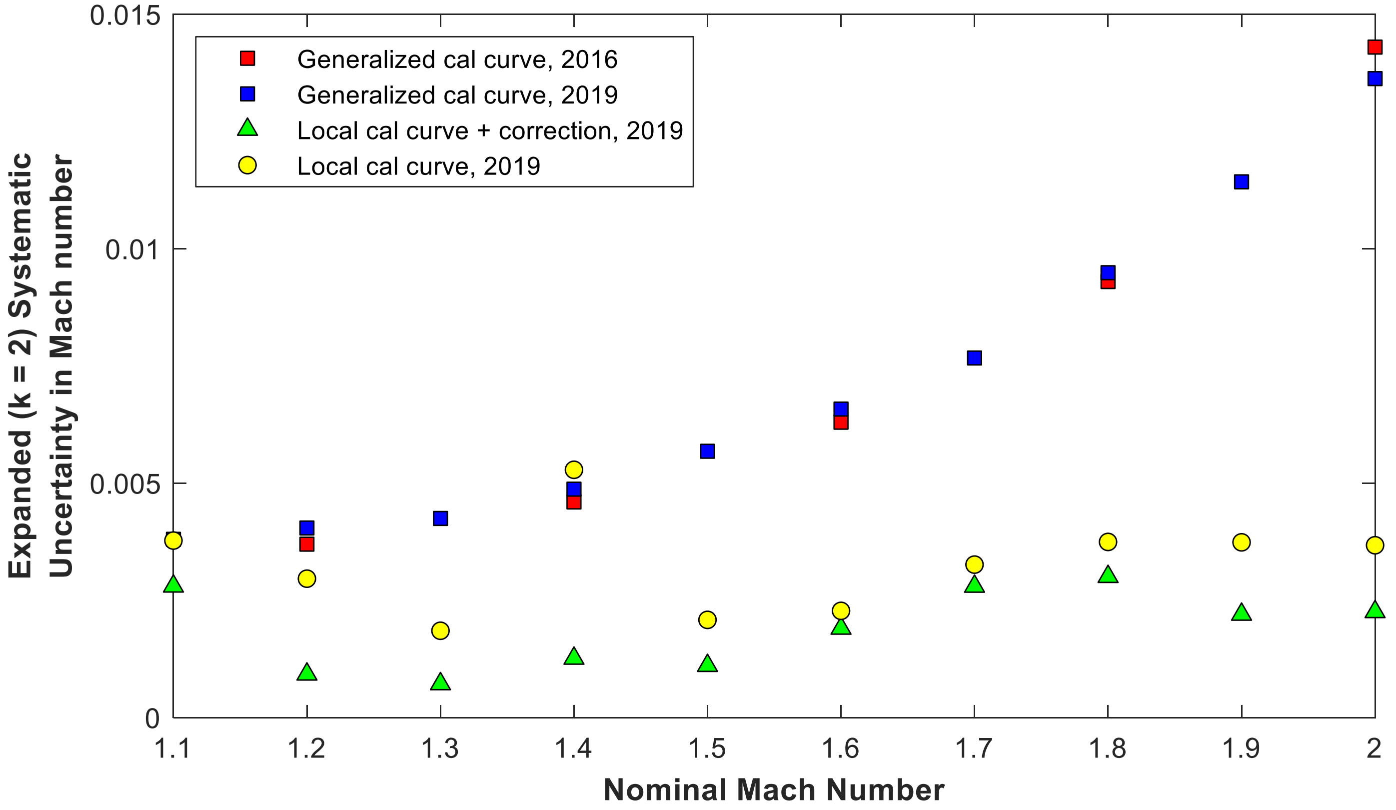
Uncertainty results for M_{ts} (generalized curve fit model)

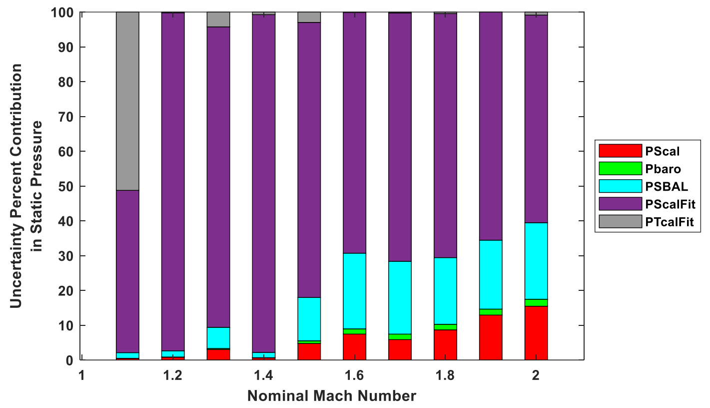




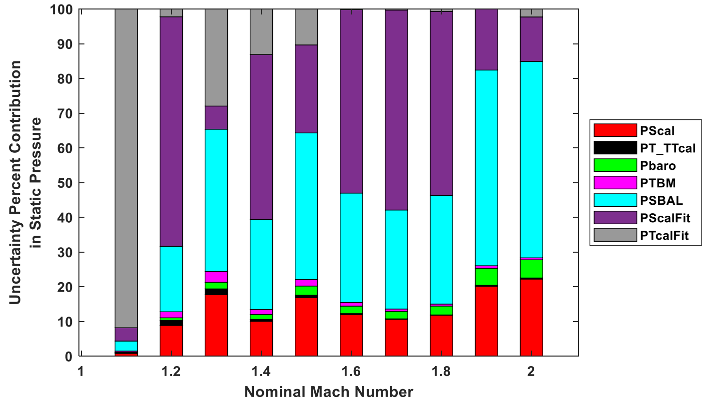


Comparison of uncertainty in M_{ts} (generalized, local, and local + correction curve fit models)



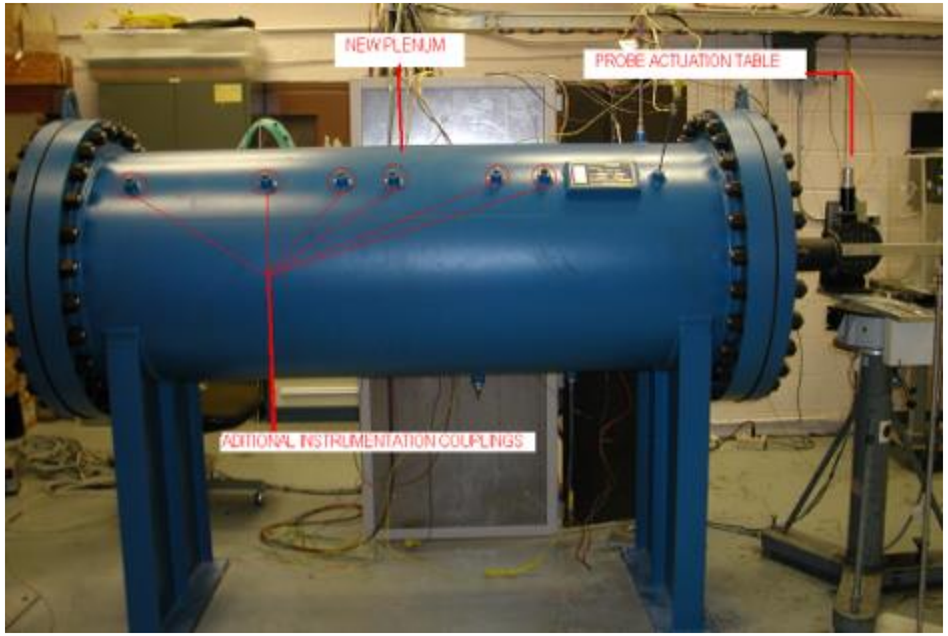


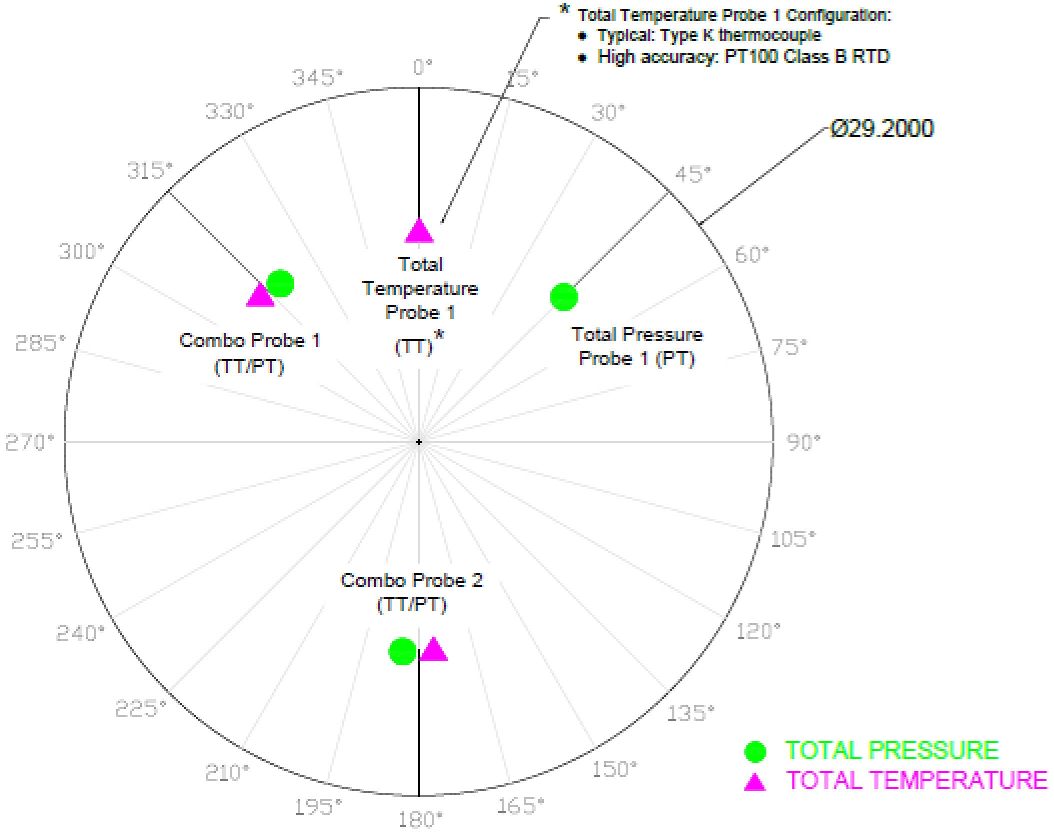
UPC, local curve fit model



UPC, local + correction curve fit model

CE-12 Free Jet Facility





Potential Changes to Decrease Uncertainty

- Change in how free stream static pressure is measured
  - From absolute measurement (PS is measured separately)
  - To differential pressure using Plenum Total Pressure as the reference
- New instrumentation
  - Use test case scenarios to estimate changes to uncertainties when using different instrumentation

Results Continued