



Measurement Uncertainty Analysis of 6x9 Icing Research Tunnel (IRT)

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Nomenclature

γ	Ratio of specific heat, heat capacity ratio, or adiabatic index (Take your pick).
AoA	Angle of Attack
CA	Flow angularity pressure correction coefficient
CB	Flow angularity pressure correction coefficient
CM	Pressure correction coefficient
Co	Total Pressure correction coefficient
IRT	Icing Research Tunnel
MTS	Mach Number in Test Section
$P(1 - 5)$	Pressures 1-5 measured by a 5-Hole Probe tip
$P2$	Static Pressure of during Aeroprobe Calibration of 5-Hole Probes
$P6$	Static Pressure measured By Static Ring on 5-Hole Probe
$PAIRAVG$	Average Spray Bar Pressure
$PAVG$	Average of P2, P3, P4, and P5 measured on a 5-Hole Probe
$PRATBM$	Ratio of Static to Total Pressure in Bellmouth
$PRATTS$	Ratio of Static to Total Pressure in Test Section
$PSBM$	Average Bellmouth Static Pressure
$PSBMN$	Bellmouth Static Pressure North
$PSBMS$	Bellmouth Static Pressure South
$PSTS$	Static Pressure in Test Section
PT	Aeroprobe facility test section total pressure
Pt	Total Pressure of during Aeroprobe Calibration of 5-Hole Probes
$PTBM$	Average Bellmouth Total Pressure
$PTBMN$	Bellmouth Total Pressure North
$PTBMS$	Bellmouth Total Pressure South
$PTTS$	Total Pressure in Test Section
QTS	Dynamic Pressure in Test Section
R	Gas constant
RTD	Resistance Temperature Detector
$TCD(11 - 83)$	D-Corner Temperatures (24 Total)
$TRTDCAVG$	Average of RTD Array temperatures
$TSTS$	Total Temperature in Test Section
$TTDC$	Average Total Temperature in D-Corner

TT_{diff}	Difference between D-Corner temperature and Test Section temperature
$TTTS$	Total Temperature in Test Section
UTS	Airspeed in Test Section
VOI	Variable of Interest
$WDPF(1 - 10)$	Spray Bar Pressures (10 Total)

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1 Abstract

This paper presents the results of the measurement uncertainty analysis that was performed on the aero-thermal characteristics of the 6- by 9-Foot Icing Research Tunnel (IRT) at the NASA Glenn Research Center. The engineering judgments and statistical methods used to determine the elemental uncertainties are described. Instrumentation uncertainty was quantified using MANTUS (Measurement Analysis Tool for Uncertainty in Systems) and instrument specification sheets. The Monte Carlo method was used to propagate systematic components of uncertainty in order to quantify the uncertainty of the Variables of Interest (VOI). A detailed description of the Monte Carlo method and the MANTUS tool can be found in the Uncertainty Analysis of the NASA Glenn 8x6 Supersonic Wind Tunnel report [1]. Detailed uncertainty results for test section airspeed and temperature as well as other variables of interest are described within this document.

2 Facility Description

The 6x9 IRT at NASA Glenn Research Center is a closed-loop atmospheric wind tunnel. The layout of this facility can be seen in Figure 1. The facility test section is 6 feet tall, 9 feet wide, and 20 feet long in the axial direction. In the test section sits a turntable used to rotate vertically mounted hardware to different angles of attack (AoA) during testing. A 5000 hp electric motor drives a 24 ft wooden fan that allows the test section to reach airspeeds ranging from 25 knots, up to 300 knots. In between Corners C and D is a heat exchanger that can adjust the air temperature from -40°C to 10°C . There are 10 rows of icing spray bars located past D-Corner and just in front of the test section. These spray bars are used to infuse water droplets into the airstream to create different icing conditions in the test section.

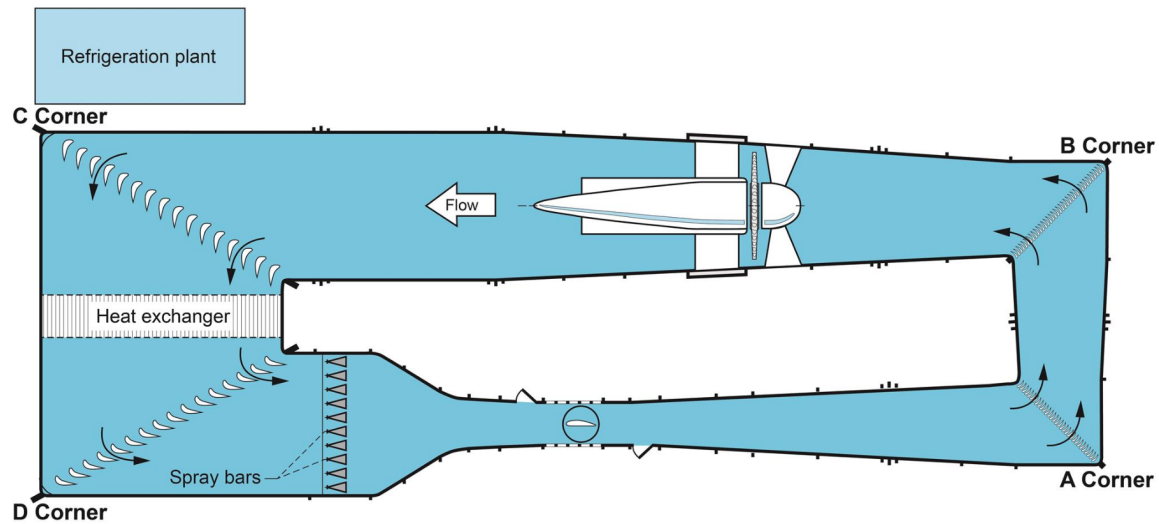


Figure 1: Schematic of 6x9 Icing Research Tunnel Facility

3 Critical Facility Measurements

There are 14 pressure and 24 temperature measurements that are key to the operation of the IRT. The 14 pressure measurements are broken up into 10 spray bar pressure measurements, two bellmouth static pressures and two bellmouth total pressures. The spray bar pressures are measured by 100 PSIG pressure transducers. There are two pitot-static probes used for the bellmouth total and static pressure, one on the north wall and one on the south wall. The measurements are made using ± 5 PSID Scanner in conjunction with a 23 PSIA Reference pressure transducer. The 24 temperature measurements are taken using an array of resistance temperature detectors (RTDs) located at D-Corner, see Figure 2. These measurements are used as inputs into the calibration models to determine the test section conditions or VOIs. Table 1 describes the measurements recorded during a customer test and Table 2 describes the functions and inputs for the test section VOIs.

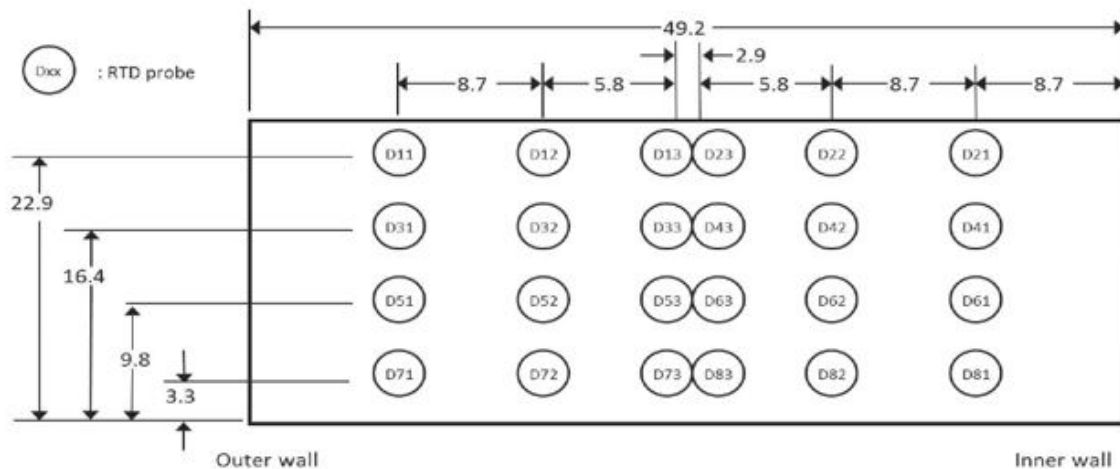


Figure 2: D-Corner RTD Probe Layout

Variable Name	Description	Number of measurements	Instrumentation
$PTBMN, PTBMS$	Bellmouth Total Pressure, PSIA	2	ESP, 5 PSID scanner, 23 PSIA reference pressure
$PSBMN, PSBMS$	Bellmouth Static Pressure, PSIA	2	ESP, 5 PSID scanner, 23 PSIA reference pressure
$TCD(11 - 83)$	D-Corner Temperature, °C	24	Accutech RTD
$WDPF(1 - 10)$	Spray Bar Pressure, PSIG	10	Honeywell 100 PSIG pressure transducer

Table 1: Description of critical measurements

Variable Name	Description	$f(x)$
$PTBM$	Average Total Pressure in Bellmouth	$f(PTMBN, PTBMS)$
$PSBM$	Average Static Pressure in Bellmouth	$f(PSMBN, PSBMS)$
$PAIRAVG$	Average Spray Bar Pressure	$f(WDPF(1 - 10))$
$PRATBM$	Ratio of Static to Total Pressure in Bellmouth	$f(PTMB, PSBM)$
$TTDC$	Average Total Temperature in D-Corner	$f(TCD(11 - 83))$
$PSTS$	Static Pressure in Test Section	$f(CPS1(0 - 2), PRATBM, PSBM)$
$PTTS$	Total Pressure in Test Section	$f(CPT1(0 - 4), PRATBM, PAIRAVG, PTBM)$
QTS	Dynamic Pressure in Test Section	$f(PSTS, PTTS)$
$PRATTS$	Ratio of Static to Total Pressure in Test Section	$f(PSTS, PTTS)$
$TTTS$	Total Temperature in Test Section	$f(CTT(0 - 14or20 - 214), PRATBM, PRATTS, PAIRAVG, TTDC)$
MTS	Mach Number in Test Section	$f(PRATTS, \gamma)$
$TSTS$	Total Temperature in Test Section	$f(TTTS, MTS, \gamma)$
UTS	Airspeed in Test Section	$f(TSTS, MTS, \gamma, R)$

Table 2: Description of critical calculated variables

4 Calibration

Facility aero-thermal calibration tests were conducted in the 6x9 IRT in 2019. The calibration uses the bellmouth static and total pressure, spray bar pressure, and D-Corner temperature to calculate test section total temperature, total pressure, and static pressure. The test section static and total pressure data was collected using the 6-ft Quick Check Rake. The rake used 5-hole pressure probes made by Aeroprobe. The total temperature data was collected using the 2D RTD Array.

4.1 5-Hole Probes

The 5-hole air pressure probes used by the 6-ft Quick Check Rake were made and calibrated by Aeroprobe. These probes were used to measure total pressure, static pressure, and flow angularity in the test section of the IRT. There were 11 probes mounted in the rake. Each probe was heated to prevent any ice buildup on the pressure ports while testing. The probes have a total of 5 pressure ports on a hemispherical tip and a static pressure ring around the base of the probe. The numbering of each pressure port can be found in Figure 3. Tables 3 and 4 show the pressure measurements made by the 5-hole probes and the calculations that are done using these measurements. It was assumed that the measured static pressure from the static ring is the true static pressure. Therefore, there is no calibration or pressure recovery for the 5-hole probe static pressure.

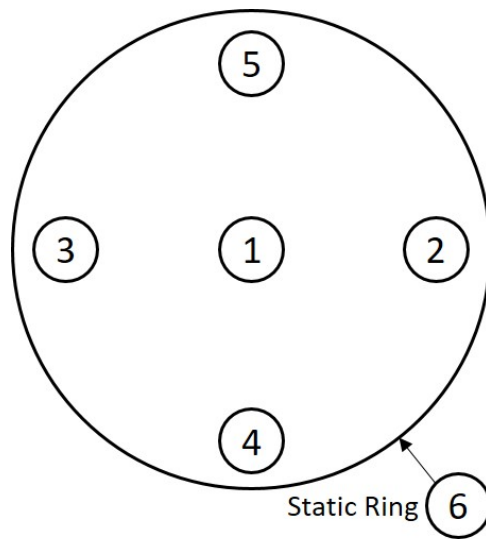


Figure 3: Aeroprobe 5-Hole Probe Pressure Port Schematic (looking down stream)

Variable Name	Description	Instrumentation
$P1$	Pressure measured at Port 1 of 5-hole probe	ESP, 5 PSID scanner, 23 PSIA reference pressure
$P2$	Pressure measured at Port 2 of 5-hole probe	ESP, 5 PSID scanner, 23 PSIA reference pressure
$P3$	Pressure measured at Port 3 of 5-hole probe	ESP, 5 PSID scanner, 23 PSIA reference pressure
$P4$	Pressure measured at Port 4 of 5-hole probe	ESP, 5 PSID scanner, 23 PSIA reference pressure
$P5$	Pressure measured at Port 5 of 5-hole probe	ESP, 5 PSID scanner, 23 PSIA reference pressure
$P6$	Static pressure measured by the static ring of 5-hole probe	ESP, 5 PSID scanner, 23 PSIA reference pressure

Table 3: Description of pressure measurements made by a single 5-hole probe

Variable Name	Description	$f(x)$
Ps, Pt	Aeroprobe facility reference static and total pressure	Measured
PT	Aeroprobe facility test section total pressure	$f(Ps, Pt)$
$PAVG$	Average of four angled pressure measurements	$f(P2, P3, P4, P5)$
CA	Calibration Pressure Coefficient	$f(P1, P4, P5, PAVG)$
CB	Calibration Pressure Coefficient	$f(P1, P2, P3, PAVG)$
CM	Calibration Pressure Coefficient	$f(P1, PAVG)$
Co	Calibration Pressure Coefficient	$f(P1, PT)$

Table 4: Description of 5-hole probe calibration critical values.

4.2 6-ft Quick Check Rake

The 6-ft Quick Check Rake is a vertical rake that holds up to 11 interchangeable probes. The base of the rake is mounted to the floor on the center line of the test section, see Figure 4. The rake configuration for this aero calibration included 11 5-hole pressure probes made by Aeroprobe.



Figure 4: IRT Quick Check Rake mounted in the IRT test section.

4.3 2D RTD Array

The 2D RTD Array is used to measure the total temperature of the test section during calibration. It is mounted to the walls, floor, and ceiling of the IRT test section just down stream of the center of the turntable, see Figure 5. It consists of a 7x7 grid of RTDs. Figure 6 shows both the numbering of the RTDs and the position of each RTD relative to the floor and wind tunnel wall. The total temperature probes used in the array are 4-wire RTDs with a ceramic capsule sensor. Table 5 shows the temperature measurements made by the RTD Array and the calculations that are done using these measurements.



Figure 5: 2D RTD Array mounted in the IRT test section

Variable Name	Description	$f(x)$ or Instrumentation
$TRTDRC_{(1 - 49)}$	Temperatures measured by RTDs in RTD Array	Accutech RTD
$TRTDCAVG$	Average of RTD Array temperatures	$f(TRTDRC_{(1 - 49)})$
$TTdiff$	Difference between D-Corner and Test Section temperature	$f(TTDC, TRTDCAVG)$

Table 5: Description of 5-hole probe calibration critical values.

		Distance from Tunnel Wall, y [inches]						
		13.5	27	40.5	54	67.5	81	94.5
Distance from Tunnel Floor, z [inches]	63	1	2	3	4	5	6	7
	54	8	9	10	11	12	13	14
	45	15	16	17	18	19	20	21
	36	22	23	24	25	26	27	28
	27	29	30	31	32	33	34	35
	18	36	37	38	39	40	41	42
	9	43	44	45	46	47	48	49

Figure 6: Numbering and positions of RTDs in the 2D RTD Array

5 Data Reduction Calculations

5.1 5-Hole Probe Calibration

At the Aeroprobe calibration facility, measured facility static and total pressures were used as reference pressures along with probe measured values $P1$ and P_{avg} to find Co , which is a total pressure correction coefficient. Coefficients CA , CB , and CM are directly derived from $P1 - 6$. Using curve fitting a 3^{rd} order model was used to describe Co using CA , CB , and CM as the independent variables. This all can be seen in Figure 7. Each 5-hole probe has its own characterization model.

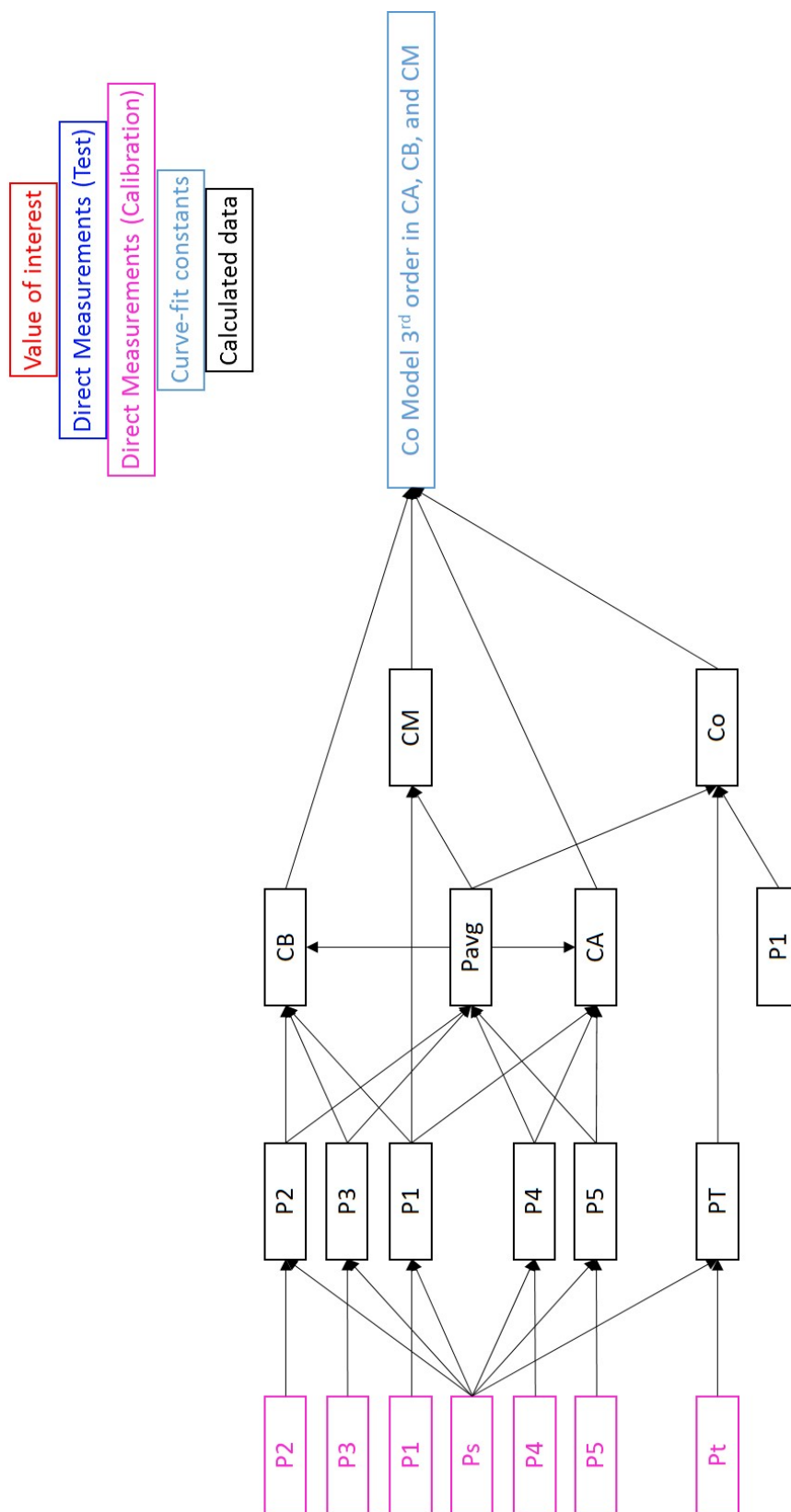


Figure 7: Aeroprobe 5-Hole Probe Calibration Data Reduction

5.2 Quick Check Rake Calibration

During the IRT characterization, the previously characterized 5-hole probes were used in the test section to find the corrected total pressure of the test section (PT_{corr}). The corrected static pressure of the test section (PS_{corr}) is assumed to be equal to P_6 . From there a curve fit model is created to relate the total and static pressure ratios (PT_{rat} and PS_{rat}) measured in the bellmouth to the test section total and static pressure ($PTTS$ and $PSTS$). This data flow chart can be seen in Figures 8 and 9.

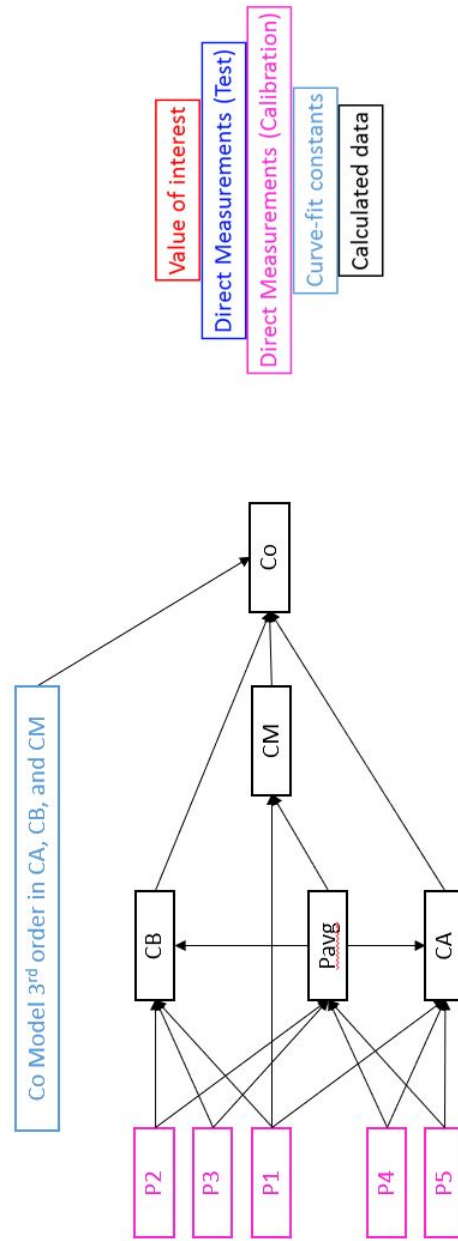


Figure 8: IRT 5-Hole Probe Calibration Data Reduction

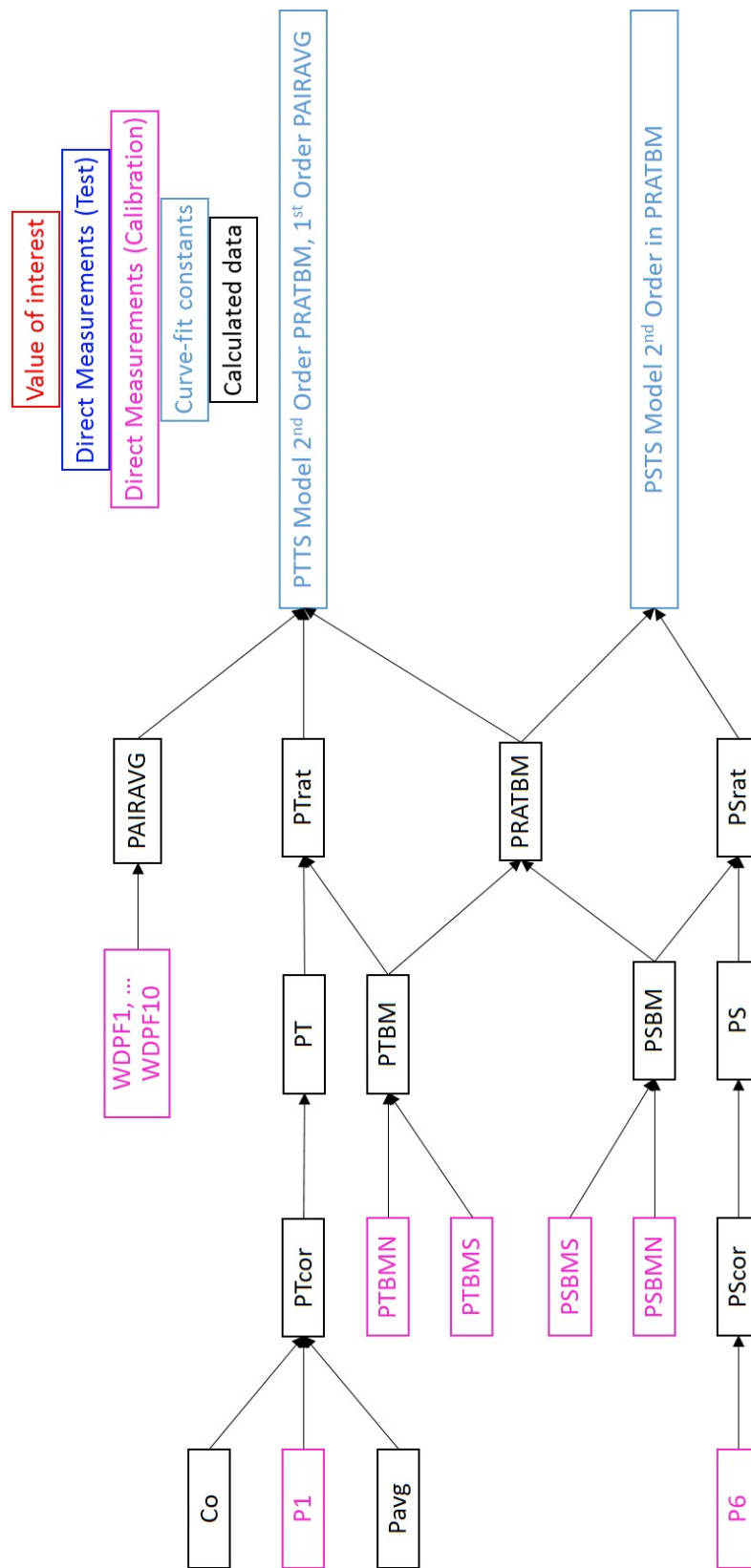


Figure 9: IRT Static and Total Pressure Calibration Data Reduction

5.3 RTD Array Calibration

The RTD Array is used to relate the test section temperature to the temperature measured by RTDs in D-Corner. Two separate curve fits are used, one for high speed and one for low speed. This was done so that the curves better fit the data. This data flow chart can be seen in Figure 10. As shown, the curve fits use the difference between the average temperature of the center 25 RTDs as measured by the RTD Array ($TRTRCAVG$) and average temperature measured in D-Corner ($TTDC$) as the dependent variable in the curve fitting. This difference in temperature ($TTdiff$) is then added with $TTDC$ to find the test section total temperature ($TTTS$).

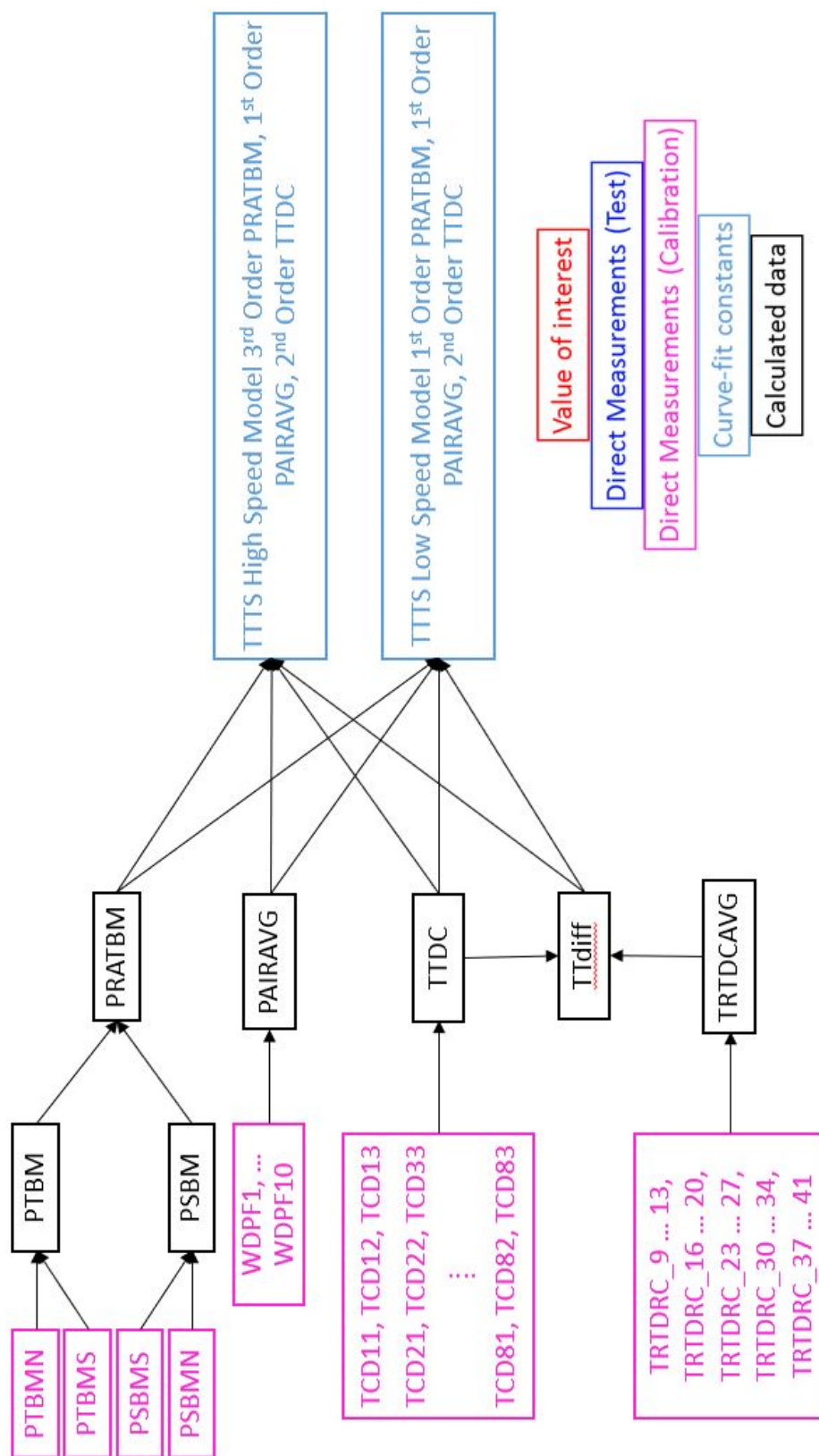


Figure 10: IRT Total Temperature Calibration Data Reduction

5.4 Customer Test

All of the IRT's aero-thermal test section VOIs listed in Table 2 are calculated using previously determined calibration coefficients along with the bellmouth and D-Corner data taken during the customer run. Data reduction flow charts for all the IRT test section VOIs are shown in Figure 11. As can be seen, all test section variables are derived from these three main calibrated variables $PSTS$, $PTTS$, and $TTTS$. Equations for the VOIs can be found below.

$$PRATTS = \frac{PSTS}{PTTS} \quad (1)$$

$$MTS = \sqrt{(PRATTS^{-\frac{\gamma-1}{\gamma}} - 1) \frac{2}{\gamma - 1}} \quad (2)$$

$$TSTS = TTTS * (1 + \frac{\gamma - 1}{2} MTS^2)^{-1} \quad (3)$$

$$UTS = MTS \sqrt{\gamma * R * TSTS} \quad (4)$$

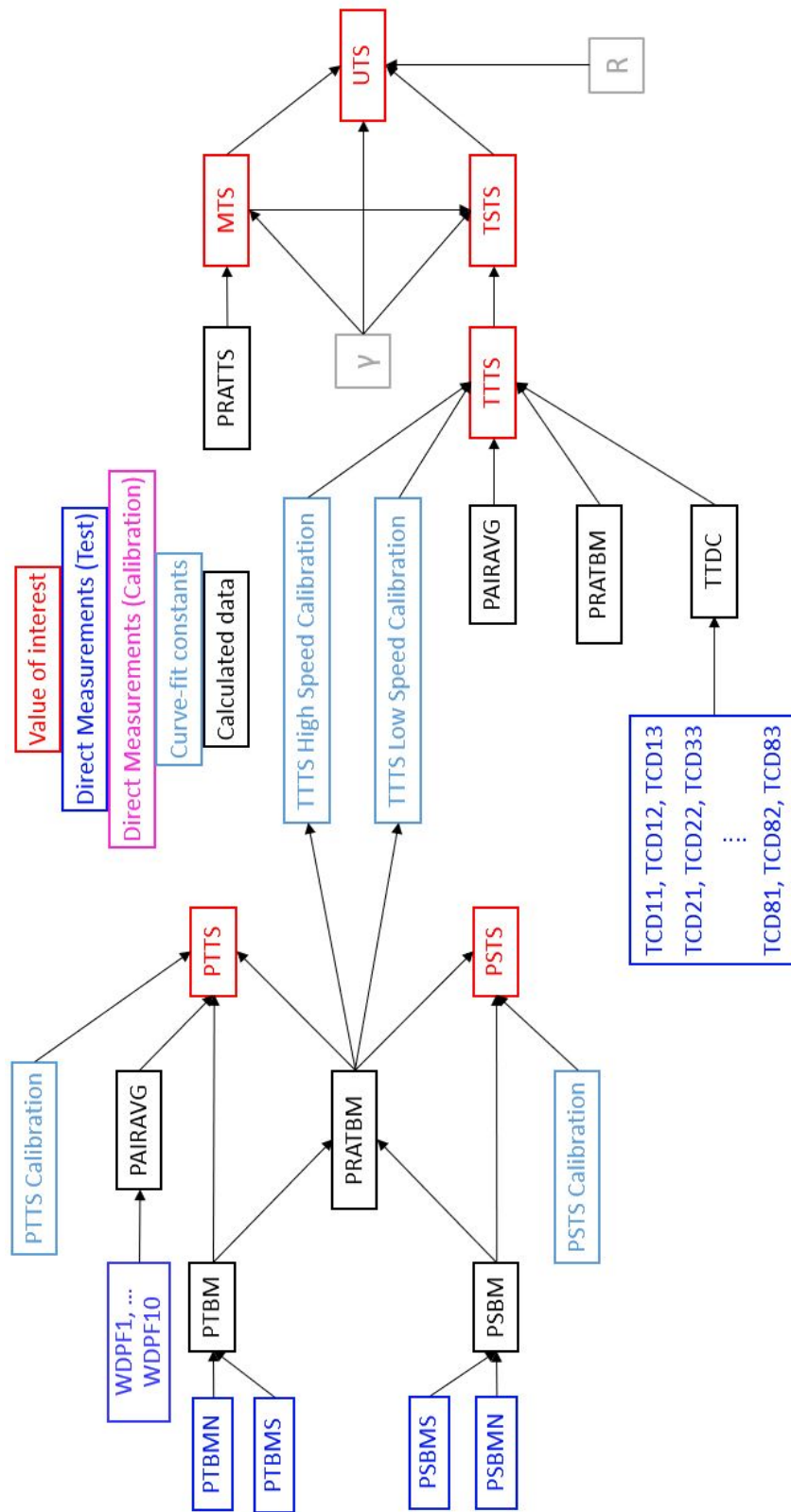


Figure 11: IRT Data Reduction During a Customer Test.

6 Uncertainty Approach

6.1 General Description

In order to capture systematic uncertainty effects from the calibration sequence referred to in Section 4, an uncertainty propagation approach has been selected to estimate uncertainty in several calculated variables of interest. Random uncertainty is also of interest but the data to support this estimate is not available at this time.

The Taylor Series Method (TSM) for uncertainty propagation is employed by MANTUS (“Measurement Analysis Tool for Uncertainty in Systems”) [2][1], an Excel[®] based tool which allows the user to break down the overall measurement into component parts, or “modules”, to easily handle the analysis of multi-level instrumentation systems. This, in essence, captures instrument chain uncertainty contributions from the point of measurement through the data system output as depicted in Figure 12.

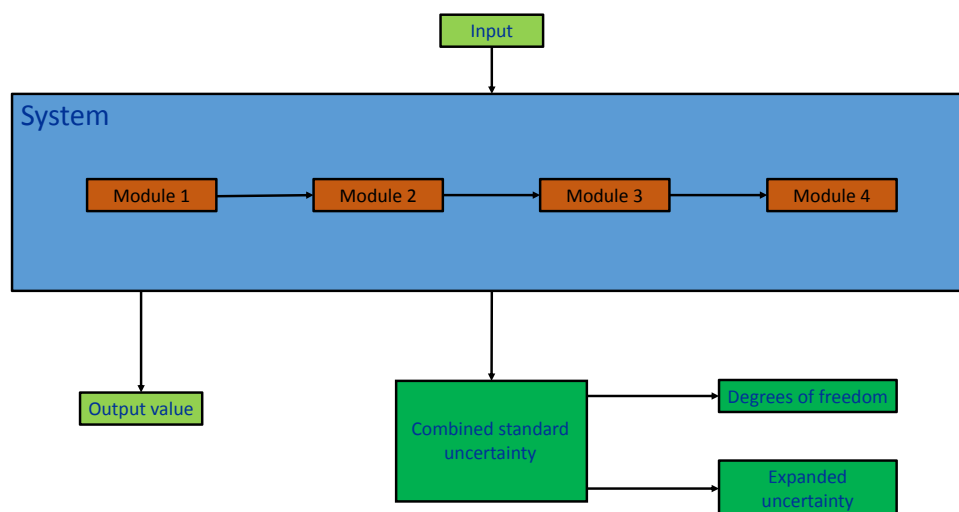


Figure 12: Instrumentation Level Uncertainty Analysis Flow

The Monte Carlo Method (MCM) of uncertainty propagation was selected to propagate systematic measurement uncertainties through the data reduction sequence for the calibration and “test time” simulations. In brief, the MCM simulates tens of thousands “synthetic realizations” of a test point, test matrix, or sequence of tests. Using uncertainty estimates, appropriate error populations are produced and added to associated measurements, simulating errors from certain uncertainty sources. This produces large populations of perturbed measurements, each of which is then sent through the entire data reduction sequence to achieve thousands of calculations of variables of interest. These simulated results can then be analyzed to assess uncertainty in each variable. A more detailed description the Monte Carlo Method can be found in Reference [1].

6.2 Elemental Standard Uncertainty Estimates

Using concepts from the ISO *Guide to the Expression of Uncertainty in Measurement* [3], Coleman and Steele [4] define an elemental standard uncertainty as "an estimate of the standard deviation of the parent population from which a particular elemental error originates." All elemental standard uncertainty estimates, sources, and quantities which serve as inputs into the error propagation are detailed in this section (standard, 1-sigma, estimates presented in this section). Elemental systematic uncertainty estimates for measurement x will be denoted as b_x , following standard nomenclature for systematic standard uncertainty categorization. As best as possible, the Monte Carlo simulation implements error population properly based on assumed error distributions uncertainty correlations between measurements. Unless otherwise noted, a normal distribution of errors is assumed for elemental uncertainties propagated. The specific heat ratio for air, γ , as well as gas constants used in the data reduction scheme are assumed to have negligible uncertainty contributions.

6.2.1 Pressure Measurements

The static and total pressure measurements for both the bellmouth and test section in the IRT are measured by ± 5 PSID range pressure units with the Netscanner 9816 system. All pressure measurements share a common 23 PSIA range reference pressure. This along with their corresponding Netscanner system means they all have correlated systematic uncertainty. The spray bar pressures were measured with 100 PSIG FPGs from Honeywell and are assumed to be uncorrelated. Standard uncertainty estimates associated with the pressure measurements are listed in Table 6.

Uncertainty Label	Standard Uncertainty Estimate	Source of Estimate
$b_{5PSID,uncorr}$	0.0017 PSI	MANTUS
$b_{23PSIA,corr}$	0.00254 PSI	MANTUS
$b_{100PSIG,uncorr}$	0.06510 PSI	MANTUS

Table 6: Elemental uncertainty estimates for pressure measurements

6.2.2 Temperature Measurements

Temperature measurements in D-Corner of the IRT are obtained using Accutech RTDs. These same types of RTDs were used in the 2D RTD Array used to calibrate total temperature in the test section. The uncertainties for the RTDs are assumed to be uncorrelated. Uncertainty estimates for temperature measurements are shown in Table 7.

Uncertainty Label	Standard Uncertainty Estimate	Source of Estimate
$b_{RTD,uncorr}$	See Figure 13	MANTUS

Table 7: Elemental uncertainty estimates for RTD measurements

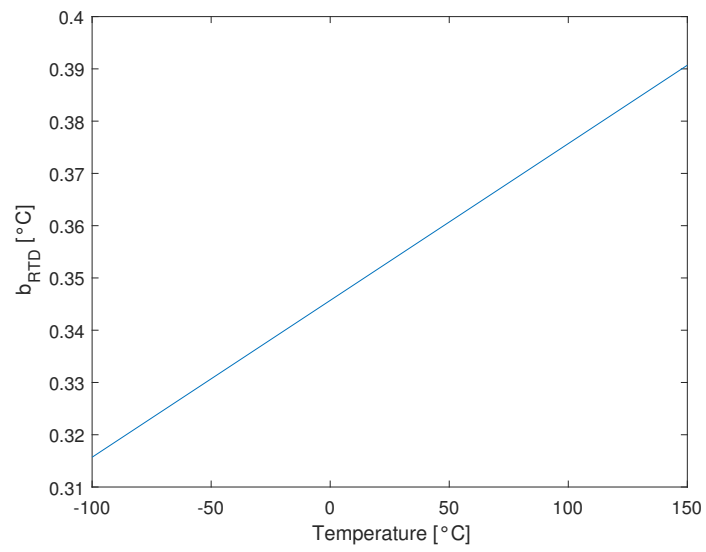


Figure 13: Systematic standard uncertainty estimate for Accutech RTD ($b_{RTD,uncorr}$)

6.3 Calibration Regression Uncertainties

When dealing with and evaluating the uncertainty associated with calibrations and curve fitting, there are two distinct parts that need to be analyzed. The first uncertainty is inherent in calibrations and is the uncertainty that is fossilized within the curve fit. This fossilized uncertainty is a result of errors in the data used to create the curve fit and is classified as systematic. To simulate these errors, a MC simulation of the calibration test is performed using the calibration data as the seed data for this simulation. Just as with the normal MCM the seed data is perturbed based on estimated uncertainties. This MC simulation results in multiple curve fits that represent the confidence interval of the calibration regression.

The second part of the uncertainty that needs to be represented is the prediction interval of the curve fit. This can be thought of as how well the regression fits the data and predicts future data points. Using the residuals from the original calibration curve fit, a visual and statistical inspection is performed to come up with a good estimate for the prediction interval of the curve fit. If the residuals are normally distributed then typically the Root Mean Square Error (RMSE) of the curve fit is used as the uncertainty estimate. Upon inspection, the IRT calibration curves for test section pressure and temperature met this criteria. The RMSE values used to estimate the prediction uncertainties can be found in Table 8.

Uncertainty Label	Standard Uncertainty Estimate
$s_{PT\ RMSE}$	4.8×10^{-5} PSI
$s_{PS\ RMSE}$	5.5×10^{-5} PSI
$s_{TT\ High\ RMSE}$	0.119 deg C
$s_{TT\ Low\ RMSE}$	0.128 deg C

Table 8: Estimated uncertainties for predicting values from IRT calibration curve fits.

7 Results

The uncertainty results described in this section are a characterization of the effects of the systematic error of the instrumentation as well as the error due to the calibration model for the Icing Research Tunnel. All results are of the systematic uncertainty. Random uncertainty was not included in this analysis as test data was not yet available.

Each result is broken down into Uncertainty Percent Contributions (UPC) so as to see where the majority of the uncertainty for a VOI comes from. All results are presented as expanded uncertainties with a 95% level of confidence. Uncertainty results for each VOI are presented as univariate with a coverage factor of $k = 2$. If these uncertainties are intended to be used in multivariate cases, the coverage factor will need to be expanded, see GUM Supplement 2 [5].

The Uncertainty Percent Contribution charts (UPC) show what the main contributing sources of uncertainty are for a given VOI. This can be useful information for "what-if" scenarios and trying to minimize uncertainty in the future. Note that in the UPC charts only errors that contributed more than 0.5%.

7.1 Test Section Pressure

The uncertainty associated with both the total and static pressure in the test section are constant across the facility operation envelope. This can be seen in Figures 14 and 15. The uncertainty value was chosen to encompass most of the Monte Carlo results without being overly conservative. Table 9 shows the uncertainty associated with the test section pressure measurements. The UPCs for both the static and total pressure show that the largest contributions to uncertainty are the bellmouth reference pressure and the associated bellmouth pressure measurements. For total pressure it can be seen in Figure 16 that the spray bar pressure does change the uncertainty percent contributions of the three contributors. This is not the case with static pressure, Figure 17, so the spray bar pressure is not shown.

Variable Name	Uncertainty [PSI]
PTTS	5.7×10^{-3}
PSTS	5.5×10^{-3}

Table 9: Two sigma uncertainty of test section pressures.

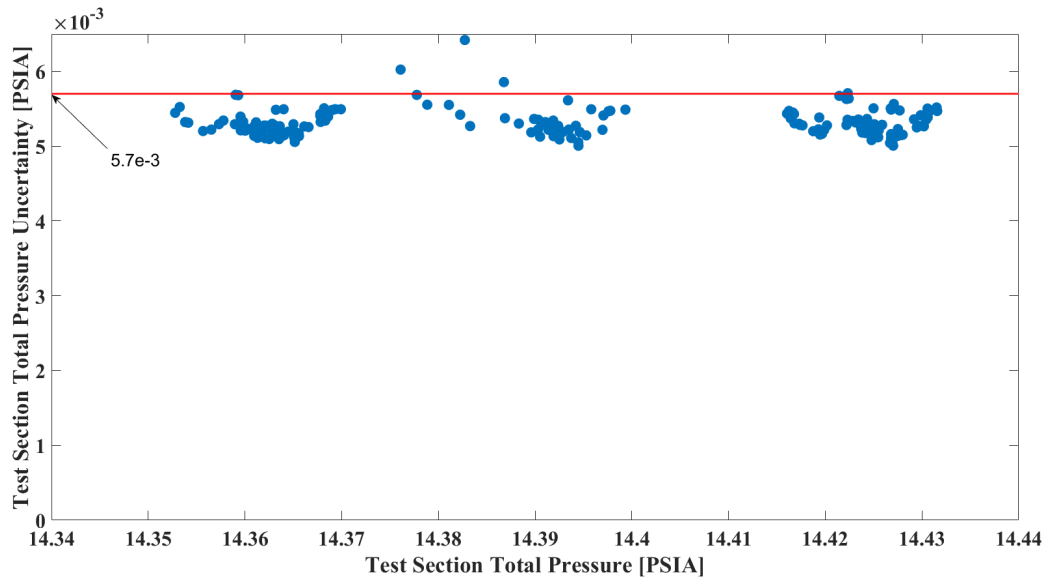


Figure 14: IRT Test Section Total Pressure Uncertainty.

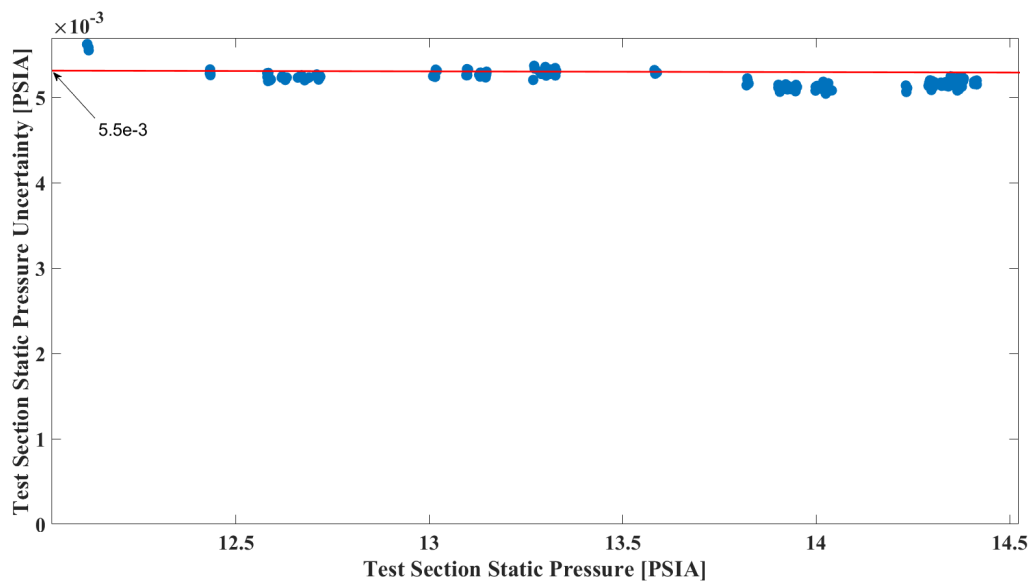


Figure 15: IRT Test Section Static Pressure Uncertainty.

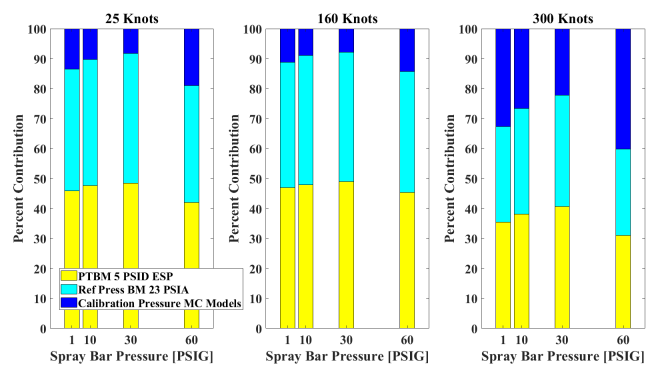


Figure 16: IRT Test Section Total Pressure UPC.

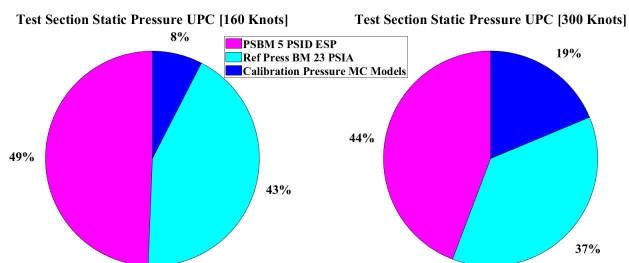


Figure 17: IRT Test Section Static Pressure UPC.

7.2 Test Section Temperature

The uncertainty for both the total and static temperature in the test section is dependent on TTTS while the test section airspeed (UTS) is between 45 and 280 knots. This can be seen in Figures 18 and 19.

When the airspeed drops below 45 knots, or increases above 280 knots other uncertainties become the major contributing factor and causes the uncertainty to increase. This can be seen in the UPCs in Figures 20 and 21. When the airspeed is below 45 knots the uncertainty from bellmouth pressure measurements start to become a major contributor and this increases the uncertainty of both static and total temperature. Also at low speed the UPCs become very dependent on spray bar pressure as shown in the bar plot, but as airspeed increases this is no longer the case and therefore not shown. An increase in uncertainty is also observed when the airspeed climbs over 280 knots, though this increase in uncertainty is due primarily to the increase in uncertainty contribution from the total temperature calibration model.

Variable Name	Airspeed [Knots]	Uncertainty [$^{\circ}\text{C}$]
TTTS	< 45	0.36
TTTS	> 45 and < 280	$0.28 + 0.00058 * TTTS$
TTTS	> 280	0.35
TSTS	< 45	0.36
TSTS	> 45 and < 280	$0.28 + 0.00056 * TTTS$
TSTS	> 280	0.35

Table 10: Two sigma uncertainty of test section temperatures.

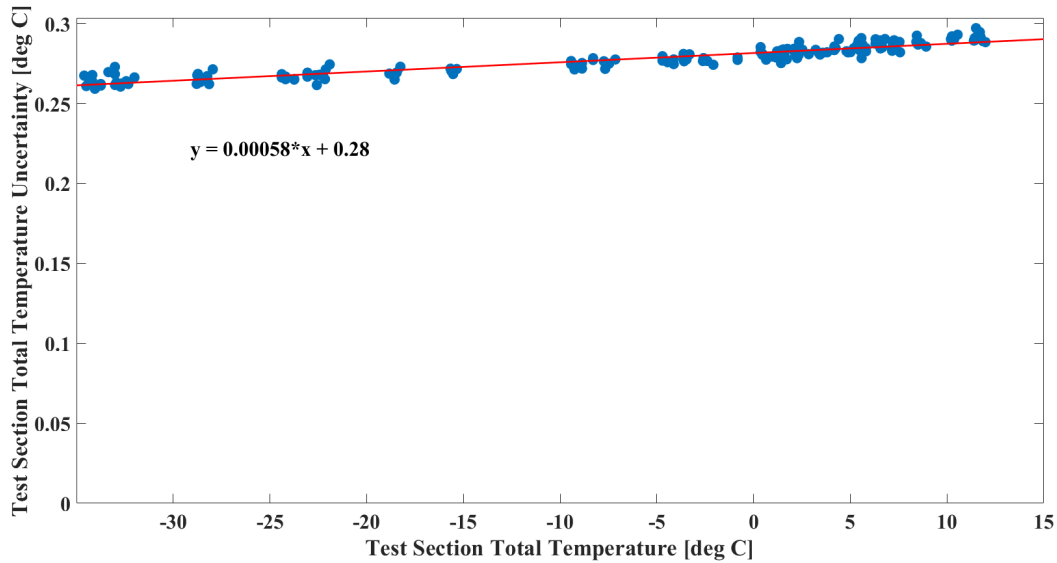


Figure 18: IRT Test Section Total Temperature Uncertainty between 45 and 280 knots.

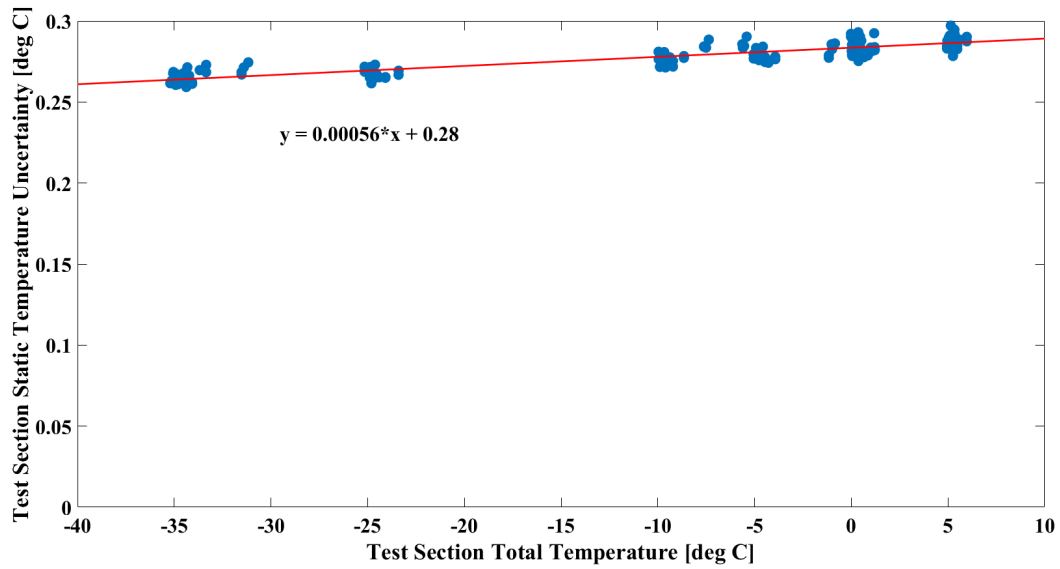


Figure 19: IRT Test Section Static Temperature Uncertainty between 45 and 280 knots.

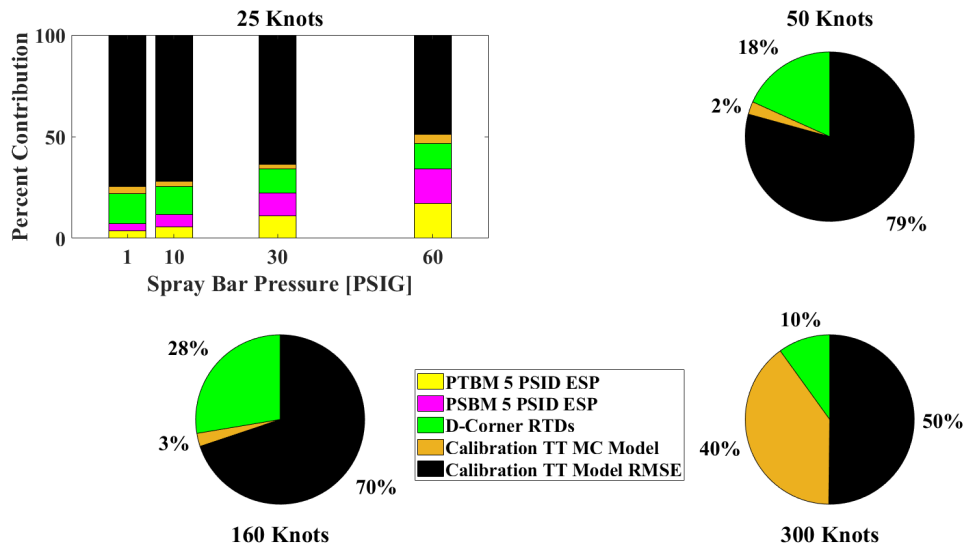


Figure 20: IRT Test Section Total Temperature UPC.

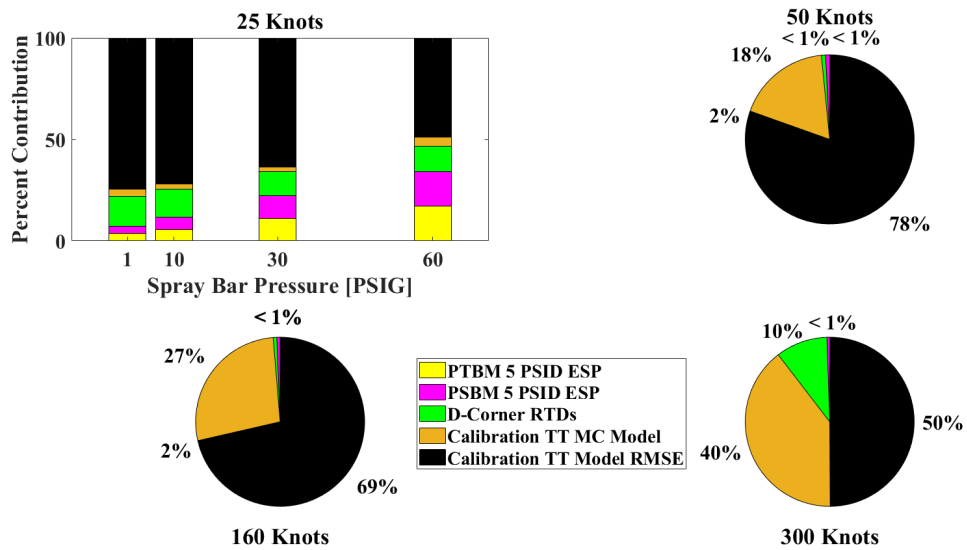


Figure 21: IRT Test Section Static Temperature UPC.

7.3 Test Section Air Speed and Mach Number

When it comes to the Mach number and airspeed uncertainties, there are very clear trends. The equations for these trend-lines can be found in Table 11. As can be seen in Figures 22 and 23, as the tunnel speeds up the uncertainty decreases asymptotically to about 0.5 knots or 0.001 for Mach number. On the other end we see a sharp rise in uncertainty below 100 knots. This rise can mostly be seen as a result of using the static to total pressure ratio in the data reduction calculations, Figure 11. When the airspeed is slow both static and total pressure are very nearly the same, so even small errors can result in larger uncertainties when propagated through the data reduction using the MCM. This can be seen in the UPCs in Figures 24 and 25. When the airspeed is low the uncertainty from bellmouth pressure measurements starts to become a major contributor and this increases the uncertainty of the Mach number and airspeed. The opposite is true when the airspeed increases; uncertainty due to the bellmouth pressures decreases to the point that other uncertainties become relevant.

Variable Name	Uncertainty Equations
MTS	$0.0003 * MTS^{-0.947}$
UTS	$84.67 * UTS^{-0.94}$

Table 11: Two sigma uncertainty of test section airspeed and Mach Number.

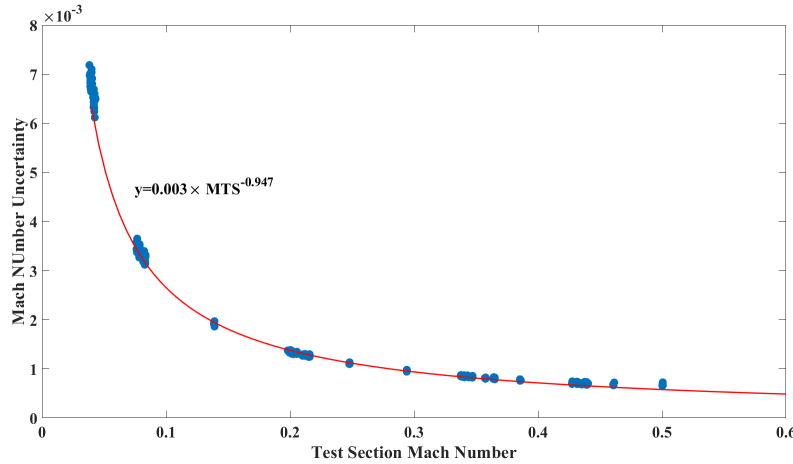


Figure 22: IRT Test Section Mach Number Uncertainty.

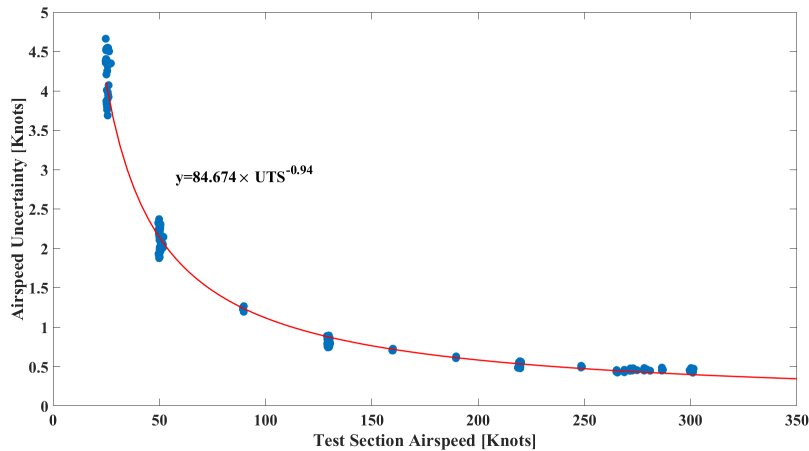


Figure 23: IRT Test Section Airspeed [Knots].

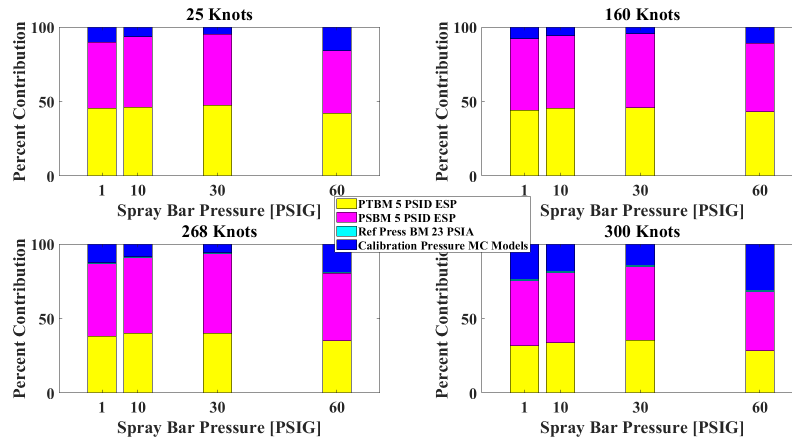


Figure 24: IRT Test Section Mach Number UPC.

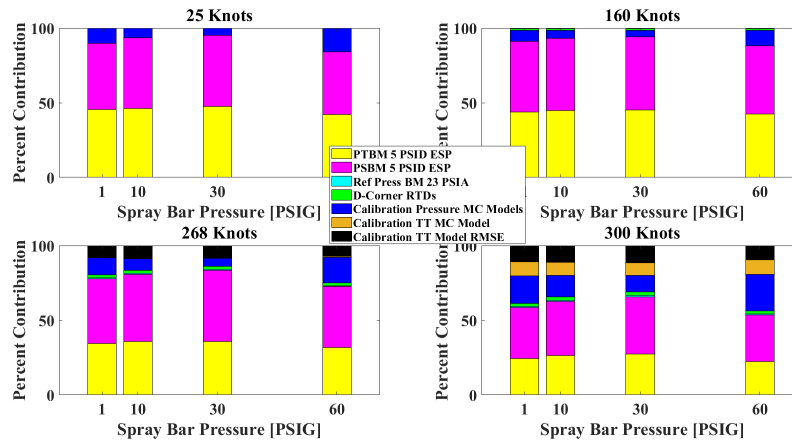


Figure 25: IRT Test Section Airspeed UPC.

8 Conclusions

The results presented in this report were created by propagating the elemental uncertainty estimates from MANTUS as well as uncertainties from characterization models. These uncertainties were propagated through the data reduction process using a Monte Carlo simulation. The results show that the characterization models and measurement instrumentation affect the final uncertainty in different amounts depending on the VOI. All results in summary Table 12 are within expected limits.

Test section variable name	Units	Uncertainty range
Total Pressure	PSIA	5.7×10^{-3}
Static Pressure	PSIA	5.5×10^{-3}
Total Temperature	deg C	0.25 - 0.36
Static Temperature	deg C	0.25 - 0.36
Mach Number		0.001 - 0.0075
Airspeed	Knots	0.5 - 5

Table 12: Summary of test section values with 95% level of confidence.

9 References

- [1] J. Stephens, E. Hubbard, J. Walter, and T. McElroy. "Uncertainty Analysis of the NASA Glenn 8x6 Supersonic Wind Tunnel". Contractor Report NASA/CR-2016-219411, National Aeronautics and Space Administration, 2016.
- [2] B. Rouse, J. Morales, and T. McElroy. "Measurement Analysis Tool for Uncertainty in Systems Overview". Contractor report, National Aeronautics and Space Administration, In Progress.
- [3] Joint Committee for Guides in Metrology. "Evaluation of Measurement Data - Guide to the Expression of Uncertainty in Measurement". Guide JCGM 100:2008, International Organization for Standardization, 2008.
- [4] H. W. Coleman and W. G. Steele. *Experimentation, Validation and Uncertainty Analysis for Engineers*. John Wiley and Sons, Inc., Third edition, 2009.
- [5] Joint Committee for Guides in Metrology. "Evaluation of Measurement Data - Supplement 2 to the "guide to the Expression of Uncertainty in Measurement" - Extension to Any Number of Output Quantities". Supplement JCGM 101:2011, International Organization for Standardization, 2011.

