Uncertainty Improvement in the NASA Glenn Research Center 8- by 6-Foot Supersonic Wind Tunnel

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Within the past decade, a measurement uncertainty analysis (MUA) team was assembled at the NASA Glenn Research Center to assist the wind tunnel characterization team with quantification of uncertainty estimates for variables of interest in wind tunnels and test cells across the center. The initial analysis performed by the team was conducted on the 8- by 6-Foot Supersonic Wind Tunnel using results from the 1996/97 full calibration test entry. These MUA results were published in 2016 which included recommendations for methods to improve the uncertainty estimates for various variables of interest, such as changes to regression models, tunnel operation philosophy, and instrumentation choices. The wind tunnel characterization team utilized the proposed methods in 2019 during a full characterization test entry. Following publication of the 2019 test section characterization results, the MUA team pursued an update to the uncertainty estimates for the facility, which validated previous recommendations and revealed significantly reduced systematic uncertainties across most variables of interest. Inclusion of within-test repeat points in the 2019 test entry allowed for higher fidelity estimates of random uncertainty to be generated, as well. This collaboration between the facility, wind tunnel characterization, and MUA teams serves as an example of the data quality benefits that can be achieved through rigorous analysis of the sources of uncertainty in a ground-test facility.

I. Nomenclature

M_{ts}	=	test section Mach number
$P_{S,bal}$	=	average static pressure in the balance chamber
$P_{S,ts}$	=	test section static pressure
$P_{T,bm}$	=	average stagnation pressure in the bellmouth
$P_{T,ts}$	=	test section stagnation pressure
$P_{T,2,ts}$	=	test section post-normal-shock stagnation pressure
$T_{T,bm}$	=	average stagnation temperature in the bellmouth
$T_{T,ts}$	=	test section stagnation temperature
UPC	=	Uncertainty Percentage Contribution
VOI	=	Variable of Interest

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II. Introduction

The emphasis on uncertainty quantification has increased over the years as instrumentation accuracies improve and aircraft component designs require smaller measurable improvements to significantly advance technologies. Within the wind tunnels at the NASA Glenn Research Center, an initiative began within the last decade to estimate the uncertainty of primary variables of interest, including the assumptions, instrumentation, and processes that contribute to those estimates. The Measurement Uncertainty Analysis (MUA) team assembled at NASA Glenn developed a computational tool for estimation of instrumentation-chain uncertainties [1]. Monte Carlo simulations are used to propagate instrumentation-level uncertainties through series of calculations and regression model formulations which replicate those same events that occur during test entries or facility characterization/calibration test entries, respectively.

The initial focus of the MUA team was the 8- by 6-Foot Supersonic Wind Tunnel (8x6 SWT). The analysis focused on using the 1996/97 test section characterization results to estimate the uncertainties associated with the calibrated test section conditions and how these "fossilized" calibration-related uncertainties propagated into subsequent customer test entry variables of interest. Results of this analysis are thoroughly documented in Ref. [2] and the 1996/97 characterization test entry description, processes, and results can be found in Ref. [3].

III. Background Information

A. Description of the 8- by 6-Foot Supersonic Wind Tunnel

The 8- by 6-foot Supersonic Wind Tunnel at the NASA Glenn Research center is an atmospheric, continuous flow wind tunnel. A schematic of the facility is shown in Figure 1. During standard operations, airflow is driven by a 7-stage compressor utilizing three 29,000-hp motors located in the drive motor building. The test section is 8 feet tall and 6 feet wide with no divergence over the test section length. The test section is divided into two testing sections: a solid-wall supersonic flow region 9 feet 1 inch in length, and a porous-wall transonic region 14 feet 5 inches in length (Figure 2). The Mach number range for the transonic test section is 0.25 to 2.0. Six configurations for the transonic test section are defined based on the length of the porous area used and porosity of the test section surfaces. This paper discusses results for the most used configuration, which is the 14-foot-long test section with 5.8-percent-porosity. For information on the other porosity configurations, see the most recent facility characterization reports [4,5].

The facility operating conditions are set by controlling compressor speed, flexible wall (flexwall) position, balance chamber pressure (test section bleed), and shock door position. The set point is determined predominantly by the ratio of the static pressure in the balance chamber to the total pressure in the bellmouth. To obtain these measurements, four static pressure measurements are taken at various locations in the balance chamber and are averaged to give $P_{S,bal}$. Two wall-mounted rakes near the exit of the bellmouth on the north and south tunnel walls acquire a total of eight total pressure measurements, which are averaged to give $P_{T,bm}$. These two bellmouth rakes also acquire three total temperature measurements, which are averaged to give $T_{T,bm}$. More details on the facility operation can be found in the facility manual [6].

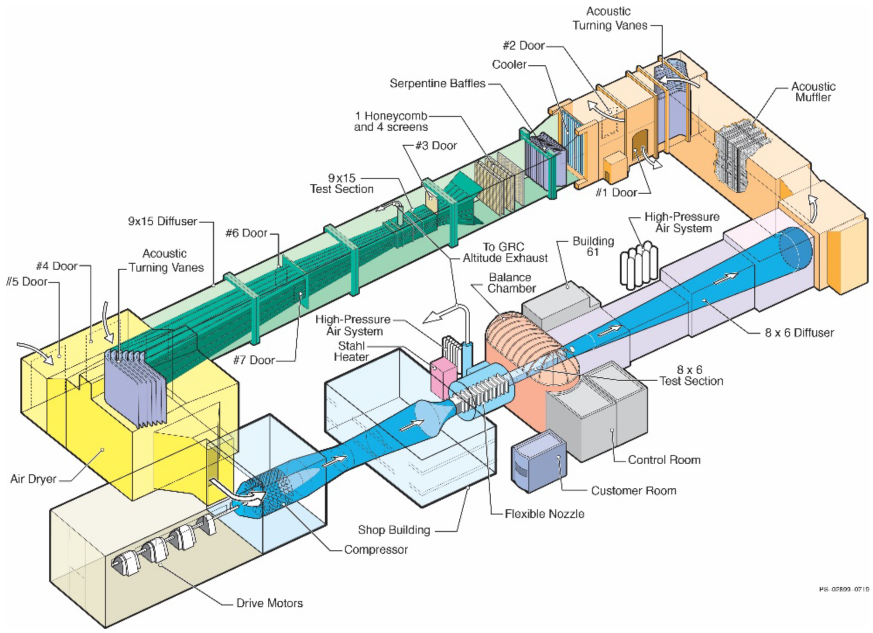

Figure 1: Overview of the 8- by 6-Foot Supersonic/9- by 15-Foot Low Speed Wind Tunnel Complex.

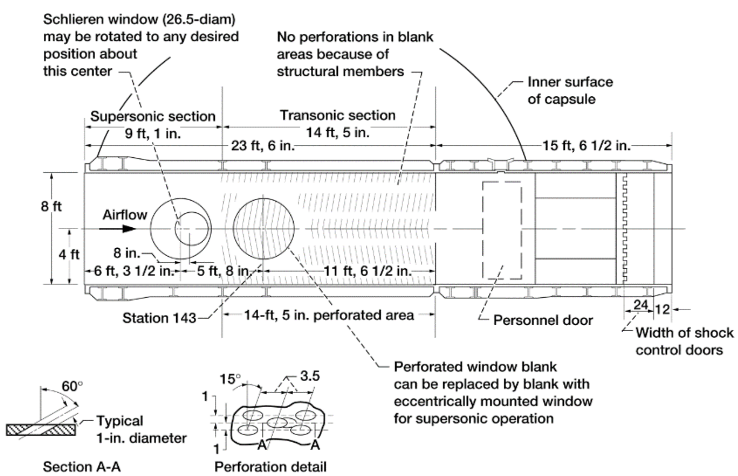

Figure 2: Elevation view of the 8- by 6-Foot Supersonic Wind Tunnel test section.

B. Characterization Tests (1996/1997 and 2019)

The 8x6 SWT was calibrated in 1996 and 1997 [3] which provided relationships between facility reference measurements and the average test section static pressure ($P_{S,ts}$), total pressure ($P_{T,ts}$), post-normal shock total pressure ($P_{T,2,ts}$), and total temperature ($T_{T,ts}$). A similar 8x6 SWT test section characterization test was performed in 2019 following significant facility modifications and upgrades, primarily to the back leg of the wind tunnel and the 9- by 15-Foot Low Speed Wind Tunnel [4]. Test section calibration data are collected using a 4-inch-diameter cone cylinder model and the transonic array. The 4-inch-diameter cone cylinder is comprised of a 10° half-angle cone with a 4-inch base diameter and a constant-diameter cylinder section. The model has a total length of 86 inches from cone tip to aft end of the cylinder and has static taps in four streamwise rows: two of 51 static taps each, two of 15 static taps each (Figure 3).

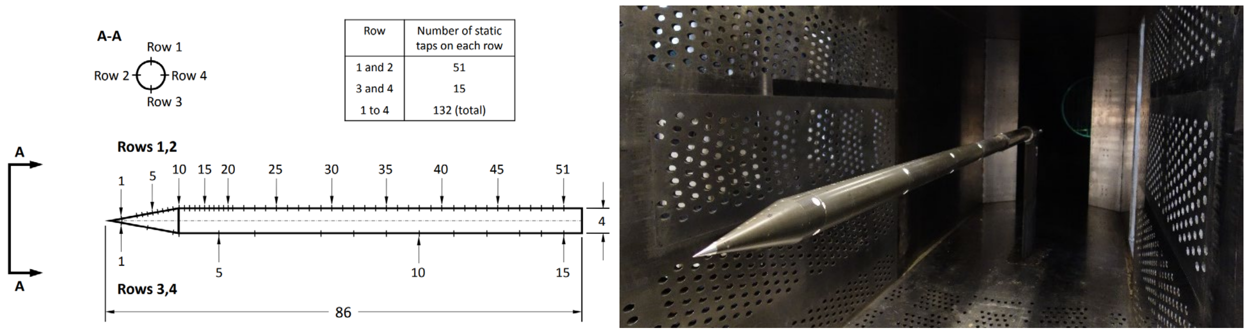

Figure 3: Instrumentation diagram (left) and installation photo (right) of the 4-inch-diameter cone cylinder in the 8- by 6-Foot Supersonic Wind Tunnel.

The transonic array consists of 6 pitot-static probes, 5 five-hole flow angularity probes, and 11 thermocouple probes (Figure 4). The array attaches to the tunnel walls, the tunnel floor via a rigid vertical support, and sting mounts to the transonic strut. Calibration data were acquired with the array at test section centerline, however, the array can be manually moved 12 and 24 inches above and below centerline. The axial position of the array can also be varied; the array probe tips are typically placed at test section station 138.4 for calibration of 14-ft test section porosity configurations.

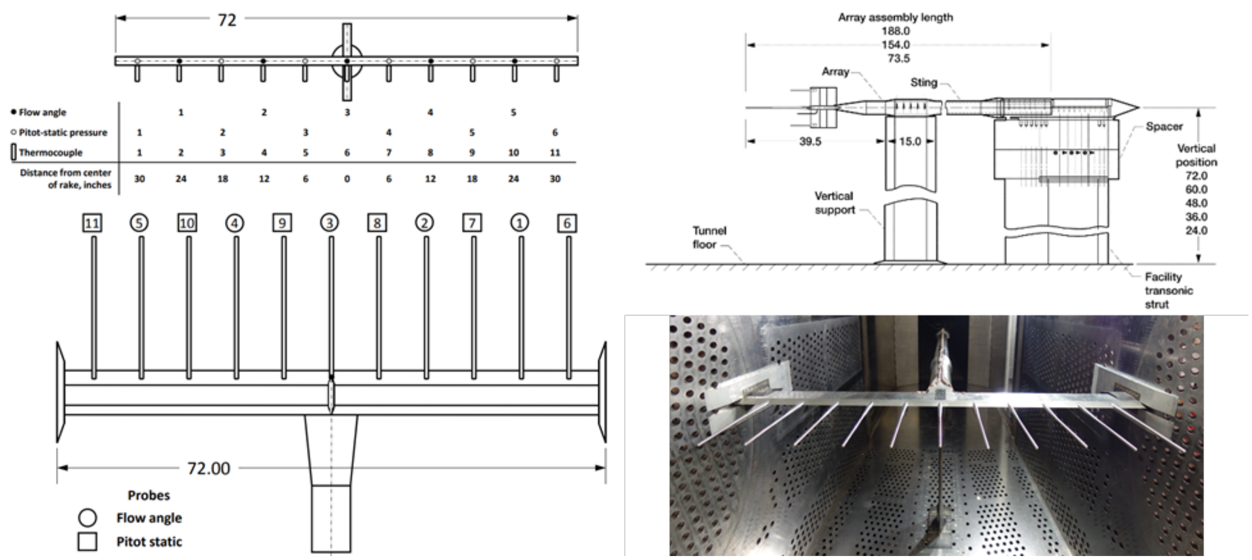

Figure 4: Instrumentation diagram (left), typical installation (top right), and installation photo at test section centerline (bottom right) of the transonic array in the 8- by 6-Foot Supersonic Wind Tunnel.

IV. Implementing Recommendations from Uncertainty Analysis

Aside from quantification of the uncertainty in calibrated test section conditions, such as test section Mach number (M_{ts}), the Monte Carlo simulations used by the MUA team have the potential to explore the sources/contributors to the uncertainty values. These were commonly referred to as "what if" scenarios which allow for evaluation of methods to reduce the contribution of the primary sources of uncertainty in various parameters. Collaboration between the MUA team and wind tunnel characterization team allowed for implementation of these ideas into the 2019 full characterization test entry. The following sections describe some of the more prominent changes made which impacted the uncertainty estimates of primary variables of interest.

A. Improved Random Uncertainty Estimation

During previous calibrations of the 8x6 SWT, such as in the 1990's, test conductors typically took three back-to-back samples of the flow field. Because this is what was available at the time, the MUA team utilized these three data points in estimates of random uncertainty of tunnel conditions. As the understanding of repeatability and their associated timescales developed within the facility, it became evident that this random uncertainty estimate was likely not representative of true within-test repeatability that a customer may encounter throughout a test program at the facility. A recommendation from the MUA team was to acquire at least three repeats of a given condition while ensuring the tunnel and all tunnel controls required to set the tunnel condition of interest were brought to a different condition prior to returning to the condition of interest.

During the 2019 characterization of the 8x6 SWT, Mach number conditions spanning the subsonic operating envelope were repeated three times throughout the entry so that random uncertainty could be estimated as a function of facility setpoint. For estimation of random uncertainty at supersonic conditions, a different approach was used. The flexwall contour is defined at discrete settings using "flats" machined into the cams which dictate the wall position at a given streamwise position within the flexwall. Each of these flexwall contours can be perceived as a unique configuration of the tunnel to produce a given flow in the test section, therefore each flexwall setting must be repeated to estimate its own random uncertainty for the variables of interest. Each of the nominal flexwall settings, Mach 1.1 to 2.0 in 0.10 increments, were repeated three times throughout the test entry while ensuring both flexwall and balance chamber pressure changes were made before returning to the condition of interest. This mode of operation increases the test time required to perform a characterization test, however, it is a valuable piece of information that must be acquired to ensure a proper combined uncertainty estimate can be generated for calibrated test section variables of interest.

B. Thermocouple Replacements

The transonic array and bellmouth rakes upstream of the 8x6 SWT flexwall used standard-grade Type-K thermocouples during the 1996/97 characterization test entry. The cable runs for these thermocouples included multiple connections prior to termination at a thermocouple reference junction. During test planning efforts for an internal customer test entry, temperature uncertainty in the facility became a primary variable of interest as it directly impacted the success of the program. In 2016, the transonic array thermocouple probes were removed and repopulated with special-limit-of-error Type E (commonly referred to as EEE) wires which were 75 feet long each. The bellmouth rake thermocouples were replaced with the same wire and 100-foot lengths. The length of the wire allowed for the thermocouples to be run from the probe to the terminations at the thermocouple reference junction without intermediate connections. The benefits of this investment in thermocouple accuracy were evident in the 2019 characterization test entry's uncertainty estimates, as will be discussed.

C. Look-up Table Approach to Calibration Models

During the 1996/97 calibration, a single regression model was used to predict test section static pressure collected across the facility operating range, including data at subsonic and supersonic conditions. This was similarly done for total temperature, relating test section total temperature to bellmouth total temperature. Stagnation pressure had a regression model for subsonic operation, relating test section total pressure directly to bellmouth total pressure. Another model was used for supersonic operation as it was necessary to relate the measured post-normal-shock total pressure normalized by bellmouth total pressure ($P_{T,2,ts} / P_{T,bm}$) to the ratio of the static pressure in the balance chamber to bellmouth total pressure ($P_{S,bal} / P_{T,bm}$) [3].

The uncertainty analysis from the 1996/97 calibration revealed that the regression models used to predict calibrated test section variables were typically the leading contributor to the variables' systematic uncertainty. The regression models which span either the full operating range of the facility (i.e., Mach 0.25 to 2.0) or the entire supersonic operating range of the facility (i.e., Mach 1.1 to 2.0) are considered generalized models in this paper. As mentioned previously, the 8x6 SWT flexwall contour moves between discrete positions dictated by the "flats" machined on the cams used to position the walls along their length. This discrete nature of the flexwall operation and the repeatability of contours from the existence of the "flats" led the tunnel characterization team to pursue unique, localized regression models for each of the flexwall settings. For each nominal flexwall setting, there is a single, nominal ratio of balance chamber static to bellmouth total pressure, $P_{S,bal} / P_{T,bm}$, which is set to achieve optimal flow quality through the test section. However, there are instances where the balance chamber pressure may change or be varied intentionally. During the 2019 test entry, surveys were conducted at off-nominal ratios of $P_{S,bal} / P_{T,bm}$ to generate localized regression models around each nominal set condition. The change from generalized models to localized models played a large role in reducing calibrated test section variables' uncertainties at supersonic operating conditions.

Another source of change in the regression models was the form of the response and predictor variables chosen. The concept of normalizing variables of interest by bellmouth stagnation conditions was applied to all calibrated variables to remove atmospheric condition variation from the models. With the use of normalized response variables, this allows for the ratio $P_{S,bal} / P_{T,bm}$ to be the predictor variable across all regression models. The changes made to the regression models between the 1996/97 calibration and the 2019 test entry are summarized qualitatively in Table 1, and the regression models can be seen in more detail in Ref. [3] and [4].

Table 1: Comparison of regression model formats and uses between the 1996/97 and 2019 characterization test results in the 8- by 6-Foot Supersonic Wind Tunnel.

	Characterization Test Entry	
Regression Models	1996/97	2019
Static Pressure, $P_{S,ts}$	Single model, includes subsonic & supersonic conditions.	Separate subsonic model, and localized supersonic models at each flexwall condition with corrections at nominal settings.
	$P_{S,ts} / P_{T,bm} = f(P_{S,bal} / P_{T,bm})$	
Total Pressure, $P_{T,ts}$	Subsonic conditions only.	
	$P_{T,ts} = f(P_{T,bm})$	$P_{T,ts} / P_{T,bm} = f(P_{S,bal} / P_{T,bm})$
Post-normal-shock total pressure, $P_{T,2,ts}$	Single model, includes all supersonic conditions.	Localized supersonic models at each flexwall condition.
	$P_{T,2,ts} / P_{T,bm} = f(P_{S,bal} / P_{T,bm})$	
Total Temperature, $T_{T,ts}$	Single model, includes all supersonic conditions.	Separate subsonic model, and localized supersonic models at each flexwall condition.
	$T_{T,ts} = f(T_{T,bm})$	$T_{T,ts} / T_{T,bm} = f(P_{S,bal} / P_{T,bm})$

V. MUA Improvements

The results shown here include uncertainty analysis results for several Variables of Interest (VOI) from the 2016 8x6 SWT uncertainty analysis [2] and the 2022 uncertainty update [7]. Each VOI is treated as univariate. Results are presented as expanded uncertainties with a coverage factor of k = 2, which is approximately equal to a 95% level of confidence. Uncertainty Percent Contribution charts (UPC) are included for some VOIs. UPC charts provide insight into the contributions of each uncertainty source to the overall systematic uncertainty of the VOI.

In the 2019 characterization test entry, the use of unique, localized regression models for each flexwall setting resulted in improvements to the overall uncertainty for many of the VOIs at the 8x6 SWT. The uncertainty analysis of this new calibration strategy reveals a significant reduction in the systematic uncertainty of the test section static and total pressures when localized regression models are used, as shown in Figure 5 and Figure 6, respectively. The uncertainty results for the generalized regression models are very similar for the 2016 and 2019 analyses, showing no significant difference. However, systematic uncertainty is significantly reduced with the use of localized curve fits. The static pressure uncertainty is further reduced when a local static pressure correction is also applied.

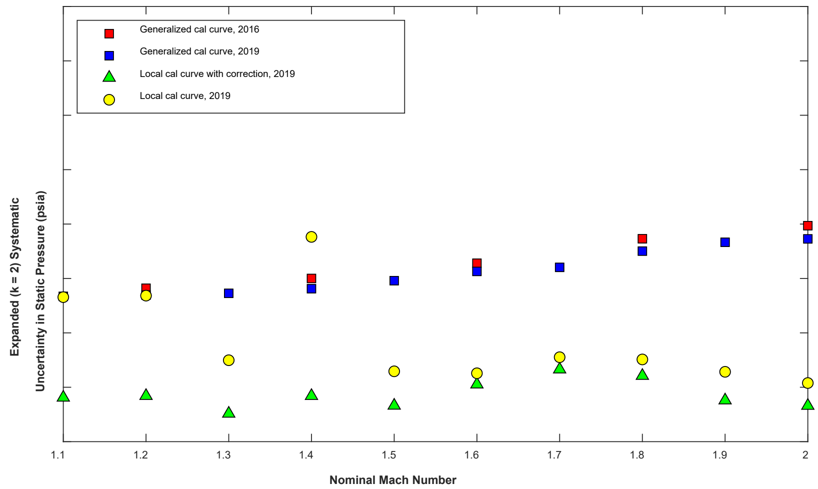

Figure 5: Test section static pressure uncertainty improvements

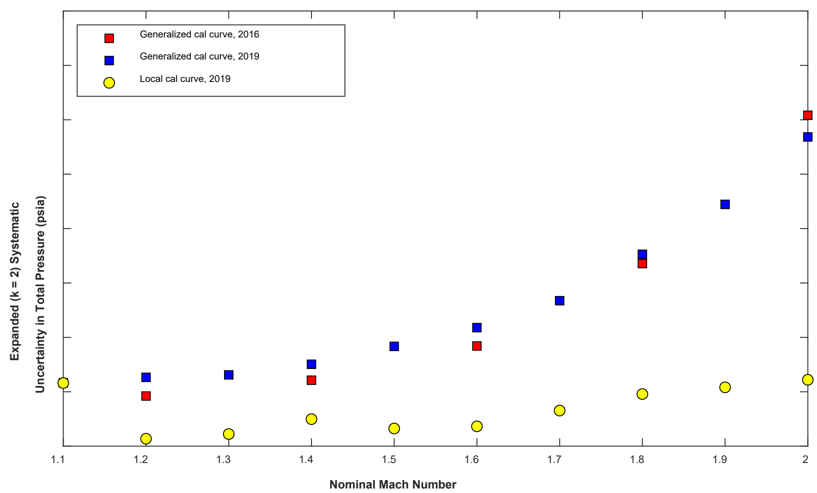

Figure 6: Test Section total pressure uncertainty comparison

In the 8x6 SWT, the calculation of Mach number is primarily a function of static and total pressure. The specific heat ratio for air, as well as gas constants used in the data reduction scheme are assumed to have negligible uncertainty contributions. Consequently, significant reductions in the uncertainty of static and total pressure result in significant reduction in Mach number uncertainty as shown in Figure 7. This improvement is most notable at the higher end of the Mach range of the 8x6 SWT, where there is nearly an order of magnitude reduction in Mach number uncertainty.

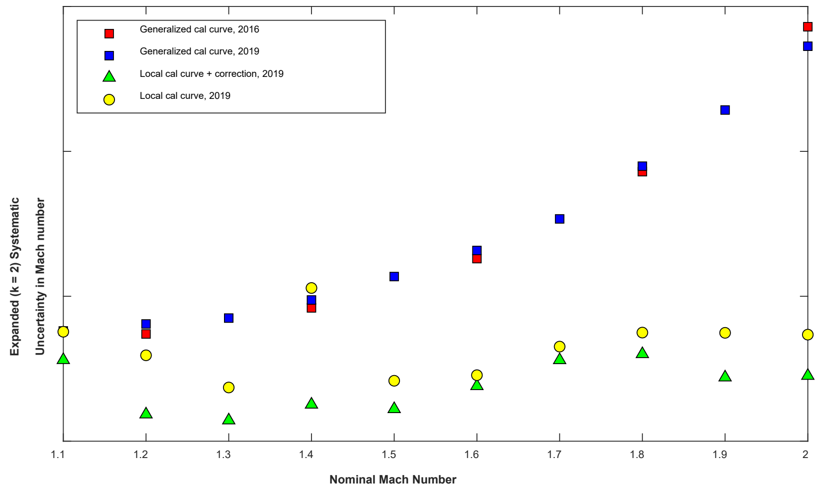

Figure 7: Test Section Mach number uncertainty comparison

Uncertainty in test section total temperature is shown in Figure 8. These results show a significant reduction, overall, in test section total temperature uncertainty following the 2019 characterization test entry. However, the uncertainty increases slightly when local regression models are used to calculate test section total temperature. This is due to two loosely related effects: uncertainty related to the calibration test that was fossilized into the calibration curve fit and the error propagation through the data reduction scheme.

The UPC chart in Figure 9, shows the source uncertainty percent contributions in the calculation of test section total temperature. The chart shows bellmouth total temperature to be the largest contributor to the uncertainty. This means that the instrumentation used to make the temperature measurements has a dominant contribution to the systematic uncertainty. For comparison, the systematic uncertainty in the temperature measurement instrumentation contributed nearly 70-75% of the total temperature uncertainty estimates from the 1996/97 data set [1]. Prior to the 2019 calibration, the temperature measurement system wiring was upgraded (Section II.B). This upgrade reduced the instrumentation uncertainty which resulted in a significant decrease in the systematic uncertainty of the calculated test section total temperature.

Uncertainty in the test section total temperature prediction is also increased when localized regression models are used in the calculation. When the localized regression model is looked at in detail, it is observed that the linear relationship between the response variable (ratio of average test section total temperature to average bellmouth total temperature) and the predictor variable (ratio of average balance chamber static pressure to average bellmouth total pressure) is not statistically significant. Therefore, when the local regression models are applied, the corrections do not improve the total temperature prediction. However, the regression models have their own uncertainty that must be propagated through the calculation, resulting in the increase in overall temperature uncertainty when the corrections are applied.

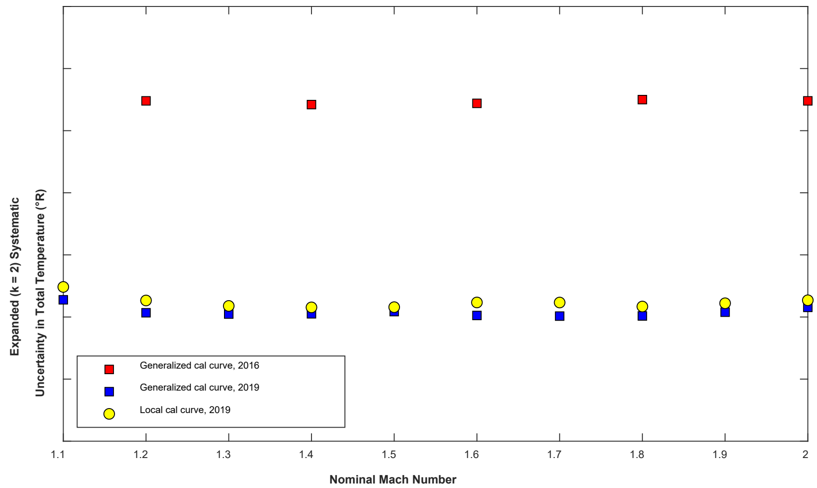

Figure 8: Test section total temperature uncertainty comparison

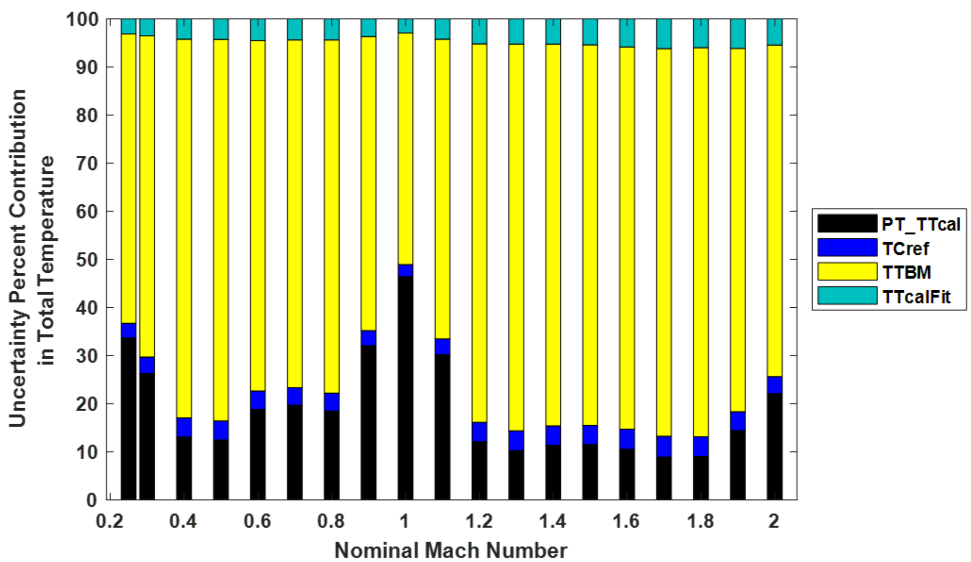

Figure 9: UPC for test section total temperature using localized curve fits (2019 test entry).

VI. Conclusion

The effort put forth by the wind tunnel characterization and MUA teams at the NASA Glenn Research Center has shown the value of a rigorous "bottom-up" approach to uncertainty estimation. Through analysis of primary contributors to uncertainties in test section conditions, methods were proposed and implemented in future facility characterizations, which resulted in significant reductions to systematic uncertainties in the 8- by 6-Foot Supersonic Wind Tunnel. The center shall continue the effort of continuously updating the estimated uncertainties and their primary contributors within the center's wind tunnels and other ground-test facilities to take advantage of opportunities for well-directed investments in test technology, processes, instrumentation, and wind tunnel characterization practices.

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