



Measurement Accuracy and Uncertainty Analysis of the X-59 Air Data Probe Calibration Test Entry One

David J. Friedlander
Glenn Research Center, Cleveland, Ohio

Michael D. Bozeman, Alaa A. Elmiligui, Jeffrey D. Flamm, Lee J. Mears, and Courtney S. Winski
Langley Research Center, Hampton, Virginia

Kurtis R. Long
Ames Research Center, Moffett Field, California

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., “quick-release” reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Fax your question to the NASA STI Information Desk at 757-864-6500
- Telephone the NASA STI Information Desk at 757-864-9658
- Write to:
NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199



Measurement Accuracy and Uncertainty Analysis of the X-59 Air Data Probe Calibration Test Entry One

David J. Friedlander
Glenn Research Center, Cleveland, Ohio

Michael D. Bozeman, Alaa A. Elmiligui, Jeffrey D. Flamm, Lee J. Mears, and Courtney S. Winski
Langley Research Center, Hampton, Virginia

Kurtis R. Long
Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

The authors would like to thank the NASA Integrated Aviation Systems Program, Low Boom Flight Demonstrator Project for funding. The authors would also like to thank Russel Stucke for data acquisition and post-processing guidance, Erin Hubbard for the calibrated test section uncertainty analysis guidance, and Kenneth Toro for assistance in performing the uncertainty analysis of the probe angles.

This work was sponsored by the Integrated Aviation Systems Program at the NASA Glenn Research Center.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

Measurement Accuracy and Uncertainty Analysis of the X-59 Air Data Probe Calibration Test Entry One

David J. Friedlander
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Michael D. Bozeman, Alaa A. Elmiligui, Jeffrey D. Flamm,
Lee J. Mears, and Courtney S. Winski
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23681

Kurtis R. Long
National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

Abstract

The X-59 is being developed to demonstrate quiet sonic boom technology. Data was obtained via two test entries in the NASA Glenn Research Center's 8- by 6-Foot Supersonic Wind Tunnel to calibrate the X-59's nose air data probe. The first entry tested two theoretically identical probes with the intention of one of the probes becoming the primary X-59 nose air data probe flight hardware and the other becoming a backup. A measurement accuracy and uncertainty analysis was performed on data obtained from the first test entry. The analysis showed that the uncertainties in the probe pressures were nearly identical for the two probes, with an average difference of 2.51×10^{-5} for the nondimensional total pressure and 2.88×10^{-5} for the nondimensional static pressures. The analysis also showed that the uncertainty in the probe yaw and pitch angles were 0.00034° and 0.01416° , respectively. This gives confidence in the X-59's flight air data system.

1.0 Nomenclature

FM	forces matrix
M	Mach number
MM	moments matrix
p, p_t	static and total pressure
RM	rotation matrix
rFM	final rotated forces matrix
rMM	final rotated moments matrix
T, T_t	static and total temperature
TM	transfer matrix
U	uncertainty
x, y, z	cartesian coordinates
β	yaw angle

γ	ratio of specific heats
θ	pitch angle
φ	roll angle

Subscripts

AoA	angle of attack
AoS	angle of side-slip
DS	downstream of the normal shock
i	array index
measured	measured quantity
TS	wind tunnel test section
US	upstream of the normal shock
uncorrected	uncorrected quantity
2	probe upper AoA pressure
3	probe forward looking aft left AoS pressure
4	probe lower AoA pressure
5	probe forward looking aft right AoS pressure
6	probe static pressure

Superscripts

*	nondimensional
---	----------------

2.0 Introduction

The Concorde was a marvel of its day, becoming the first supersonic commercial aircraft to fly the skies. The Concorde fleet flew for 27 years before being retired in 2003. One of the draw backs of the Concorde was that its sonic booms were loud and destructive, which is why the United States banned commercial supersonic flights over its territories. Despite the ban (Ref. 1), there is a growing interest within the aviation industry to bring back commercial supersonic flights (Refs. 2 to 4). Because of this interest, NASA has spent the past several years investing in quiet sonic boom technology and has commissioned the X-59 to demonstrate that a quiet sonic boom can be achieved (Ref. 5). To gauge whether the X-59's sonic boom is at acceptable noise levels, the aircraft will be flown over select communities to gather community response data to be delivered to the U.S. and international regulators (Ref. 5). Early vehicle design focused on reducing the sonic boom signature loudness by using a set of computational tools, which led to a preliminary design becoming a test case for the 3rd AIAA Sonic Boom Prediction Workshop (Refs. 6 to 8). As the vehicle development matured from design to manufacturing, the details of the instrumentation became important. One such piece of instrumentation was the X-59's nose air data probe. The probe would be the primary source of information for computing the aircraft's airspeed, pressure altitude, angle of attack (AoA), and angle of sideslip (AoS). A Rosemount Collins 857CK multifunction air data probe was chosen as the baseline nose probe for the X-59. The specific probe was chosen per the recommendation of Rosemount Collins based on the X-59's mission requirements. Two wind tunnel test entries were performed at the NASA Glenn Research Center's 8- by 6-Foot Supersonic Wind Tunnel (SWT) (Ref. 9) to calibrate both the primary and backup probes. One

reason the 8- by 6-Foot SWT was chosen for the calibration tests was that it is an atmospheric tunnel that has the capability to run at the Mach numbers relevant to the X-59, such as sea level take-off and landing (Mach 0.2), subsonic cruise (Mach 0.9), and supersonic cruise (Mach 1.4). The second test entry was required as an unusual trend in the probe static pressure was seen around the aircraft's supersonic cruise Mach number. Data was successfully obtained from the wind tunnel test entries at Mach numbers ranging from 0.25 to 1.66 and when combined with computational fluid dynamics data, allowed for the derivation of the probe calibration curves (Ref. 10). It is important to understand how the measurement accuracy and uncertainties from the experimental data impact the computed quantities of interest in the calibration curves to demonstrate confidence in the air data system for safety of flight. This paper discusses the measurement accuracy and uncertainty analysis of the data obtained from the first test entry, with all uncertainties quoted at the 95 percent confidence level (i.e., two sigma).

3.0 Test Hardware

3.1 Multifunction Nose Probe

A Rosemount Collins 857CK multifunction air data probe was chosen as the baseline nose probe for the X-59. The probe measures total pressure, a four-port manifolded static pressure, two independent AoA pressures, and two independent AoS pressures. The locations of the pressure ports are depicted in Figure 1. The test entries obtained data from two theoretically identical probes (probe A and probe B) with the intention of one becoming the primary X-59 nose probe flight hardware while the other one would be a backup. The determination of which probe was to be the primary and which one was to be the backup was unknown prior to the test entries.

3.2 Setup

The hardware used in the calibration tests included the multifunction nose probe(s), a probe sting, and the NASA Ames Research Center's small model roll mechanism (SMRM). These in turn were attached to the wind tunnel supersonic strut. A photograph of the setup with the test components labelled is shown in Figure 2. The two multifunctional probes were tested independently of each other, as shown in Figure 2. Further information on the test set up and the installed hardware can be found in Reference 11.

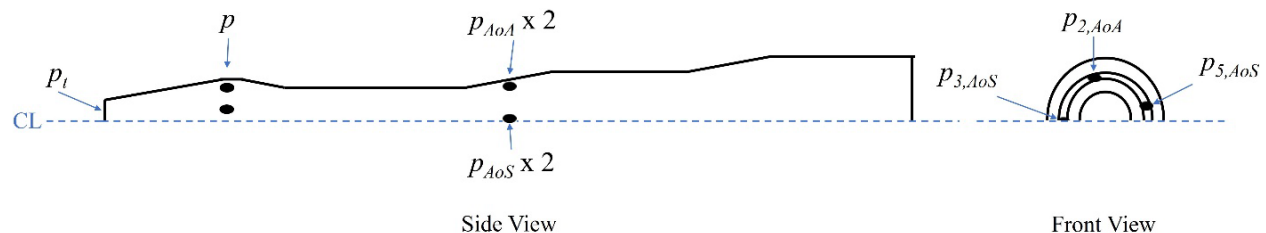


Figure 1.—Probe pressure port locations. For simplicity, the static and total pressure ports are omitted from the front view (not to scale).

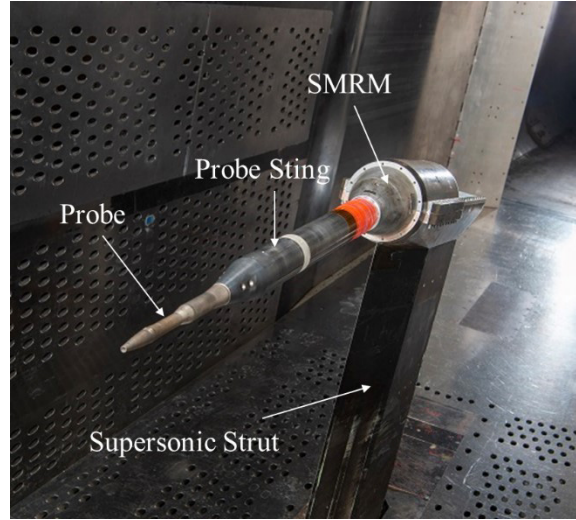


Figure 2.—Photograph of the test hardware installed in the test section with the components labelled.

4.0 Calibrated Test Section Analysis

One source of uncertainty for the probe calibration tests was the measured quantities from the wind tunnel facility. To help reduce this uncertainty, test section static pressure, total pressure, and total temperature were acquired during one of the latest 8- by 6-Foot SWT calibrations (Ref. 12). The pressure measurements were made using Electronically Scanned Pressure (ESP) modules that had a range of ± 15 psid with a quoted accuracy of ± 0.0075 psi. This equates to an uncertainty in the pressure measurements of 0.005 psi (without accounting for thermal effect) or 0.0092 psi (including for thermal effects)¹. Both values are listed here as there was an initial concern regarding thermal effects at the higher Mach numbers tested. The temperature measurements were made using K-type and E-type thermocouples with measurement uncertainties of ± 1.98 R for the K-type and ± 1.80 R for the E-type¹. The calibrated test section Mach numbers were calculated per Equation (1) for the subsonic regime and Equation (2) for the supersonic regime (Ref. 13), both of which used the measured test section static and total pressures.

$$\frac{p_{t,TS}}{p_{TS}} = \left[1 + \left(\frac{\gamma-1}{2} M_{TS}^2 \right) \right]^{\gamma/(\gamma-1)} \quad (1)$$

$$\frac{p_{t,TS,DS}}{p_{TS,US}} = \left[\frac{(\gamma+1)M_{TS,US}^2}{2} \right]^{\gamma/(\gamma-1)} \left[\frac{\gamma+1}{(2\gamma M_{TS,US}^2) - (\gamma-1)} \right]^{1/(\gamma-1)} \quad (2)$$

where $\gamma=1.4$.

The computed systematic uncertainties for the calibrated test section Mach number, static pressure, total pressure, and total temperature are presented in Table I as a function of the calibrated test section Mach number (Ref. 14). The table only shows information for the calibrated test section Mach numbers that were of interest to the wind tunnel test. Two of the calibrated test section Mach numbers of interest were not included in Reference 14. This is because both the random and systematic uncertainties were not available at those calibrated test section Mach numbers. For estimation purposes, this paper computed the systematic uncertainties at a calibrated test section Mach number of 0.85 via linear interpolation while the computed systematic uncertainties at a calibrated test section Mach number of 0.95 used the calibrated

¹Private communication

TABLE I.—UNCERTAINTIES IN THE CALIBRATED TUNNEL PARAMETERS (REF. 14)

M_{TS}	$U_{M_{TS}}$	$U_{p_{TS}},$ psi	$U_{p_{t,TS}},$ psi	$U_{T_{t,TS}},$ R
0.25	0.0013	0.0066	0.0048	1.17
0.40	0.0009	0.0062	0.0038	1.02
0.50	0.0007	0.0062	0.0034	1.04
0.60	0.0006	0.0065	0.0040	1.06
0.70	0.0006	0.0064	0.0034	1.08
0.80	0.0006	0.0064	0.0043	1.05
0.85	^a 0.0006	^a 0.0066	^a 0.0047	^a 1.11
0.90	0.0006	0.0067	0.0051	1.17
0.95	^b 0.0006	^b 0.0067	^b 0.0051	^b 1.17
1.07	0.0039	0.0267	0.0590	1.14
1.19	0.0040	0.0269	0.0633	1.03
1.25	0.0043	0.0274	0.0658	1.03
1.35	0.0049	0.0281	0.0753	1.03
1.45	0.0057	0.0297	0.0927	1.05
1.55	0.0066	0.0313	0.1764	1.01
1.66	0.0077	0.0322	0.1332	1.01

^aLinear interpolated value, independent of Reference 14.^b $M_{TS} = 0.90$ uncertainties used as a surrogate.

test section Mach number 0.90 uncertainty values as a surrogate. The reason for using the surrogate in lieu of linear interpolation is because the systematic uncertainties show a step increase when going from subsonic to supersonic that would yield an unrealistic value for the systematic uncertainties at the calibrated test section Mach number of 0.95.

5.0 Probe Pressures Analysis

Another source of uncertainty for the probe calibration tests was the probe itself. This section discusses the accuracy and uncertainty of the probe pressure measurements while Section 6.0 discusses the accuracy and uncertainty of the probe orientation with respect to the wind tunnel. The probe pressures were measured using the ESP modules described in the previous section. Table II to Table VII show the computed uncertainties for the nondimensional probe total and static pressures as a function of the calibrated test section Mach number. The nondimensional probe total pressures shown in Table II were nondimensionalized by the downstream calibrated total pressure when $M_{TS} > 1$. The values quoted in the tables are for data at a θ_{measured} and φ_{SMRM} of zero degrees and were nondimensionalized by their respective calibrated tunnel pressure. The uncertainties were computed using the standard deviation approach for computing uncertainties (Ref. 15), as demonstrated in Equation (3) to (6).

$$p_t^* = \frac{p_t}{p_{t,TS}} \quad (3)$$

$$U_{p_t^*} = p_t^* \sqrt{\left(\frac{U_{p_t}}{p_t}\right)^2 + \left(\frac{U_{p_{t,TS}}}{p_{t,TS}}\right)^2} \quad (4)$$

$$p^* = \frac{p}{p_{TS}} \quad (5)$$

$$U_{p^*} = p^* \sqrt{\left(\frac{U_p}{p}\right)^2 + \left(\frac{U_{p_{TS}}}{p_{TS}}\right)^2} \quad (6)$$

where

$$U_{p_t} = U_p = 0.0092 \text{ psi} \quad (7)$$

From Table II to Table VII it can be seen that the uncertainty in the nondimensional pressures generally increases with increasing calibrated test section Mach number, with a maximum uncertainty of 9.73×10^{-3} for the nondimensional total pressure and 9.98×10^{-3} for the nondimensional static pressures. As expected, there is a step increase in the uncertainties between calibrated test section Mach numbers of 0.95 and 1.07. The step increase in the uncertainty is present because the nondimensionalization scheme used the calibrated test section pressures, who's uncertainties also showed a step increase. Table II to Table VII also reveal that the uncertainties in the nondimensional pressures are nearly identical between the two probes, with an average difference of 2.51×10^{-5} for the nondimensional total pressure and 2.88×10^{-5} for the nondimensional static pressures. The two probes are statistically the same because (1) the average differences in the uncertainties are nearly identical and (2) the average differences in the uncertainties are nearly two orders of magnitude lower than the maximum nondimensional probe pressure uncertainties.

TABLE II.—UNCERTAINTIES IN THE NORMALIZED
AIR DATA PROBE TOTAL PRESSURE (p_t^*)

M_{TS}	$U_{p_t^*} (\times 10^{-3})$	
	Probe A	Probe B
0.25	0.68	0.67
0.40	0.60	0.59
0.50	0.60	0.60
0.60	0.57	0.57
0.70	0.56	0.56
0.80	0.59	0.58
0.85	0.61	0.61
0.90	0.62	0.62
0.95	0.63	0.63
1.07	3.46	3.41
1.19	3.69	3.63
1.25	3.82	3.79
1.35	4.29	4.32
1.45	5.17	5.09
1.55	9.73	9.72
1.66	7.27	7.17

TABLE III.—UNCERTAINTIES IN THE NORMALIZED
AIR DATA PROBE STATIC PRESSURE (p_s^*)

M_{TS}	$U_{p_s^*} (\times 10^{-3})$	
	Probe A	Probe b
0.25	0.77	0.77
0.40	0.74	0.73
0.50	0.80	0.80
0.60	0.81	0.81
0.70	0.88	0.87
0.80	0.97	0.96
0.85	1.05	1.04
0.90	1.11	1.10
0.95	1.18	1.18
1.07	3.18	3.13
1.19	3.87	3.81
1.25	4.05	4.02
1.35	4.89	4.89
1.45	5.40	5.33
1.55	6.36	6.38
1.66	7.50	7.39

TABLE IV.—UNCERTAINTIES IN THE
NORMALIZED AIR DATA PROBE
UPPER AoA PRESSURE (p_2^*)

	$U_{p_2^*} (\times 10^{-3})$	
M_{TS}	Probe A	Probe A
0.25	0.77	0.77
0.40	0.74	0.73
0.50	0.81	0.81
0.60	0.83	0.83
0.70	0.90	0.89
0.80	1.00	1.00
0.85	1.09	1.08
0.90	1.17	1.17
0.95	1.25	1.26
1.07	3.88	3.82
1.19	4.73	4.66
1.25	5.17	5.13
1.35	6.06	6.05
1.45	7.19	7.10
1.55	8.33	8.35
1.66	9.96	9.82

TABLE V.—UNCERTAINTIES IN THE NORMALIZED
AIR DATA PROBE FORWARD LOOKING
AFT LEFT AoS PRESSURE (p_3^*)

	$U_{p_3^*} (\times 10^{-3})$	
M_{TS}	Probe A	Probe B
0.25	0.77	0.77
0.40	0.74	0.73
0.50	0.81	0.81
0.60	0.83	0.83
0.70	0.90	0.89
0.80	1.00	1.00
0.85	1.09	1.08
0.90	1.16	1.16
0.95	1.25	1.25
1.07	3.87	3.81
1.19	4.71	4.64
1.25	5.16	5.12
1.35	6.06	6.06
1.45	7.24	7.15
1.55	8.31	8.33
1.66	9.97	9.83

TABLE VI.—UNCERTAINTIES IN THE
NORMALIZED AIR DATA PROBE
BOTTOM AoA PRESSURE (p_4^*)

	$U_{p_4^*} (\times 10^{-3})$	
M_{TS}	Probe A	Probe B
0.25	0.77	0.77
0.40	0.74	0.73
0.50	0.81	0.81
0.60	0.83	0.83
0.70	0.90	0.89
0.80	1.00	0.99
0.85	1.09	1.08
0.90	1.16	1.16
0.95	1.25	1.25
1.07	3.87	3.81
1.19	4.73	4.66
1.25	5.15	5.10
1.35	6.05	6.05
1.45	7.28	7.18
1.55	8.31	8.33
1.66	9.98	9.84

TABLE VII.—UNCERTAINTIES IN THE NORMALIZED
AIR DATA PROBE FORWARD LOOKING
AFT RIGHT AoS PRESSURE (p_5^*)

	$U_{p_5^*} (\times 10^{-3})$	
M_{TS}	Probe A	Probe B
0.25	0.77	0.77
0.40	0.74	0.73
0.50	0.81	0.81
0.60	0.83	0.82
0.70	0.90	0.89
0.80	1.00	0.99
0.85	1.09	1.08
0.90	1.16	1.16
0.95	1.25	1.25
1.07	3.87	3.80
1.19	4.73	4.66
1.25	5.16	5.11
1.35	6.03	6.03
1.45	7.18	7.08
1.55	8.25	8.27
1.66	9.93	9.79

6.0 Probe Orientation Analysis

The probe roll angle was measured using an Avago Technologies HEDL-5540 encoder, which when installed in the SMRM, was measured to have 51700 encoder counts per SMRM revolution². This equates to an accuracy of 0.007°. However, due to slop within the SMRM, the actual uncertainty in the roll angle was 0.2°. The slop within the SMRM was measured using an Angle Measurement System. The probe pitch angle was measured using a Q-FLEX QA-2000 accelerometer, with a quoted accuracy of 0.005°. The Q-FLEX calibration used in the experiment utilized the coefficients that came with the Q-FLEX along with two offset values. The first offset value was derived from comparing the QA-2000 accelerometer measurement with a measurement taken by a Wyler Clino 2000 digital inclinometer. The digital inclinometer had a quoted accuracy defined by Equation (8) (Ref. 16).

$$U_{Wyl\text{er}} = (0.027 \times \text{Reading}) + (12/3600) \quad (8)$$

The second Q-FLEX calibration offset value was derived from comparing the QA-2000 accelerometer measurement with a measurement taken by the Angle Measurement System (AMS), with the AMS measurement having an uncertainty of 0.01°. Propagating these uncertainties yields the uncertainties in the computed probe yaw and pitch angles shown in Table VIII. These values were computed by first defining the forces, moments, rotation, and transfer matrices, as defined by Equations (9) to (12).

$$FM = [0 \quad \theta_{\text{measured}} \quad YAWCORR] \quad (9)$$

$$MM = [0 \quad 0 \quad 0] \quad (10)$$

$$RM = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi_{SMRM}) & \sin(\varphi_{SMRM}) \\ 0 & -\sin(\varphi_{SMRM}) & \cos(\varphi_{SMRM}) \end{bmatrix} \quad (11)$$

$$TM = \begin{bmatrix} 0 & z & -y \\ -z & 0 & x \\ y & -x & 0 \end{bmatrix} \quad (12)$$

where $YAWCORR$ is the corrected measured probe yaw angle and φ_{SMRM} is the measured SMRM roll angle. Given that $x = y = z = 0$, the intermediate rotation matrix $MXFER$ and the rotation corrected moments matrix $MMRC$ were computed by Equation (13) and (14).

$$MXFER = (FM) (TM) = [0 \quad 0 \quad 0] \quad (13)$$

$$MMRC = MM + MXFER = [0 \quad 0 \quad 0] \quad (14)$$

Given that $YAWCORR = 0$, the final rotated forces and moments matrices were computed by Equation (15) and (16).

$$rFM = (FM)(RM) = [0 \quad \theta_{\text{measured}} \cos(\varphi_{SMRM}) \quad \theta_{\text{measured}} \sin(\varphi_{SMRM})] \quad (15)$$

$$rMM = (MMRC) (RM) = [0 \quad 0 \quad 0] \quad (16)$$

²Private communication

The uncorrected beta and theta angles were computed by Equation (17) and (18).

$$\beta_{\text{uncorrected}} = -rFM_{i=3} = -\theta_{\text{measured}} \sin(\varphi_{SMRM}) \quad (17)$$

$$\theta_{\text{uncorrected}} = rFM_{i=2} = \theta_{\text{measured}} \cos(\varphi_{SMRM}) \quad (18)$$

The corrected beta and theta angles were defined as the uncorrected values plus a delta term. Given that the delta terms were both zero yields Equation (19) and (20).

$$\beta = \beta_{\text{uncorrected}} = -\theta_{\text{measured}} \sin(\varphi_{SMRM}) \quad (19)$$

$$\theta = \theta_{\text{uncorrected}} = \theta_{\text{measured}} \cos(\varphi_{SMRM}) \quad (20)$$

The uncertainties in the yaw and pitch angles were then computed using the standard deviation approach for computing uncertainties, as demonstrated in Equation (21) and (22), where all angles are in radians.

$$U_{\beta} = \sqrt{(-U_{\theta_{\text{measured}}} \sin(\varphi_{SMRM}))^2 + (-U_{\varphi_{SMRM}} \theta_{\text{measured}} \cos(\varphi_{SMRM}))^2} \quad (21)$$

$$U_{\theta} = \sqrt{(U_{\theta_{\text{measured}}} \cos(\varphi_{SMRM}))^2 + (-U_{\varphi_{SMRM}} \theta_{\text{measured}} \sin(\varphi_{SMRM}))^2} \quad (22)$$

where θ_{measured} and φ_{SMRM} were the average values of the scan and $U_{\theta_{\text{measured}}}$ was computed via Equation (23).

$$U_{\theta_{\text{measured}}} = \sqrt{U_{QASTRUT}^2 + U_{PROBE OFF}^2} \quad (23)$$

where

$$U_{PROBE OFF} = \sqrt{U_{QA}^2 + U_{AMS}^2} \quad (24)$$

$$U_{QASTRUT} = \sqrt{U_{QA}^2 + U_{Wylter}^2} \quad (25)$$

TABLE VIII.—UNCERTAINTIES IN
THE PROBE ORIENTATION

Parameter	Value
U_{β}	0.00034°
U_{θ}	0.01416°

7.0 Conclusions

A measurement accuracy and uncertainty analysis was performed on data obtained during the first X-59 Air Data Probe Calibration test entry. The test entry was necessary to aid in the development of the calibration curves for the X-59's primary and backup nose probes. The analysis showed that the two independently tested probes are statistically the same. This was determined as the average difference in the uncertainties between the two probes was minimal and nearly two orders of magnitude lower than the maximum nondimensional probe pressure uncertainties. The importance of this is that it gives confidence that the backup probe will give data consistent with the installed flight nose probe. The analysis also showed that the uncertainties were generally small and within the acceptable range, including the uncertainties in the probe yaw and pitch angles of 0.00034° and 0.01416° , respectively. The overall take-away from this analysis is a strengthened confidence in the flight air data system.

References

1. Civil Aircraft Sonic Boom, 14 C.F.R. § 91.817 2022.
2. McMillin, M., "Spike Aerospace Enlarges Supersonic Jet Development Effort," *The Weekly Business of Aviation*, 26 Jan. 2017, pp. 4.
3. Norris, G., "'Baby Boom' Supersonic Demonstrator Unveiled," *Aviation Daily*, 15 Nov. 2016, pp. 3.
4. Jeong, A., "American Airlines to buy supersonic jets amid clamor for ultra-fast travel," *The Washington Post* [online newspaper], 17 Aug. 2022, URL: <https://www.washingtonpost.com/transportation/2022/08/17/american-airlines-boom-supersonic-jets/> [retrieved 28 March 2023].
5. "Quesst," URL: <https://www.nasa.gov/X59> [retrieved 28 March 2023].
6. "3rd AIAA Sonic Boom Prediction Workshop," URL: <https://lbpw.larc.nasa.gov/sbpw3/> [retrieved 28 March 2023].
7. Alaa, E., Mohagna, P. J., Carter, M. B., Boris, D., and Nayani, S. N., "USM3D Simulations for the Third AIAA Sonic Boom Prediction Workshop," *Journal of Aircraft*, Vol. 59, No. 3, 2022, pp. 647-659.
8. Spurlock, W. M., Aftomis, M. J., and Nemec, M., "Cartesian Mesh Simulations for the Third AIAA Sonic Boom Prediction Workshop," *Journal of Aircraft*, Vol. 59, No. 3, 2022, pp. 708-742.
9. Soeder, R. H., "NASA Lewis 8- By 6-Foot Supersonic Wind Tunnel User Manual," NASA-TM-105771, February 1993.
10. Long, K. T., Winski, C. S., Bozeman, M. D., Elmiligui, A., and Friedlander, D. J., "Neural Net Algorithms Used to Calibrate the X-59 Air Data System Nose Probe Using Wind Tunnel Data," AIAA Paper (to be published).
11. Winski, C. S., Bozeman, M., Elmiligui, A., Long, K., and Friedlander, D., "X-59 Air Data Probe Calibration Wind Tunnel Test," AIAA Paper 2023-4491, June 2023.
12. Johnson, A. M., and Rinehart, D. A., "Characterization of the NASA Glenn Research Center 8- by 6-Foot Supersonic Wind Tunnel (2019 Test)," NASA/CR-2020-5006102, April 2021.
13. Arrington, E. A., Pickett, M. T., and Soeder, R. H., "Baseline Calibration of the NASA Lewis Research Center 8-By 6-Foot Supersonic Wind Tunnel (1991 and 1992 Tests)," NASA/TM-97-107431, January 1998.
14. Poljak, P., "Uncertainty Analysis of the NASA Glenn 8x6 Supersonic Wind Tunnel 2019 Characterization Test: 14-ft, 8.5% Test Section Porosity," NASA/CR-20230002128, March 2023.

15. Lindberg, V., “Uncertainties, Graphing, and the Vernier Caliper,” July 2000, URL: <https://www.geol.lsu.edu/jlorenzo/geophysics/uncertainties/Uncertaintiespart2.html> [retrieved 22 March 2023].
16. “Clino 2000 Precision Inclinometer: Operator’s Manual,” Wyler AG, Winterthur, Switzerland, URL: https://www.wylerag.com/fileadmin/pdf/manuel/man_c20e.pdf [retrieved 28 March 2023].

