X-59 Air Data Probe Calibration Wind Tunnel Test

Courtney S. Winski*, Michael Bozeman†, Alaa Elmiligui‡, Jeffrey Flamm§, Lee Mears¶
NASA Langley Research Center, Hampton, VA 23681, USA

Kurtis Long‖
NASA Ames Research Center, Mountain View, CA 94035, USA

David Friedlander**
NASA Glenn Research Center, Cleveland, OH 44135, USA

NASA aeronautical innovators are working with Lockheed Martin to design and build a supersonic X-plane, the X-59, under the Low Boom Flight Demonstrator (LBFD) Project, that produces a gentle thump rather than a loud sonic boom. The plane will be used by the QueSST mission to collect human response data over select U.S. communities. The data from the X-59 test flights will be provided to U.S. and international regulators to potentially allow supersonic flight over land, drastically reducing travel time within the U.S. and around the world.

Two wind tunnel tests were conducted in the NASA Glenn Research Center (GRC) 8- by 6-Foot Supersonic Wind Tunnel to calibrate the nose probe for the X-59. The probe was successfully tested and calibrated at 19 Mach numbers between Mach 0.25 and Mach 1.7. Most data were collected using continuous roll angle sweeps at a set Mach number and pitch angle. About 725 high quality data runs were recorded during testing to be used in the calibration of the probe. A backup nose probe was also run through the same test matrix as the primary probe.

The probe will be the primary instrument for the flight test of the X-59 for determining angle of attack, angle of sideslip, airspeed, and pressure altitude of the aircraft in flight. Knowing the aircraft's speed and attitude is critical for flight safety and is also critical data for the Quesst mission. Areas of interest for the test were sea level takeoff and landing at Mach 0.2, subsonic cruise at Mach 0.9, and supersonic cruise at Mach 1.4. During Phase I flight testing, the air data nose probe and air data system as a whole will be further calibrated in flight to account for additional installed effects of the airframe on the air data system.

Notice to the Reader - The nose probe on the X-59, including its predicted performance and certain other features and characteristics, is considered commercially sensitive by the manufacturer. To comply with the commercially sensitive restrictions, details such as absolute values have been removed from some plots and figures in this paper. It is the opinion of the authors that despite these alterations, there is no loss of meaningful technical content.

I. Nomenclature

α or alpha	=	Angle of attack, °
β or beta	=	Sideslip angle, °
M_{TS}	=	Test section Mach number
P1 to P6	=	Probe pressures
PAB	=	Average of P2, P3, P4, and P5 pressure data from the nose probe
$P_{S,bal}$	=	Balance chamber static pressure, psia

*Research Aerospace Engineer, Configuration Aerodynamics Branch, Mail Stop 499, AIAA Senior Member.
†Research Aerospace Engineer, Configuration Aerodynamics Branch, Mail Stop 499, AIAA Member.
‡Research Aerospace Engineer, Configuration Aerodynamics Branch, Mail Stop 499, AIAA Senior Member.
§Research Aerospace Engineer, Configuration Aerodynamics Branch, Mail Stop 499, AIAA Associate Fellow.
¶Research Aerospace Engineer, Configuration Aerodynamics Branch, Mail Stop 499, AIAA Member.
‖Research Engineer, Experimental Aero-Physics Branch, P.O. Box 273, AIAA Member.
**Aerospace Engineer, Inlets and Nozzles Branch, Mail Stop 5-12, AIAA Member.

$P_{S,ts}$	=	Test section static pressure, psia
$P_{T,bm}$	=	Bellmouth total pressure, psia
$P_{T2,ts}$	=	Test section total pressure downstream of a normal shock (supersonic), psia
$P_{T,ts}$	=	Test section total pressure (subsonic) , psia
Φ	=	Bellmouth total pressures ratio
ϕ or phi	=	Roll angle, °
Q_{TS}	=	Test section dynamic pressure
RE_u	=	Reynolds number per unit length, 10^6/ft
$T_{T,ts}$	=	Test section total temperature, $^\circ R$
$T_{S,ts}$	=	Test section static temperature, $^\circ R$
Θ or theta	=	Model support system inclination angle, °
Θ_{probe}	=	Probe pitch angle, Cartesian, °

Acronyms and Abbreviations

AMS	=	Angle Measurement System
AOA	=	Angle of Attack
AOS	=	Angle of Sideslip
CAD	=	Computer aided design
CFD	=	Computational Fluid Dynamics
COBRA	=	Collect, Observe, Broadcast, Record, and Analyze Data System
CST	=	Commercial Supersonic Technology Project
ESP	=	Electronically Scanned Pressure
GRC	=	Glenn Research Center
LaRC	=	Langley Research Center
LBFD	=	Low Boom Flight Demonstrator project
MFP	=	Multi Function Probe
NASA	=	National Aeronautics and Space Administration
QA	=	Quality Assurance
SMRM	=	Small Model Roll Mechanism (Ames)
TC	=	Thermocouple
TS	=	Tunnel Station

II. Introduction

NASA aeronautical innovators are working with Lockheed Martin to design and build a supersonic X-plane, the X-59, that produces a gentle thump rather than a loud sonic boom. The plane will be used to collect human response data over select U.S. communities, and the data from these test flights will be provided to U.S. and international regulators to potentially allow supersonic flight over land, drastically reducing travel time within the U.S. and around the world [1].

The construction and flight testing of the X-59 is managed by the Low Boom Flight Demonstrator (LBFD) Project , under the NASA Integrated Aviation Systems Program (IASP) [2]. IASP is run under the NASA Aeronautics Research Mission Directorate (ARMD).

Figure 1 shows an artists rendition of the X-59 aircraft in flight.

Two wind tunnel tests were conducted in the NASA Glenn Research Center (GRC) 8- by 6-Foot Supersonic Wind Tunnel (8x6) to calibrate the nose probe for the X-59 (Figure 2). The first test (GRC-86-21-C005 or C005) was conducted between March and June of 2021. The second test (GRC-86-22-C007 or C007) was conducted in January, 2022. The probe was retested after some unexpected trends were seen in the probe pressure data around the supersonic cruise Mach number during the first tunnel entry. An accurate calibration approach using a neural net technique was demonstrated using the wind tunnel data that can provide critical data needed for flight control of the X-59 [3]. During the initial test entry the probe was tested and calibrated at 19 Mach numbers between Mach 0.25 and Mach 1.7. Most data were collected using continuous roll angle sweeps at a set Mach number and pitch angle. About 725 high quality data runs were recorded during testing to be used in the calibration of the probe. A backup nose probe was also run through the same test matrix as the primary probe.

Fig. 1 Artist rendition of the X-59 in flight [Sourse: NASA].

The 8x6 tunnel ran a targeted wind tunnel check calibration in three tunnel locations where the probe was to be installed and tested prior to a second tunnel entry. During testing, the probe was run in multiple locations in the tunnel at Mach numbers between 0.25 and 1.67, 7 probe pitch angles, and rolled 360°. Over 170 data runs were collected (including repeats). High resolution Schlieren video and images were also recorded.

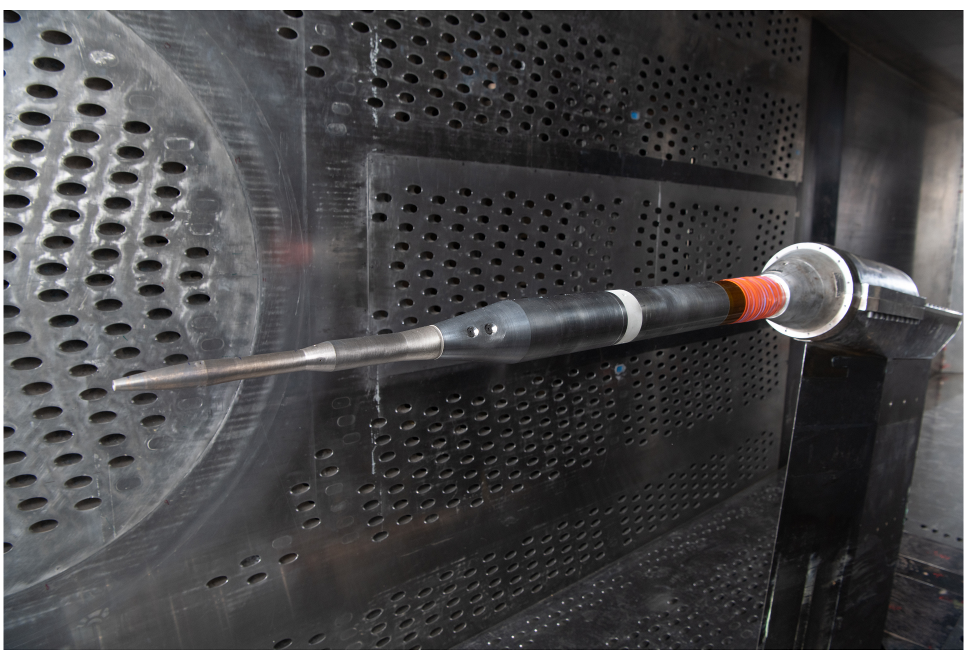


Fig. 2 X-59 nose probe installed in the Glenn 8x6 Supersonic Wind Tunnel [Sourse: NASA].

The probe will be the primary instrument for the flight test of the X-59 for determining angle of attack, angle of sideslip, airspeed, and pressure altitude of the aircraft in flight. Knowing the aircraft's speed and attitude is critical for flight safety and is also critical data for the Sonic Boom mission. Areas of interest for the test were sea level takeoff and landing at Mach 0.2, subsonic cruise at Mach 0.9, and supersonic cruise at Mach 1.4. Data were collected at conditions outside the normal flight envelope to allow for all potential flight conditions. During Phase I flight testing, the air data nose probe and air data system as a whole will be further calibrated in flight to account for additional installed effects of the airframe on the air data system.

III. Experimental Set Up

A. NASA Glenn Research Center 8- by 6-Foot Supersonic Wind

The NASA Glenn Research Center 8- by 6-Foot Supersonic Wind Tunnel, or GRC 8x6, is an atmospheric wind tunnel, with continuous flow. Figure 3 shows the 8x6 and 9- by 15-Foot Low Speed Wind Tunnel (9x15) complex circuit. A seven-stage axial compressor (18-foot inlet diameter), powered by three wound-rotor 29,00-hp electric motors (87,000 hp total), drives the airflow through the facility [4]. This test used both 3-motor and 1-motor drive modes. When operating in closed loop (aerodynamic cycle) mode, which was how the entirety of this test was conducted, air is drawn in through the dryer and circulates around the tunnel loop. The tunnel is able to run in continuous operation because a cooler (finned-tube water-type heat exchanger) in the return leg removes the heat of compression [5]. The cooler was designed to cool the air entering the air dryer to 85 °F.

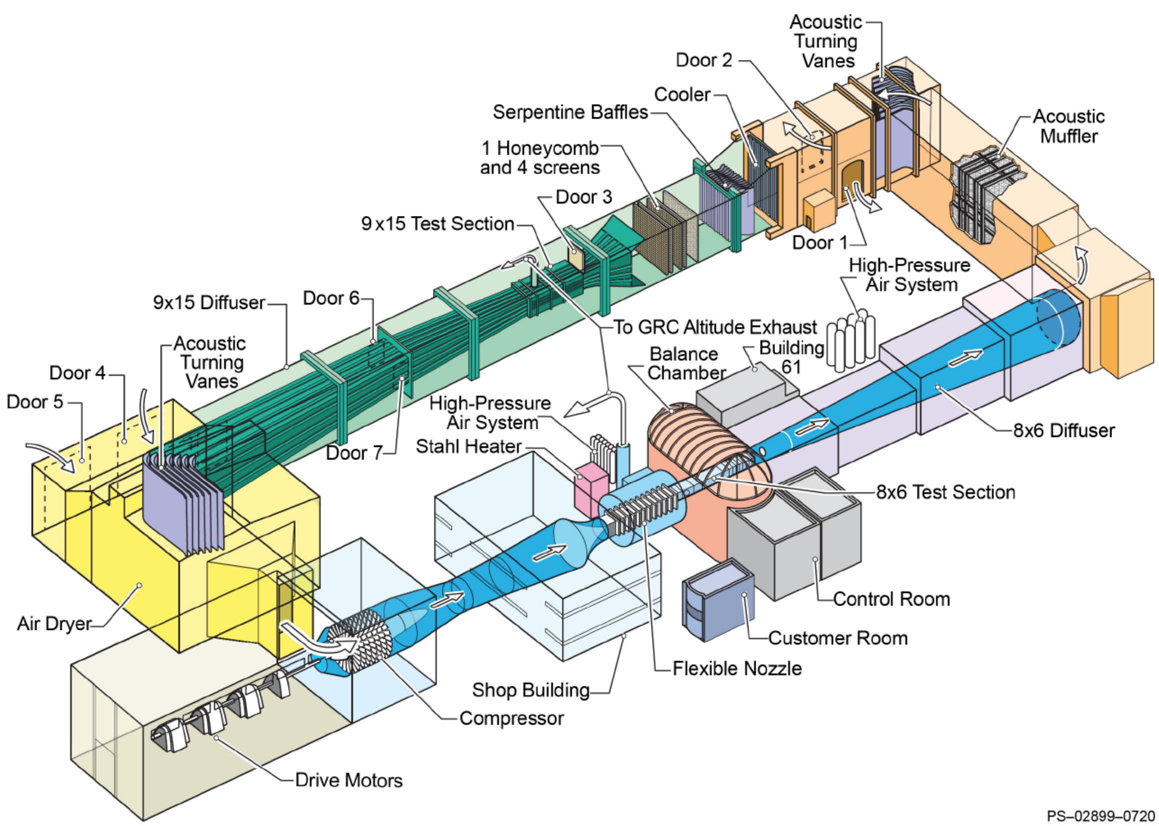


Fig. 3 8x6 Supersonic Wind Tunnel Complex circuit.

The tunnel has an air dryer to remove moisture from the air. The air dryer contains activated alumina and is used during supersonic operations at Mach 1.4 and above, and is bypassed during subsonic operations. Once the air dryer is saturated the alumina needs to be reactivated, which requires 4 hours of heating time, and 2 to 4 hours of cooling time. The reactivation process cannot happen while the tunnel is running. For this reason, supersonic runs are conducted first on each shift, and once the activated alumina is saturated then the tunnel switches over to the subsonic runs in the matrix.

Compressor speed, flexwall positioning, balance chamber pressure (test section bleed), and shock door (second throat) position are used to control the test section conditions [4]. The flexwall positioning is controlled with hydraulically operated screw jacks, and Mach numbers are set on the "flats" where the wall is in a known and repeatable position. Because of this wall setting, the tunnel is run at discrete Mach numbers rather than having a continuous Mach range. The tunnel was operated in both 3-motor and 1-motor drive modes for this test. Altitude exhaust from the Central Process System (CPS) was used to control balance chamber pressure for adjusting Mach number, shock location, and controlling the growth of boundary layer on the test section walls [6].

The tunnel conditions run during the first entry's test campaign at strut position 6 and during the retest at strut positions 10 and 11 are shown in Table 1. These conditions are specific to test section configuration 1 (Table 2). While there are multiple ways to achieve each Mach number, calibrated Mach numbers use the same setting each time.

Table 1 Tunnel Conditions for Test Section Configuration 1.

Mach Nominal	Mach TS	P_T psia	P_T psfa	P_S psia	P_S psfa	Q psia	Q psfa	T_T $^\circ R$	T_S $^\circ R$	Re_u 10^6/ft
0.25	0.25	15.203	2189.2	14.558	2096.3	0.635	91.4	548.4	541.6	1.661
0.4	0.4	16.516	2378.2	14.79	2129.7	1.659	238.8	569.9	552.2	2.641
0.5	0.5	16.817	2421.7	14.174	2041.1	2.484	357.7	577.5	549.9	3.18
0.6	0.6	17.34	2497	13.594	1957.5	3.427	493.5	589.1	549.5	3.662
0.7	0.7	17.39	2504.2	12.534	1804.9	4.302	619.6	593.2	540.2	4.026
0.8	0.8	17.002	2448.3	11.151	1605.7	4.999	719.8	591.8	524.6	4.248
0.85	0.85	16.7	2404.8	10.415	1499.7	5.265	758.1	590.4	515.9	4.305
0.9	0.901	16.677	2401.5	9.855	1419.1	5.594	805.6	591.6	509	4.391
0.95	0.951	16.569	2385.9	9.256	1332.9	5.863	844.3	590.1	499.7	4.461
1.1	1.073	17.299	2491.1	8.375	1206	6.751	972.1	597.5	485.7	4.723
1.2	1.184	17.518	2522.6	7.375	1062.1	7.238	1042.3	598.1	467.1	4.827
1.3	1.252	17.382	2503	6.689	963.2	7.344	1057.6	601.8	458.1	4.75
1.4	1.355	18.133	2611.1	6.064	873.2	7.799	1123.1	607.9	444.6	4.847
1.5	1.457	18.984	2733.7	5.501	792.2	8.175	1177.3	615	431.7	4.912
1.6	1.553	19.771	2847.1	4.985	717.8	8.417	1212	622	419.6	4.925
1.7	1.663	20.951	3016.9	4.488	646.2	8.687	1250.9	629.6	405.4	4.969

Flow straightening honeycomb and 10 mesh turbulence reducing screens are located in the settling chamber ahead of the test section. The test section has porous walls, floor, and ceiling allowing for air to be drawn out of the test section into an enclosed balance chamber that surrounds the test section. The Central Process System (CPS) altitude exhaust (vacuum) controls the pressure in the balance chamber, which is used to help control Mach number, reduce the boundary layer growth, and gives some control of the thermal shock location [5].

The tunnel has numerous static pressure taps in and around the test section. At tunnel station (TS) 17.0, there are 6 static pressure taps on the ceiling, called out as Row 1 Tunnel Ceiling Static Pressures. Row 2 Ceiling Static Pressures has 10 pressure taps, and are located at TS 72.25. There are 8 diffuser ceiling static pressures running from TS 567.1875 to 736.9375, 31 tunnel ceiling static pressure running from TS 10.0 to TS 543.313, and 23 static pressure taps on the tunnel south wall running from TS 104.875 to TS 321.00.

1. 8x6 Test Section

The 8x6 test section is 8 ft high, and 6 ft wide. The entirety of the test section is 23 ft 6 in long, with parallel side walls, and parallel top and bottom plates, and has no divergence. To compensate for the blockage of the transonic strut the side walls past the test section exit diverge from 6 ft to 6 ft 4 in. In the test section all four plates are made of 1 in thick stainless steal. The supersonic region of the tunnel is 9 ft 1 in long, and has solid walls. The transonic region of the test section, which is downstream of the supersonic section, is 14 ft 5 in long and all four walls are perforated with 1 in diameter holes inclined forward at 60° arranged in a herringbone pattern. Figure 4 shows an elevation view of the test section. The test section can be configured 7 different ways, varying the test section length and porosity. Table 2 lists the 7 test section configurations. The 14 ft test section setup uses the entire 14 ft 5 in porous area (the 8 ft test section uses the aft 8 feet of the porous section) [4].

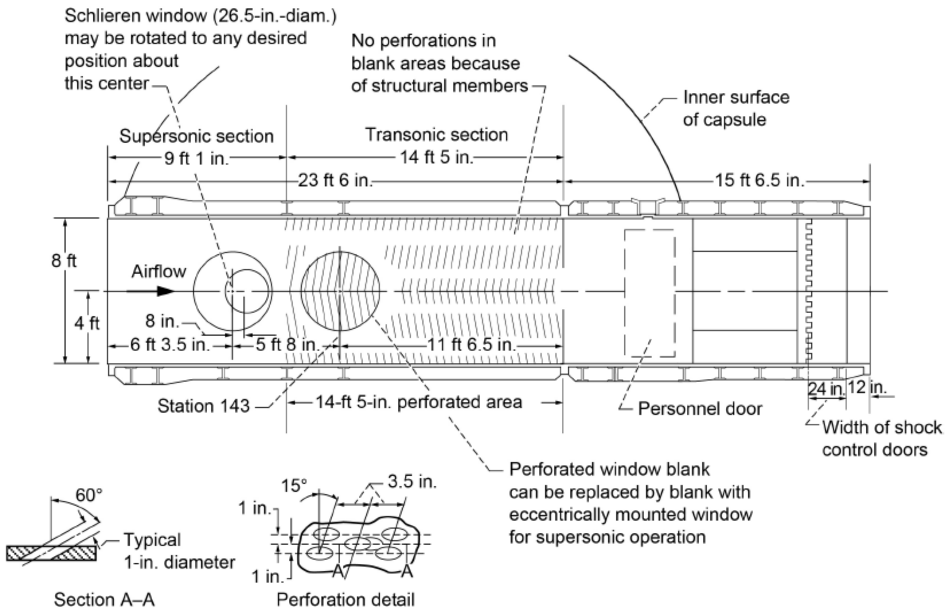


Fig. 4 8x6 test section.

The entirety of the first entry was run in Configuration 1 (strut position 6). During the retest the test section was setup in both Configuration 1 (strut positions 11 and 10) and in Configuration 7 (strut positions 2 and 1 in the supersonic test section).

Table 2 Test Section Configurations.

Number	Configuration
1	14 ft, 5.8% porosity *strut positions 6, 10 and 11*
2	8 ft, 6.2% porosity
3	8 ft, 3.1% porosity
4	8 ft, 6.2% porosity modified
5	8 ft, 3.1% porosity modified
6	14 ft, schlieren windows installed
7	Supersonic test section *strut positions 1 and 2* (transonic test section Configuration 2, 8 ft, 6.2% porosity)

For the first probe calibration test, C005, the test section was set in Configuration 1 (14 ft., 5.8% porosity) for the entirety of the test, with porous window blanks in the transonic test section. Schlieren windows were installed upstream in the supersonic test section to allow cameras to be setup for viewing the test article. For the second entry, C007, the test section was set in Configuration 1 for supersonic strut positions 10 and 11, and in Configuration 7 for supersonic strut positions 1 and 2.

B. X-59 Multi Function Nose Probe

A Rosemount Collins 857CK sharp-lipped multifunction air data probe (MFP) is the baseline X-59 nose probe. It is roughly 15 inches long. The probe will be installed 2° nose down on the aircraft for drainage, but was installed level in the tunnel. A sting was designed and built to extend the probe into the tunnel flow, and to attach the probe to the tunnel hardware.

The probe has 9 pressure ports used for determining angle of attack, angle of sideslip, pressure altitude, and airspeed.

There is a total pressure (P_t) port on the tip of the nose, 4 flush static pressure ports located aft on a shaped compensation bump that are all manifolded together to provide accurate static pressure (P_s) measurement requiring minimal source error correction, and 4 flush ports are located further aft to independently measure AOA and AOS. Table 3 lists the pressure ports on the probe.

Table 3 Probe Pressure Ports.

Port	Measurement
P1	Total Pressure, air data probe
P2	Air Data Probe Angle of Attack - Upper
P3	Air Data Probe Angle of Sideslip - Left
P4	Air Data Probe Angle of Attack - Bottom
P5	Air Data Probe Angle of Sideslip - Right
P6	Static Pressure Air Data Probe - Manifolded static ring

C. Model Support System

The 8x6 supersonic strut cradle was located at strut position 6 in the tunnel for the first test entry, C005. The 8x6 supersonic strut cradle was located at strut positions 1, 2, 10 and 11 for the second entry, C007. There are eleven discrete axial locations where the strut can be positioned in the tunnel, each spaced 7 inches apart. Strut position 6 placed the strut in the center of the range (TS 148.25), strut position 1 was the most forward strut position, and strut position 11 was the most rear position for the supersonic strut. The strut has a -5° to +20° pitch range. The Ames Small Model Roll mechanism (SMRM) was installed in the 8x6 supersonic strut cradle with a bushing, and is angled at -7.5°, giving the probe a pitch range of -16° to +12°. A sting was designed and fabricated to attach the probe to the SMRM, and also to position the probe out in front of any flow interference from the SMRM and the strut cradle. The probe was installed level in the tunnel, but will be installed at -2° on the aircraft, therefore, when the probe was at +12° in the tunnel it related to the aircraft being at +14°. Figure 5 shows the probe and the support setup in the tunnel for strut positions 6, 10 and 11. Figure 6 shows the probe and support setup with the sonic boom stub sting in the supersonic section of the tunnel for strut positions 1 and 2. During testing in supersonic strut position 1 and 2 the sonic boom stub sting was used to put the probe in the calibrated area of the supersonic test section. The placement in supersonic strut position 1 with the sonic boom stub sting placed the probe in the schlieren windows area, allowing for the use of high quality schlieren imaging.

The height of the strut was adjusted throughout testing to keep the probe tip in the center of the test section as much as possible. At more negative pitch angles, the probe tip dropped below the centerline of the tunnel due to strut height limitations [6].

When the probe was level in supersonic strut position 6, at 0° pitch, the tip of the nose probe was located at tunnel station 148.25, and a height of 48 inches above the tunnel floor, in the center of the 8 foot high test section. When the probe was level in supersonic strut position 10 the nose of the probe was located at tunnel station 175.9 (169.8 at -6°), and in supersonic strut position 11 the tip of the nose probe was located at tunnel station 182.9 (176.8 at -6°).

Table 4 shows the test hardware, and the angles of the test hardware. Table 6 also lists the hardware used in the test setup, as well as instrumentation.

Strut pitch was measured using a Q-Flex inclinometer (QA-2000) mounted in the strut cradle. The strut pitch was used to calculate the probe pitch, Θ_{probe}, denoted as PROBEANG in the data files. The sting rotation, and therefore the probe roll angle, was measured by a roll sensor built into the SMRM. The SMRM had a Maxon Precision Systems RE40motor with a HEDL encoder. The probe height in the tunnel was calculated from a potentiometer interfaced with strut drive system. Table 5 lists the probe location parameters and the inputs used to calculate those parameters.

1. Small Model Roll Mechanism (SMRM)

The Ames SMRM was used to roll the sting and probe during testing. Both the encoder (by GRC) and taper (by Modern Machine and Tool) were repaired before this wind tunnel test. The SMRM has a knuckle that angles down 7.5°. The rolling mechanism is forward of the knuckle, and therefore does not affect the pitch or create a coning angle of the probe when the probe and sting are rolled. The SMRM is able to roll continuously at 3 seconds per degree with no limitations to the rotation other than the test setup. Because the pressure tubing for the probe and the gauge wires were

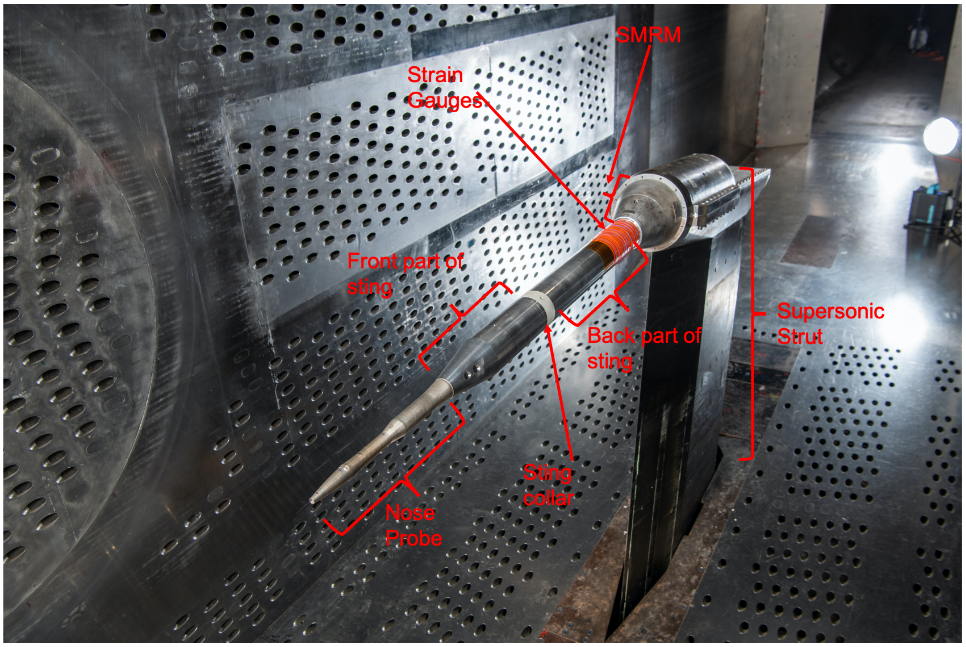


Fig. 5 Nose probe and support setup in the Glenn 8x6 Supersonic Wind Tunnel [Source: NASA].

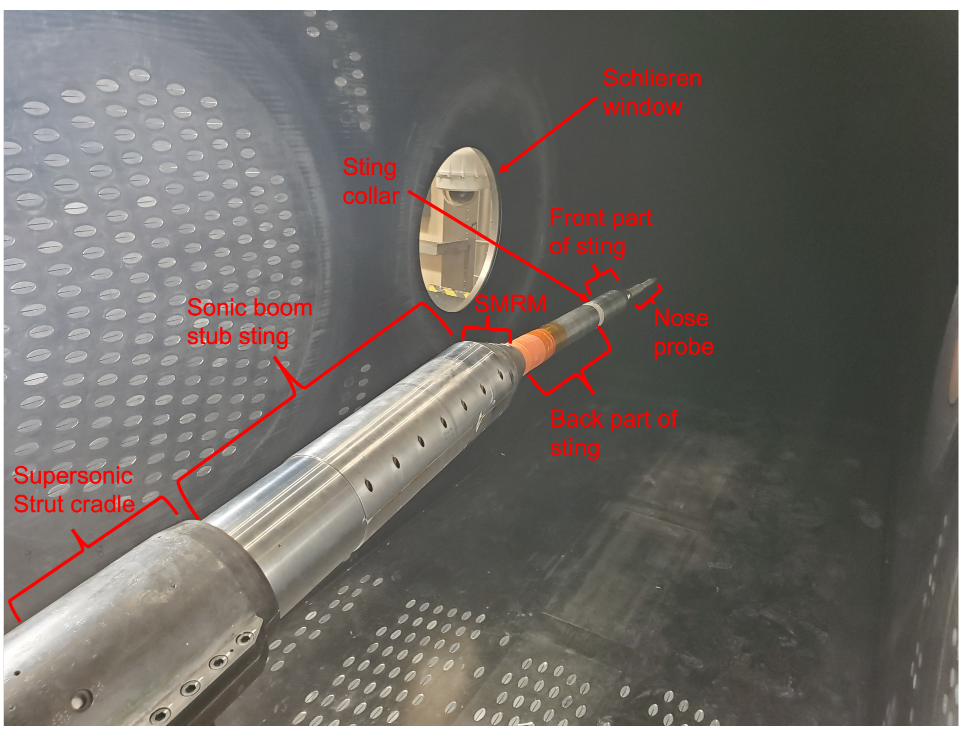


Fig. 6 Nose probe and support setup with the supersonic stub sting in the Glenn 8x6 Supersonic Wind Tunnel [Source: NASA].

Table 4 Installation Hardware and Angles.

Item	Angle
Suppersonic strut	-5° to 20°
Ames SMRM	-7.5°
Sonic boom stub sting	0°
Probe sting	0°
MFP	0°
Full setup	-12.5° to 12.5°
MFP installed on aircraft	-2°
MFP relative to aircraft install	-10.5° to 14.5°

Table 5 Probe Location.

Paramater	Description	Unit	Input
Θ_{probe}	Probe pitch angle	degrees	Strut Q-Flex inclinometer
ϕ_{SMRM}	Probe roll	degrees	HEDL #110512 encoder
H_{probe}	Probe height	inches	Potentiometer

running through the SMRM, testing stuck to 0° to 360°, and 360° to 0° to avoid issues with twisted tubing and wiring if we continued rolling in the positive direction multiple times. Figure 7 shows a GRC-made sketch of the SMRM.

Using an Angle Measurement System (AMS) mounted to the mounting plate on the sting, the roll slop in the SMRM was measured to be +/- 0.10° (0.20° total slop). The slop check was done 3 times by hand, and all resulted in the same measurement.

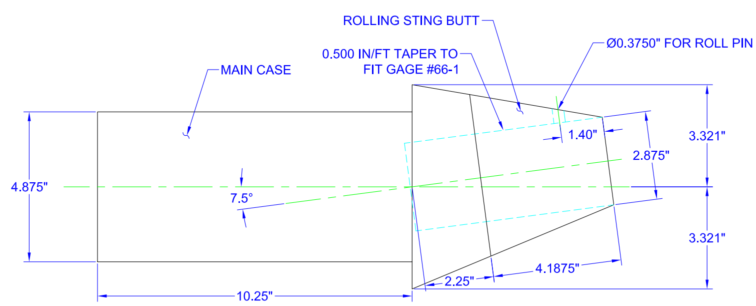


Fig. 7 SMRM sketch.

2. Sting

A new sting was designed by Don Morr at Ames. The original fabrication of the sting was done at Micro Craft, without the Air Data Probes in hand. Micro Craft also built an AMS leveling plate for the sting, and a loading leveling block that attached out the front of the sting where the probe would be mounted.

Once both the sting and probes arrived at Modern Machine and Tool (MM&T), it was discovered that the pressure tubing and connectors coming out the back of the probe were slightly wider than the probe itself and did not fit in the sting. The sting was modified by MM&T to fit the probe tubing and connectors. The sting was cut into 2 pieces lengthwise (Figure 8), and the front piece, where the probe connected, was bored out to allow the tubing and connectors to fit. A flange was machined into the aft sting piece, so the two sting pieces would bolt together, and a collar was machined to smooth over the connection between the 2 sting pieces during testing (Figure 9). To install the probe, it was inserted through the back of the front half, then the 2 sting pieces were pinned and fastened together (Figure 10). The aft end of the sting was 25 inches long, and the forward part of the sting assembly was 10.8 inches long, for a total sting length of 35.8 inches.

CFD runs were done ahead of time to make sure that the chosen sting length would put the probe far enough ahead of any strut or SMRM feed forward interference.

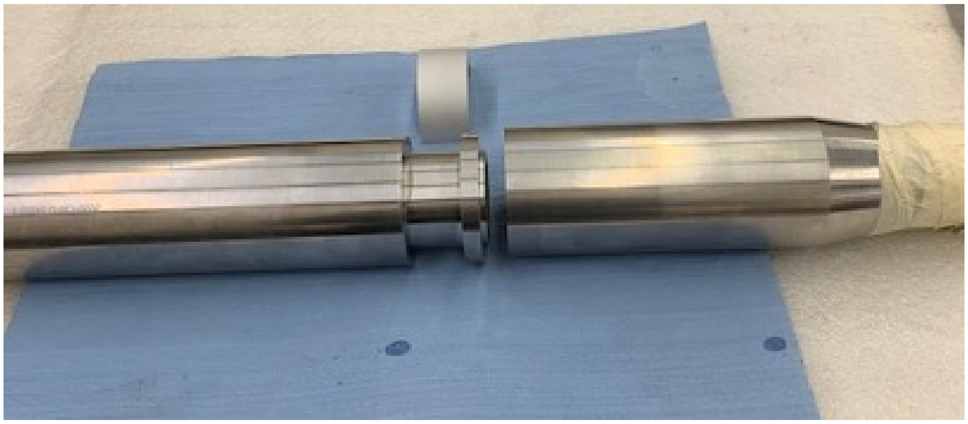


Fig. 8 Two pieces of the sting, showing the flange on the aft part of the sting [Source: MM&T].

Fig. 9 The sting with the collar between the two halves [Source: MM&T].

3. Cap Assembly/Pressure Connectors

Pressure connectors were fabricated at Ames to attach the pressure tubing in the probe to the tunnel pressure measurement system. The connectors on the probe side were at the limit in diameter to fit through the sting, the cap assemblies were made to avoid adding to the outside diameter at the connection point, and to shorten the total length of the hard connections coming out the back of the probe. The caps were Scanivalve, purchased through McMaster Carr (50715K512 purchased 9, probe required 4, 50715K513 purchased 3, probe required 1), and a 1/16" diameter hole was drilled in the end of the caps and stainless steel tubing (0.063 OD) was brazed on to the connectors. Figure 11 shows a picture of two of the cap assemblies. Five cap assemblies were used in total to connect the probe pressures to the tunnel system. The connections between the pressure lines were in the sting, where the pressure tubing ran through the sting, the SMRM, the supersonic strut, and out the bottom of the strut to the tunnel's ESP modules. Figure 12 shows the tunnel tubing coming out of the strut being connected to the stainless steel tubing attached to the cap assembly.

Each cap assembly was pressure tested (vacuum, 20 psi) for 10 minutes with no leaks.

Fig. 10 Installation of the probe into the back part of the sting [Source: NASA].

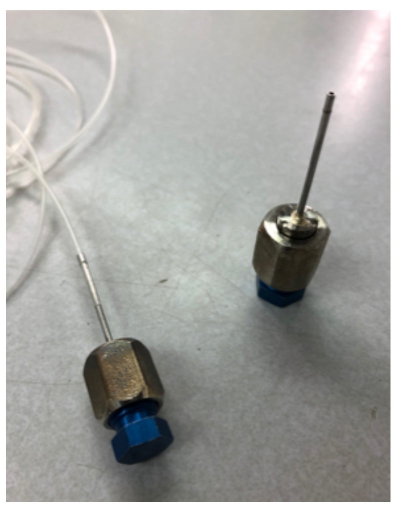


Fig. 11 Cap assembly used to connect the probe pressure lines to the tunnel measurement system [Source: NASA].

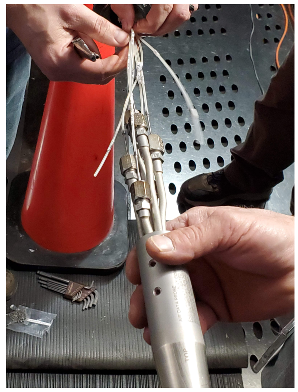


Fig. 12 Hookup of the cap assembly to the pressure lines running from the tunnel measurement system [Source: NASA].

D. Data Acquisition

The NASA Glenn 8x6 Tunnel uses the COBRA (Collect, Observe, Broadcast, Record and Analyze) data system. The COBRA data system consists of servers, data acquisition systems, display stations, operator stations, synchronised time source, and output devices. Instrumentation and calculations are all sampled and calculated at 12.5 Hz, for any time duration that is requested throughout the test. Readings and calculations can be provided in both an averaged format over the time duration and/or the scanned format with all of the sample data. COBRA interfaces with the Optimus ESP system and the Ovation facility control system [7].

E. Sign Conventions

The GRC 8x6 sign convention being followed by this test is shown in Figure 13. Positive pitch is nose up. Positive yaw is nose right (positive beta is nose left). Positive roll is right wing down. This follows with the Lockheed coordinate system in Figure 14.

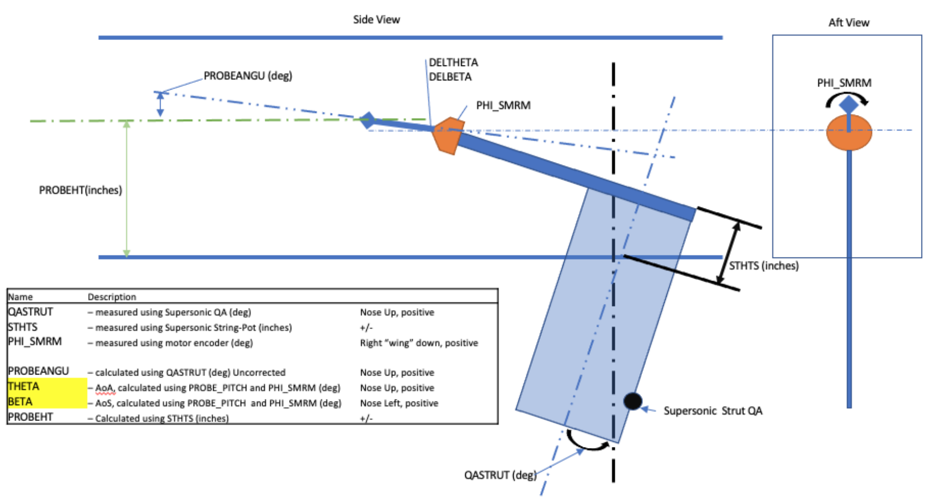


Fig. 13 Sign convention.

F. Run Procedure

Two probes were run during the initial test entry, Probe 1 and Probe 2. Only probe 1, the flight probe, and the probe that was scanned for CFD, was run during the second entry. The test matrix was run by setting Mach, then either theta

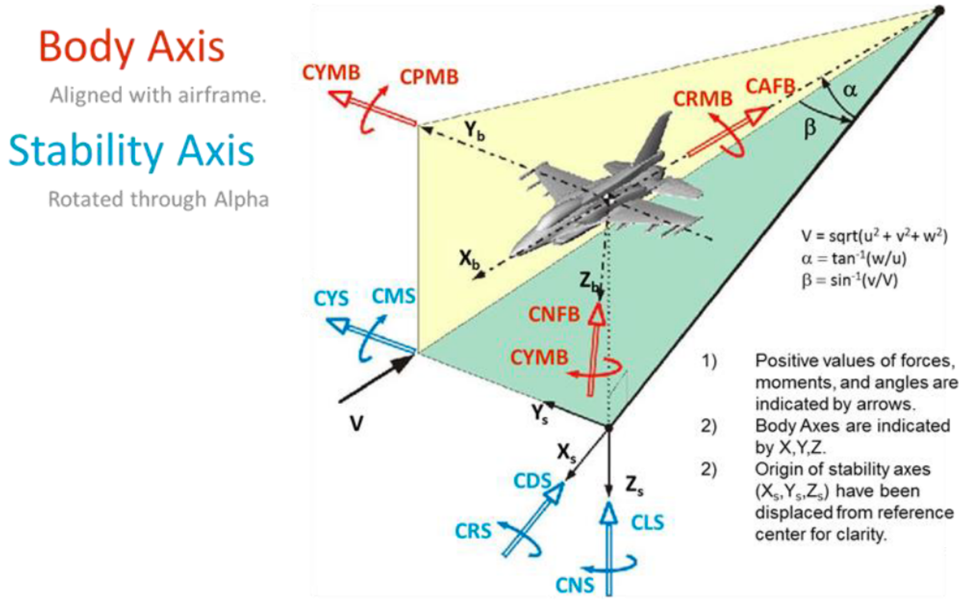


Fig. 14 Coordinate system.

or phi was set at an angle, and the probe was either rolled or pitched to acquire a combination of theta and phi points. The probe would then be moved to the next theta or phi, at the same Mach number, and data were again collected as the probe was either pitched or rolled. The majority of test data were collected by setting Mach number and a pitch/theta angle, and collecting continuous data as the probe was rolled 360°. During the second entry, some 10 second dwell points were collected at each Mach number at 0° theta, 0° phi. Because of the test hardware setup, all theta angles were negative (excluding zero). The final calibration will be using alpha and beta (pitch and yaw), but using a roll mechanism in the tunnel to roll instead of changing knuckles constantly (requiring the tunnel to be brought down, an entry made, and the tunnel restarted) allowed for a more reasonable test schedule. The matrix was selected to cover the envelope the X-59 aircraft could see in flight, and slightly beyond the safe flying conditions to allow for calibration interpolation. The X-59 aircraft has more restrictive angle limits at higher Mach numbers, therefore, the theta range was reduced in the test matrix at higher Mach numbers.

Initially a screening matrix was run on Probe 1 during the first test entry, in which Mach was set, then either theta or phi was set, and the probe was either rolled or pitched in increments, and a 10 second averaged data point was taken at the theta phi location while the model was not moving. These points are referred to in this paper as point-pause data.

After some test runs, it was found that setting a theta angle, and taking data continuously while the probe was rolled 360°, at 3 seconds per degree, the data were repeatable with the point-pause data, and data collection time was greatly reduced. These data are referred to in the paper as continuous data. Both probes were run through the same full test matrix of continuous runs. Runs were conducted in a zigzag pattern, i.e., 0° to 360° then 360° to 0°.

Supersonic Mach numbers, which required the dryers to run, were always run first thing during a shift, until the dryer beds were saturated, then the tunnel would switch to subsonic runs that did not require the dryer beds. An 8 hour drying cycle would be run off shift to reactivate the aluminum in the dryers.

A sweep is a set of averaged readings, at a set Mach number, and at a set theta or phi. A reading is all of the samples for the time duration of the data point was taken at. For the point-pause data, a sweep consisted of multiple averaged readings at a set Mach number, and a set theta or phi, and each reading was at an incremental discrete angle. For the continuous data, each sweep was a single reading at a set Mach and a set theta, that was recorded for about 5 minutes (10 minutes during the second entry) while the probe was rolled 360°. The Sweep data files have the averaged data for each reading. The reading data files have each scan that gets averaged for the sweep data files.

IV. Instrumentation and Measurements

Several types of instrumentation were used to obtain quantitative data during the test. The sections below outline the types of measurements made during the test and the instrumentation that was used to obtain those data. Table 6 lists the test hardware and instrumentation that was used during testing. The hardware in this list is discussed in Section III.C.

Table 6 Test Hardware and Instrumentation.

Description	Quantity	ID
Supersonic Strut	1	
Ames Small Model Roll Mech	1	
Sting	1	
Loading block	1	
AMS Leveling Plate	1	
Cap Assembly/Pressure connectors	5	50715K512 (4), 50715K513 (1)
Strain Gauge	2	SK-06-060CD-10C
Temperature Gauge	2	K-type thermocouple (TC)
AMS package for sting deflections and angle calcs	1	NASA LARC AMS-14
Strut Qflex	1	
FARO Arm CMM Machine	1	5010062

A. Strain Gauge Measurements

A study was conducted at GRC to determine what type of strain gauge should be used, and where they should be placed on the sting to best record forces to calculate sting bending. Two SK-06-060CD-10C strain gauges were installed near the rear of the sting (Figure 15). Pretest calculations showed that sting bending during testing would be negligible, however, it was decided to install the strain gauges in case they may be needed. Both the pitching moment and yawing moment gauges had K-type thermocouples (TC) for temperature compensation. Each bridge had voltage power, monitor, and sense, and the two strain gauge bridge voltages were measured by COBRA using Precision Filters. Bridge resistance checks were done at MM&T, and the gauges were heat cycled before the sting was shipped to Glenn. Once at Glenn, the signal conditioner for the strain gauges was tuned, followed by a strain gauge characterization.

The strain gauge voltage and TC temperatures were recorded throughout the first test entry, but not applied in calculations since the sting bending was within the accuracy of the angle measurements from the system. The largest force seen during testing was 15 lbs at Mach 1.7 and 10° of pitch. The maximum deflection seen during the strain gauge calibration, which went up to 20 lbs applied force, was 0.02°.

The strain gauges were not connected up for the second test entry, since they were never used during the first test, and calibration would have required close to a week of additional build up time.

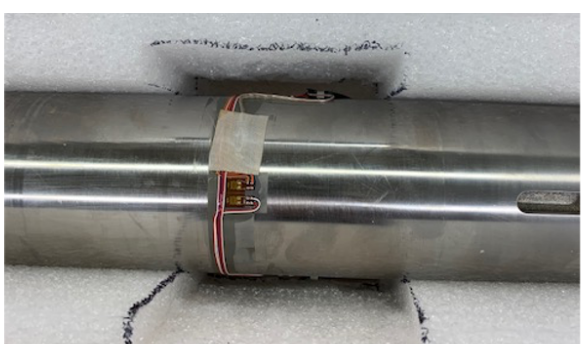


Fig. 15 Strain gauges on the sting [Source: NASA].

B. Pressure Measurements

The 5 pressure lines coming out the back of the probe were attached into the tunnel system, and measured by ESPs with a ±15 psi range. The pressures from the ESPs interface with the COBRA data system through the Optimus ESP system. The ESP modules have a 0.0075 psi quoted accuracy.

Table 3 shows the naming scheme for the pressure ports.

C. Tunnel Parameters

Tunnel parameters were measured using the standard tunnel instrumentation, and calculated using standard GRC 8x6 data reduction methods. A calibration of the tunnel was done in 2019 [4], after modifications were made to the tunnel between 2016 and 2019. The main tunnel parameters are calculated using calibration constants determined from the 2019 calibration. The tunnel is operated by setting nominal conditions for compressor speed, flexible wall position, shock door position, and a balance chamber static to bellmouth total pressures ratio Φ, shown in Equation 1. Φ is selected based on lookup tables in the facility operations manual, and is achieved and maintained through control of a bleed valve in the balance chamber.

$$\Phi = \frac{P_{Sbal}}{P_{T,bm}} \tag{1}$$

Table 7 lists the main test section parameters of interest and the inputs to calculate those parameters.

Table 7 Test Section Parameters.

Parameter	Description	Units	Inputs
M_{TS}	Test section Mach number	-	flex wall setting, fan speed, $P_{S,bal}$, bleed valve position
$P_{T,ts}$	Test section total pressure (subsonic)	psia	$P_{T,bm}$ (ESPs)
$P_{T2,ts}$	Test section total pressure downstream of a normal shock (supersonic)	psia	$P_{T,bm}$, $P_{S,bal}$ (ESPs)
$T_{T,ts}$	Test section total temperature	°R	Type-E thermocouples
$P_{S,ts}$	Test section static pressure	psia	$P_{T,bm}$, $P_{S,bal}$ (ESPs)
$T_{S,ts}$	Test section static temperature	°R	$T_{T,ts}$, M_{TS}
ATDEW	Test Section Dewpoint	°F	Vaisala

Test section Mach number (M_{TS}) was set using the flex wall settings, fan speed, balance chamber pressure, and having the bleed valve open or closed. The flex wall was set using a camshaft encoder which measured the rotational angle of the shaft. The camshaft has known orientations that produce a calibrated contour between Machs 1.1. and 2.0. Mach number is computed using isentropic relations, measured pitot pressure, and calibrated $P_{S,ts}$ [4].

The Optimus Data System, which interfaces with COBRA, was used to acquire steady-state pressure data from electronic pressure scanners (ESP–32HD digital temperature compensation (DTC) Gen-1 and Gen-2). The ESP pressure scanners are miniature electronic differential pressure measurement units which have individual piezoresistive pressure sensor for each channel. The ESPs each had 32 channels, and were 15-psid.

Test section total pressure, $P_{T,ts}$, is calculated from pressures located on two bellmouth rakes. The two bellmouth rakes have 4 total pressure probes each (measured by ESPs on the Optimus system) that are used to measure the bellmouth total pressure, $P_{T,bm}$, and are located near the exit of the bellmouth upstream of the test section. Both rakes also have a fifth pitot tube that is fed to the tunnel control system. One rake is mounted on the north wall of the tunnel, and the other is mounted to the south wall of the tunnel approximately at tunnel centerline.

When the tunnel is supersonic ($\Phi < 0.533$), test section total pressure 2, $P_{T2,ts}$, is used instead of $P_{T,ts}$ since it is the test section total pressure calculated downstream of the normal shock. The calculation for $P_{T2,ts}$ includes $P_{T,bm}$ as well as the balance chamber static pressure, $P_{S,bal}$, which is measured from four static pressure ports located around the balance chamber which surrounds the test section.

Test section static pressures, $P_{S,ts}$ is calculated using the bellmouth rake total pressure, $P_{T,bm}$, and balance chamber static pressure, $P_{S,bal}$.

Test section total temperature, $T_{T,ts}$ is measured on same bellmouth rakes discussed above. The bellmouth rakes have two total temperature probes each. One of the 4 total temperature probes is exclusively used by the tunnel control system. The temperatures are measured by type-E thermocouples, with "special-limit-of-error" wire and with aspirated probe tips

Section III.A discusses the static pressure ports located along the test section ceiling, wall, and around the diffuser. These static taps are all measure on ESP modules read by the Optimus system.

D. Computations

The test was run in theta (θ) and phi (ϕ) Cartesian coordinates, and the calibration will use the alpha (α) and beta (β) polar coordinates computed from theta and phi (Equations 2 and 3).

$$\alpha = \frac{atan(cos(\phi * \frac{\pi}{180}) * \frac{sin(\theta * \frac{\pi}{180})}{cos(\theta * \frac{\pi}{180})})}{\frac{\pi}{180}} \tag{2}$$

$$\beta = \frac{asin(sin(\theta * \frac{\pi}{180})) * sin(\phi * \frac{\pi}{180}))}{\frac{\pi}{180}} \tag{3}$$

The continuous data were not down sampled.

Lockheed will use the coefficient of pressure for pressure 6 in their calibration. Equation 4 was used to calculate $C_{P_{P6}}$ with the wind tunnel data.

$$C_{P_{P6}} = \frac{P6 - P_S}{P1 - P6} \tag{4}$$

V. Calibrations and Checkouts

The following section discusses calibrations and checks done on the model and tunnel both pretest, and during testing. All calibrations were performed using GRC 8x6 best practices. GRC 8x6 best practices were also used for all testing procedures, including in-test checks and corrections applied to the data.

A. Wind Tunnel Calibrations

Standard pretest tunnel calibrations were conducted using GRC 8x6 best practices. The tunnel had been down for an extended period of time before the first test entry because of the COVID-19 shutdowns, so a full wind on tunnel check was done before installing the model.

1. Winter 2021 8x6 Check Calibration

Prior to the second entry, a tunnel check calibration was done. The calibration is discussed in the Winter 2021 8x6 Check Calibration Summary [8]. Tunnel static pressure, $P_{S_{TS}}$, which was used in C005, is computed based on the average static pressure measurements from the calibration probe run during the 2019 tunnel calibration, with the measurements taken at multiple x locations in the tunnel. Post first entry, it was discovered that the x location of the X-59 probe in the tunnel was outside of the x tunnel locations the calibration probe P_S measurements used to calculate $P_{S_{TS}}$, leading to questions about whether $P_{S_{TS}}$ was representative of the tunnel static pressure at the X-59 probe's location in the tunnel. Part of the winter 2021 check calibration included running a single calibration probe (Figure 16) on tunnel centerline at strut positions 9, 10, and 11 collecting static pressure data. The measured static pressure from these runs was used to create a lookup table for the data system to give a local static pressure based on the X-59 nose probe position in the tunnel named $P_{S_{Local}}$.

Fig. 16 Single 8x6 check calibration probe installed in the tunnel [Source: NASA].

B. Pretest Hardware Checkouts

Test specific hardware was checked before being installed in the test section, following GRC 8x6 best practices. The sting was taper fit checked to the SMRM and met the tunnel safety requirement for contacting surface area (80% is the minimum requirement).

The pressure ports on the nose probe were all leak checked prior to testing, and each time the nose probe was changed out.

A Faro Arm and team were brought in to take measurements on the probe and the sting (Figure 17). These data were used to check misalignment angles between the probe and the sting for both the initial test and the second entry.

A dial gauge was used to check the coning angle at the tip of the probe when the probe was set to zero theta and rolled 360° (Figure 18). For the second entry the largest runout of the probe tip was 0.012".

C. Model Calibrations

Before the probe was installed in the sting, the loading block (Figure 19) was installed to load the system and measure sting angular deflection. The loading block had loading points and a place to attach the AMS on all 4 sides (Figure 20).

Sting angular deflections were measured using the strain gauges bonded to the sting with multiple loads on normal force, pitching moment, side force, and yawing moment. Sting bending checks were also done both on a cold sting, and a heated sting (using a heating pad). An AMS was attached on the leveling block to measure accurate angles, a weight pan was hung on the leveling block as a point source, and weights were placed on the weight pan. Figure 21 shows the initial loading setup, and Figure 22 shows weights on the weight pan during the calibration. For each set of loadings a preload was applied then removed, then data was taken as the sting was loaded with weights in prescribed increments, and as the weights were removed in increments (a point was also taken during preloading)

For running loads (20 lbs), the maximum deflection was 0.02°. For unstart loads (110 lbs) the max deflection was 0.1°. The heated loads did not make a difference in the deflections, and the temperature was not stable enough for a temperature compensation computation. The running loads deflections were within the accuracy of the system and were therefore not applied to the test data. An alarm was set on the measured running loads to alert tunnel staff if a load over

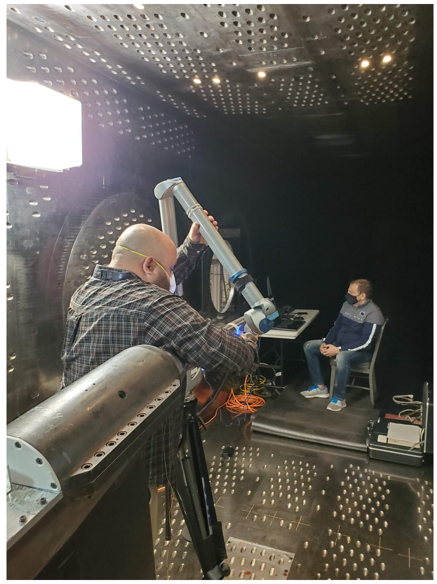
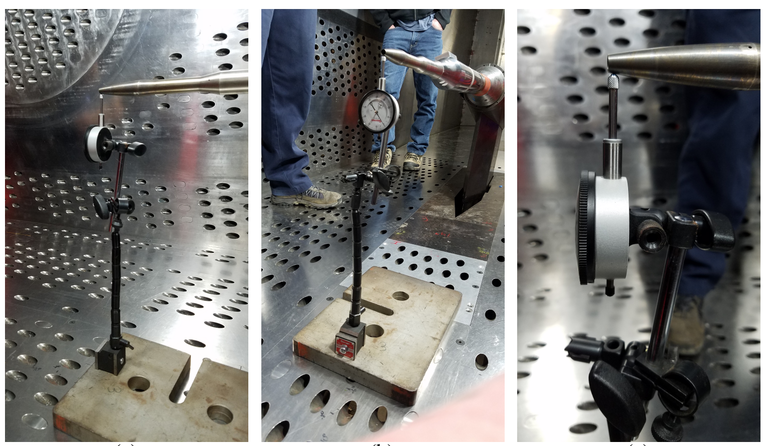


Fig. 17 Faro Arm Coordinate Measuring Machine (CMM) measurements [Source: NASA].



(a) (b) (c)

Fig. 18 Measurement of probe tip runout [Source: NASA].

20 lbs was applied to the system, but that level of load was never reached during testing. The strain gauge readings were recorded so if it is decided later to apply the bending calculations the data can be rereduced to include it.

D. In Test Checks and Corrections

During the first test entry the strain gauges on the sting were continuously monitored, and an alarm set which would sound if the strain gauges saw a force over 20 lbs (the load it was determined that sting bending may have an effect on the level of the probe). A force that high was not seen during testing.

ESP calibrations were done at the beginning of each shift, and after the tunnel was warmed up, right before the first data point. Check pressures were monitored, and if they drifted out of tolerance a calibration was done. The tunnel had a standard calibration interval during testing every 2 hours. The 2 hours interval was flexible (as long as the check pressures were in tolerance), and could happen earlier or later, depending on what is happening in the tunnel (e.g., at 2 hrs and 10 min to finish a sweep, or sequence of data points, or conversely after 50 minutes after changing model positions/Mach number/tunnel settings and it is the opportune time to calibrate). The check pressures ports were a single port on each mini-module that was fed an “independent” check pressure. The check pressure was compared to

Fig. 19 The loading block and the leveling plate installed on the sting [Source: NASA].

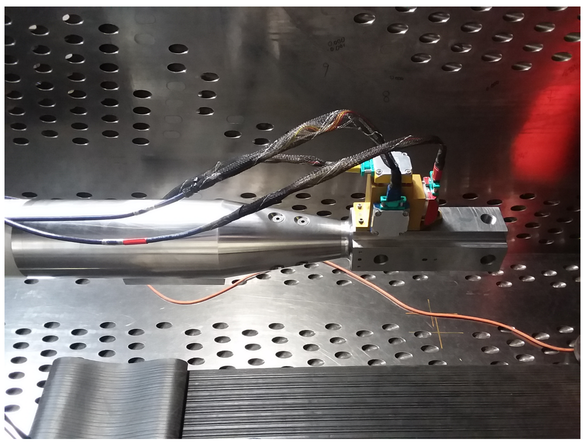


Fig. 20 AMS installed on the loading block [Source: NASA].

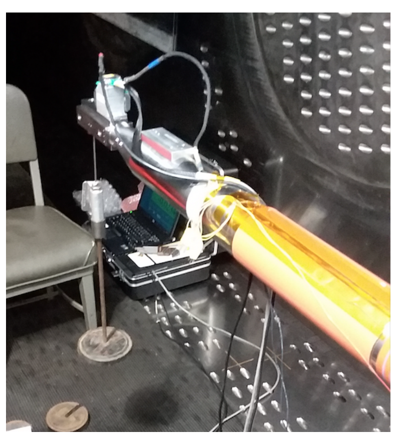


Fig. 21 Setup for loading [Source: NASA].

Fig. 22 Weights being loaded on the loading block [Source: NASA].

a secondary pressure measurement system, and if there was a significant differential, we would also then conduct a calibration.

The AMS leveling plate was installed on the sting each morning after wind on running was completed for the night. An AMS was installed (Figure 23) to check the sting level to be sure nothing had shifted, and nothing was out of alignment.

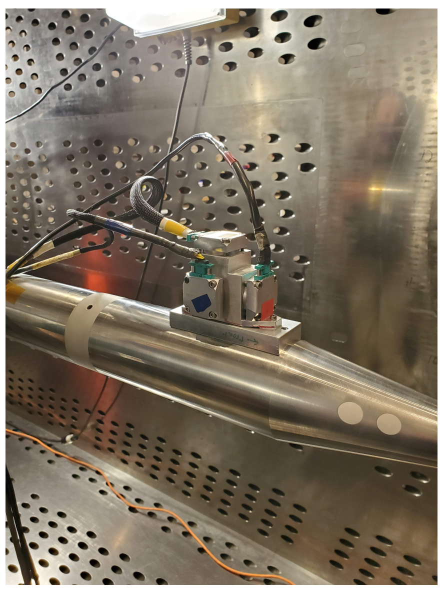


Fig. 23 AMS installed on the sting leveling plate [Source: NASA].

VI. Test Results and Discussion

It was decided that the C007 strut position 11 data would be used for the supersonic portion of the calibration, and the C005 (strut position 6) data would be used for the subsonic calibration. To see a wind tunnel data comparison to CFD see the paper by Bozeman et al. [9]. A neural net calibration was developed by NASA using data from the wind tunnel test that could provide low-error calibrations to the measured data which is discussed in Long et al. [3]. A discussion of the measurement accuracy and uncertainty analysis of the wind tunnel data is found in Friedlander et al. [10].

A set of select few variables used in the plots can be found in Table 8 for easy reference.

Because of the way the point-pause data were acquired, points were often grabbed from separate sweeps for plots.

The continuous data were acquired in single continuous roll sweeps with data collected at 12.5 hz. The data will likely have some smoothing or averaging done for the calibration, but for this paper no smoothing, averaging, filtering, or down sampling of the data was done, unless otherwise specified. Since the continuous data in the paper were not averaged one can see the scatter in the data that would be averaged out in point-pause mode.

A. Data Repeatability

A select few repeat plots were selected to be shown in this paper as representative examples.

1. Continuous vs. Point-Pause and Probe Repeatability, C005

During the first entry, Test C005, repeat runs between probes were acquired, and point-pause vs. continuous repeats were acquired during testing. All repeats were long term repeats, since probe changes were done between the runs. Only the subsonic continuous ϕ sweeps with Probe 32913 from C005 will be used in the probe calibration.

Figures 24 to 26 show a representative range of repeats with both point-pause and continuous sweeps. The two continuous repeat sets on each plot are from the two different probes tested during C005. The trends between sweeps repeat very well. Some overall pressure shifts can be seen between repeat sweeps, however they are within the ±0.0092 psi computed pressure measurement uncertainty [10]. Of note is that the continuous and point-pause data are almost on top of each other for the sweeps, but the coarseness of the point-pause data sometimes misses the wiggles in the trends, as can be seen in Figure 26 with Pressures 2, 3, 4 and 5 at the lowest dips.

2. Selected Calibration Data Repeatability

From all of the wind tunnel data that were collected, a subset was selected to be used for the neural net calibration, the subsonic runs from Test C005 and the supersonic runs from Test C007 when the probe was located at station 11. Figures 27 to 29 show a representative range of repeats of the calibration data from both Test C005 (subsonic runs) and Test C007 (supersonic runs). The trends between sweeps repeat very well. Some overall pressure shifts can be seen between repeat sweeps, however they are within the ±0.0092 psi computed pressure measurement uncertainty [10].

B. Data Trends

To check the continuity of the data, some trends were plotted. All data shown in the trend plots are calibration data unless otherwise specified. A select few plots are shown in this paper as a representation of what was seen during testing.

1. Mach Number Effects in Pitch

All of the calibration data Φ sweeps for each probe angle were plotted together, showing the Mach number effects in pitch. Figures 30 to 32 show a selection of the probe pressure plots at Θ_{probe} 0, -3, and -8, respectively. As Θ_{probe} increases, the pressures have larger variations during the roll sweeps as expected.

Table 8 Data Plot Variables.

Data Variable	Definition
M_{TS}	Mach
P1 to P6	Probe Pressure, psi
ϕ_{SMRM}	Roll angle of the probe, degree
Θ_{probe}	Pitch angle of the probe, degree
$P_{S_{TS}}$	Test section static pressure, psi
$P_{S_{Local}}$	Test section static pressure, 2nd entry, psi
P_S	Test section static pressure, psi
$P_{T_{TS}}$	Test section total pressure, psi
$C_{P_{P6}}$	Coefficient of pressure P6
S	Sweep Number

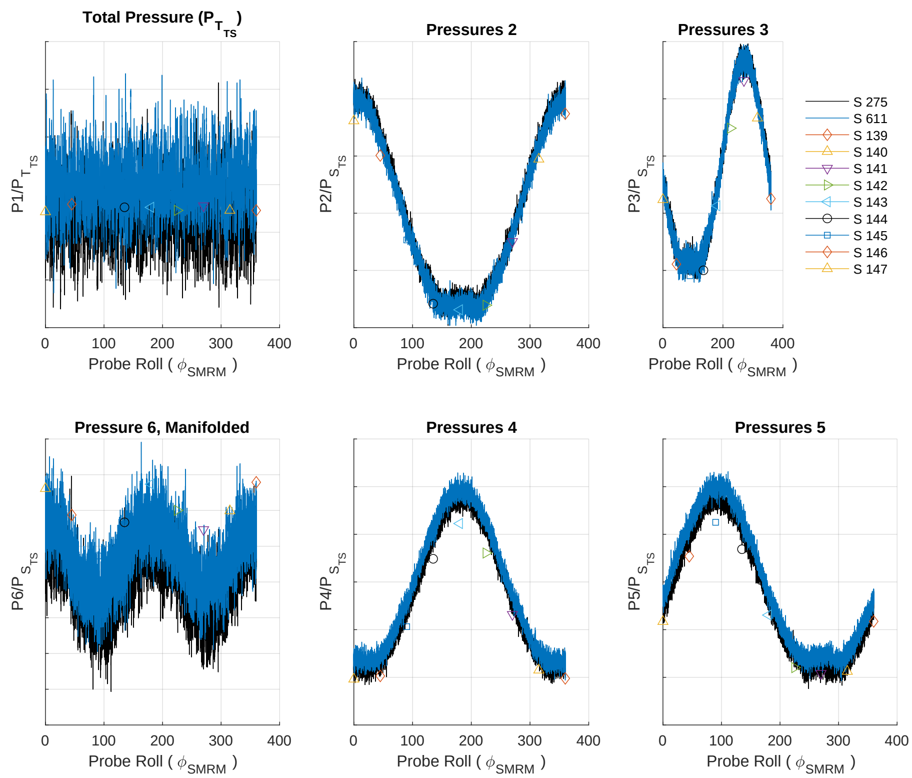


Fig. 24 Repeat roll sweep at Mach 0.26, Θ_{probe} -2°, Test C005 data.

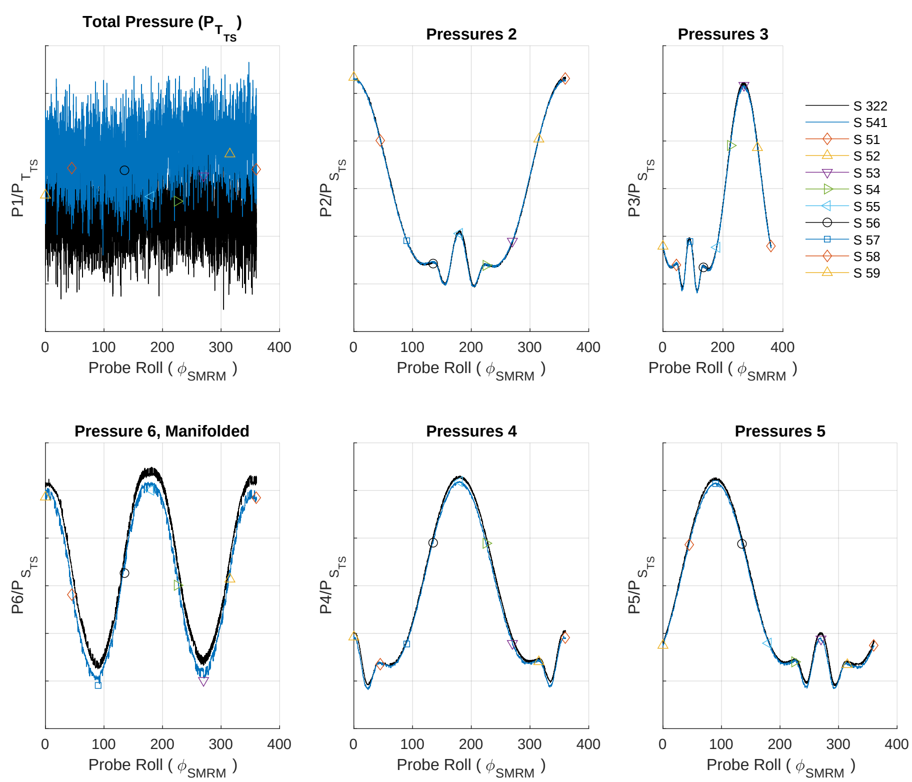


Fig. 25 Repeat roll sweep at Mach 1.25, Θ_{probe} -8°, Test C005 data.

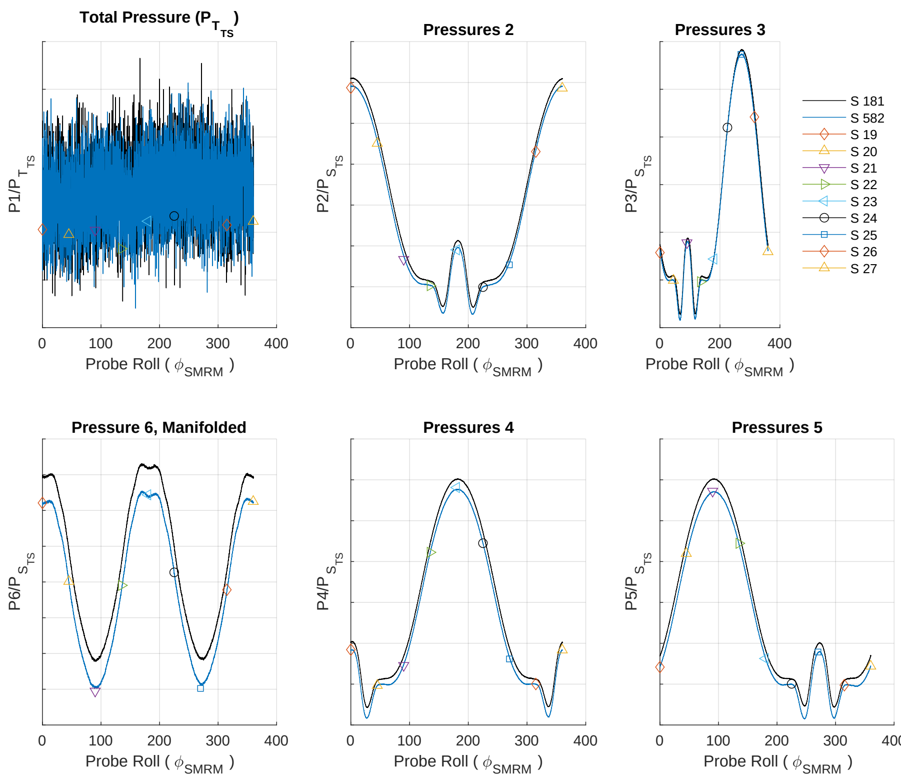


Fig. 26 Repeat roll sweep at Mach 1.46, Θ_{probe} -8°, Test C005 data.

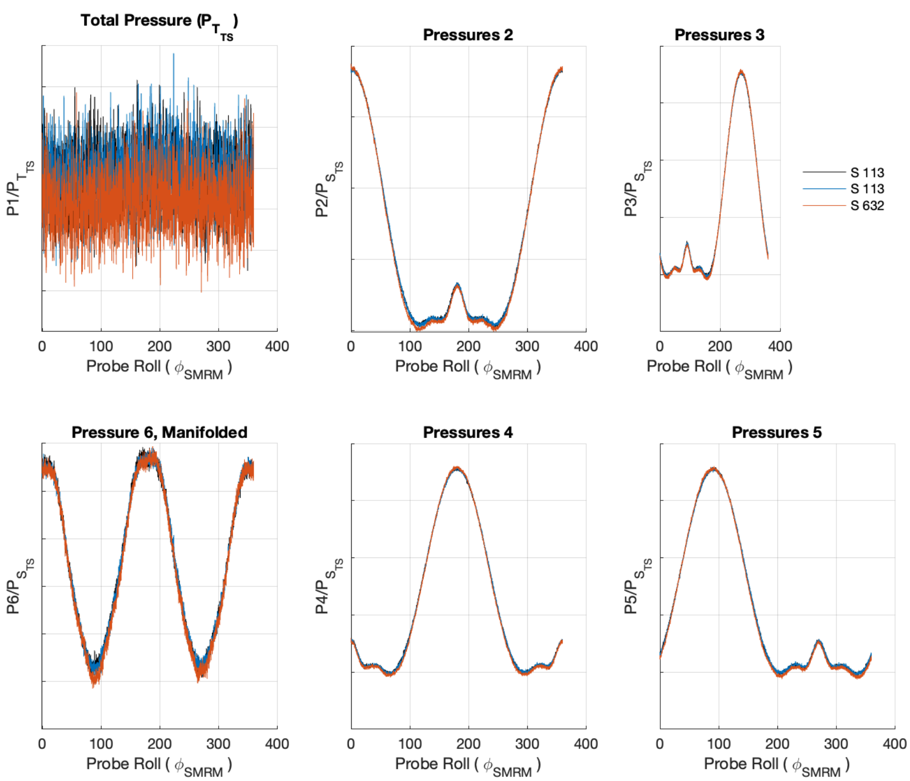


Fig. 27 Repeat roll sweep at Mach 0.4, Θ_{probe} -8°, Test C005 data.

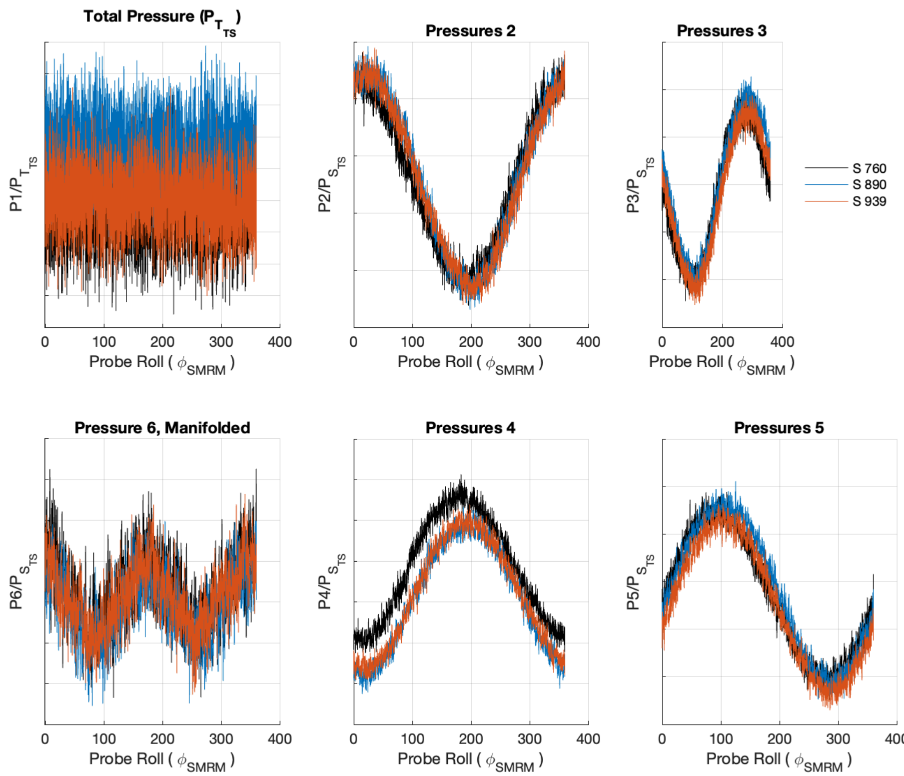


Fig. 28 Repeat roll sweep at Mach 1.35, Θ_{probe} 0°, Test C007 data.

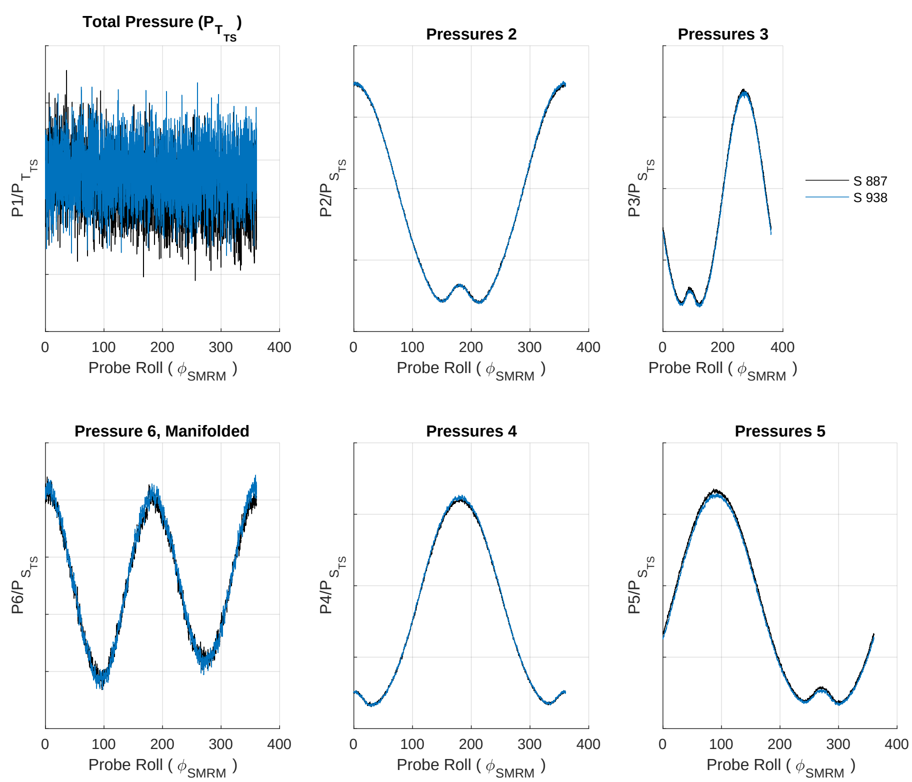


Fig. 29 Repeat roll sweep at Mach 1.46, Θ_{probe} -4°, Test C007 data.

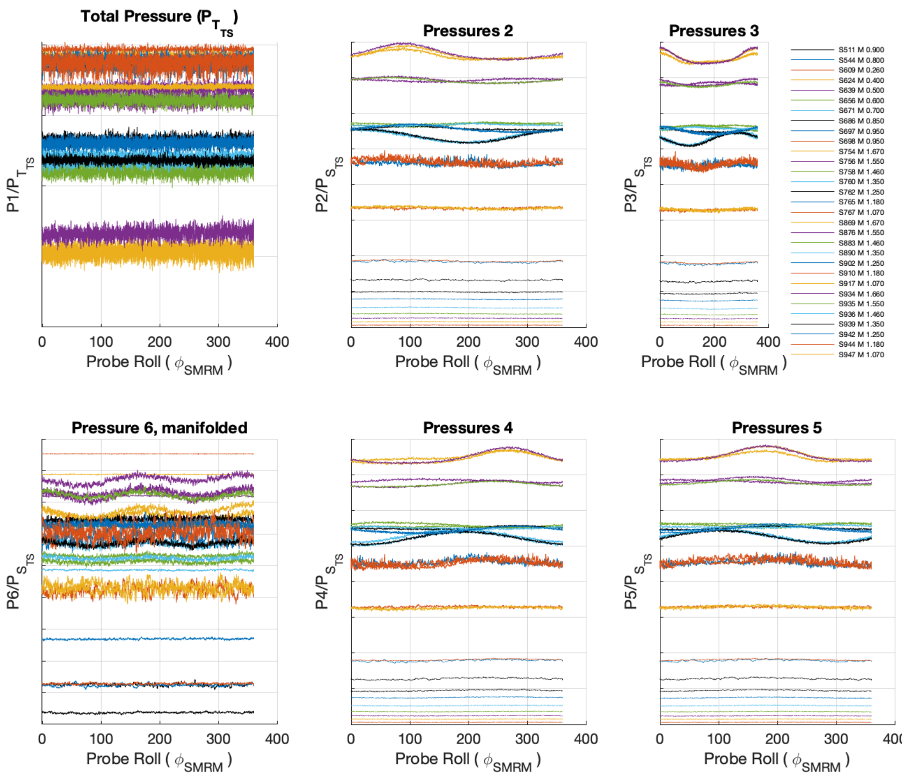


Fig. 30 Mach effects on continuous roll sweeps at Θ_{probe} 0°.

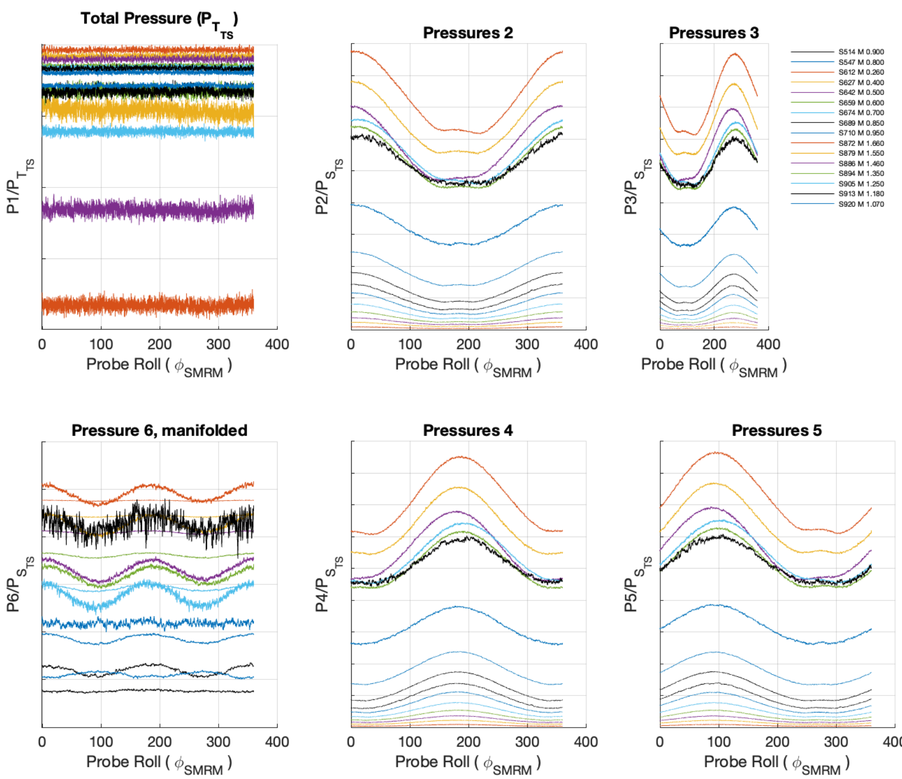


Fig. 31 Mach effects on continuous roll sweeps at Θ_{probe} -3°.

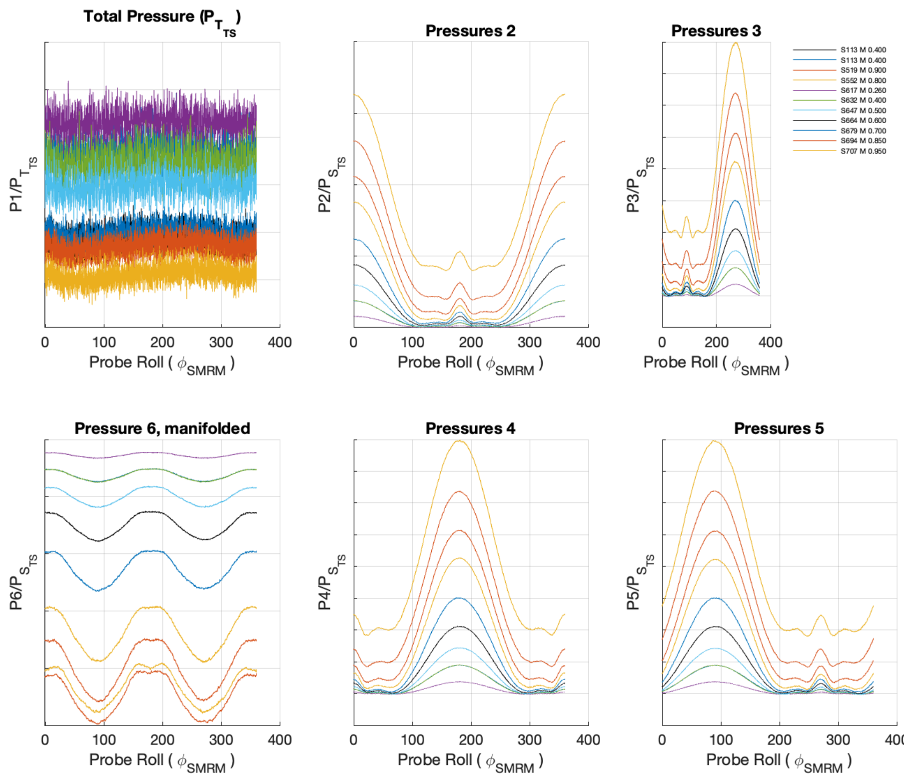


Fig. 32 Mach effects on continuous roll sweeps at Θ_{probe} -8°.

2. Probe Angle Effects in Mach

All calibration data Φ sweeps for each Mach number were plotted together, showing the probe angle effects in Mach. Figures 33 to 35 show a selection of the probe pressure plots at Machs 0.26, 0.8, and 1.25, respectively.

C. Mach Sweeps

Figure 36 shows P1 - P6 as a Mach sweep of the calibration data. All calibration data phi sweeps, with the zero data extracted, are shown in these plots. Each phi sweep collected thousands of scans while the probe rolled 360°, and the scans with ϕ at 0° were filtered out and averaged for these plot points.

VII. Concluding Remarks

The X-59 will fly with a nose probe as its primay instrument for determining airspeed, pressure altitude, angle of attack, and angle of sideslip of the aircraft in flight. The X-59 nose probe and an alternate probe were calibrated in the NASA Glenn Research Center 8- by 6-Foot Supersonic Wind Tunnel over two test campaigns. The probe was successfully tested and calibrated at 19 Mach numbers between Mach 0.25 and Mach 1.7. Most data were collected using continuous roll angle sweeps at a set Mach number and pitch angle. This allowed for the collection of large amounts of data in a smaller amount of time than point-pause data collection would allow. Knowing the aircraft's speed and attitude is critical for flight safety and is also critical data for the Sonic Boom mission.

GRC 8x6 best practices for wind tunnel testing were followed, including conducting pretest, installation, and in-test checks, calibrations and corrections. Long term repeat runs were plotted and reviewed, including comparing point-pause and continuous data. Repeat data were within the expected tolerances. Trend plots for Mach and roll at set probe angles were plotted and reviewed and showed expected trends.

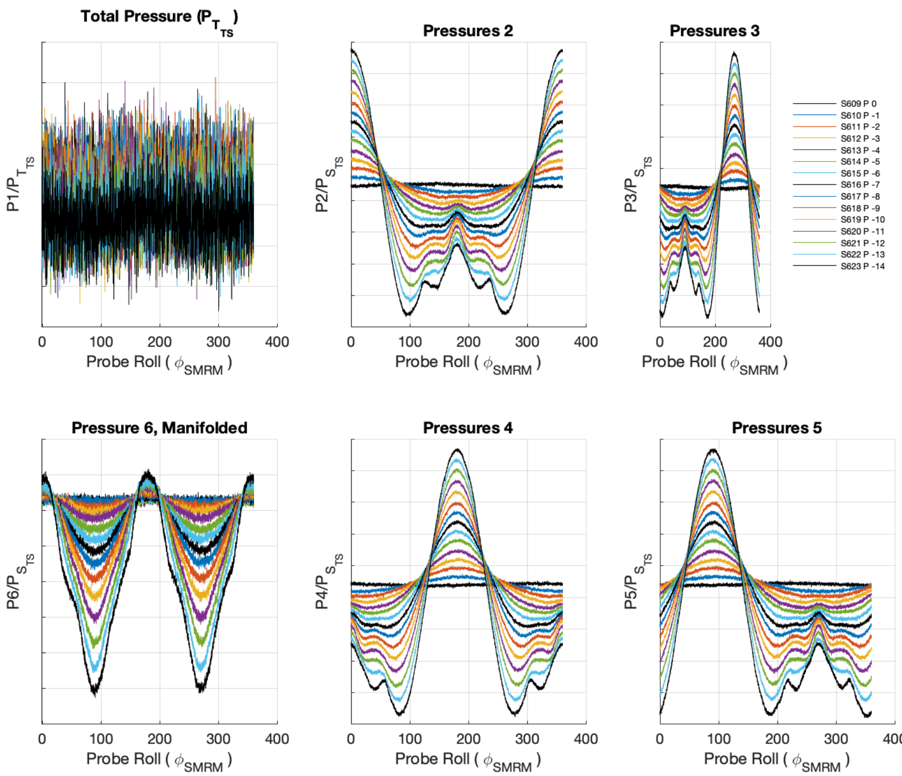


Fig. 33 Probe pitch angle effects on continuous roll sweeps at Mach 0.26.

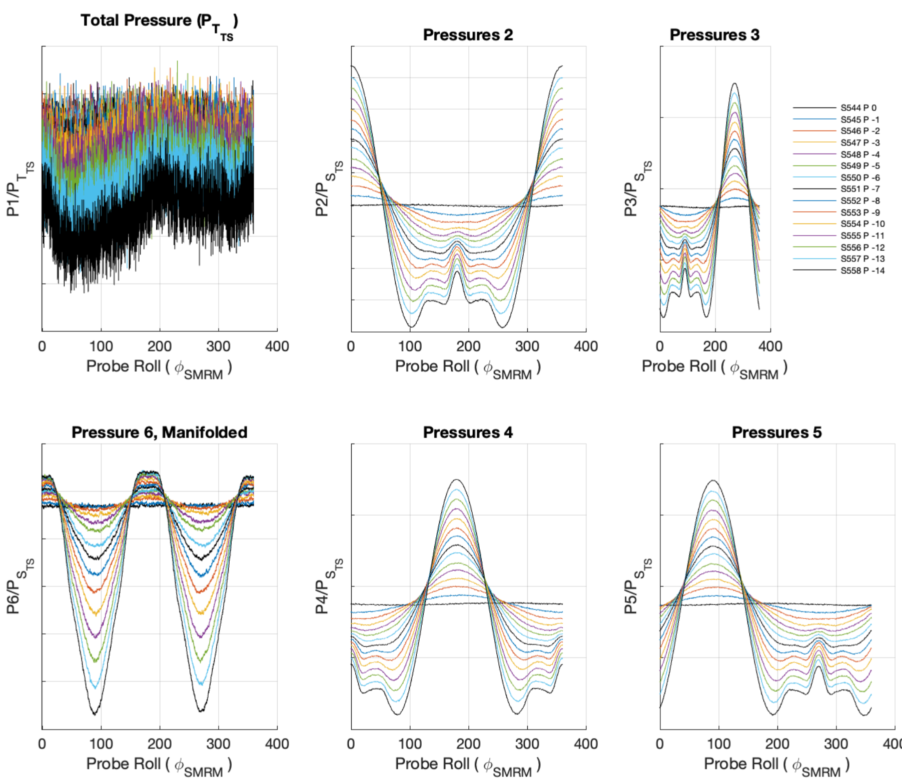


Fig. 34 Probe pitch angle effects on continuous roll sweeps at Mach 0.8.

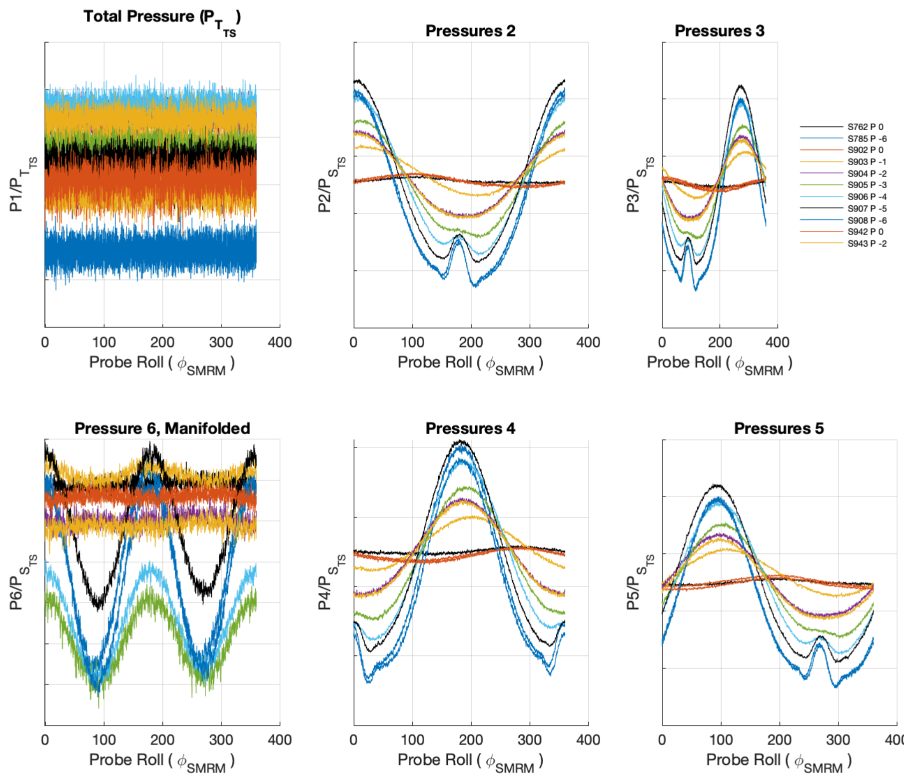


Fig. 35 Probe pitch angle effects on continuous roll sweeps at Mach 1.25.

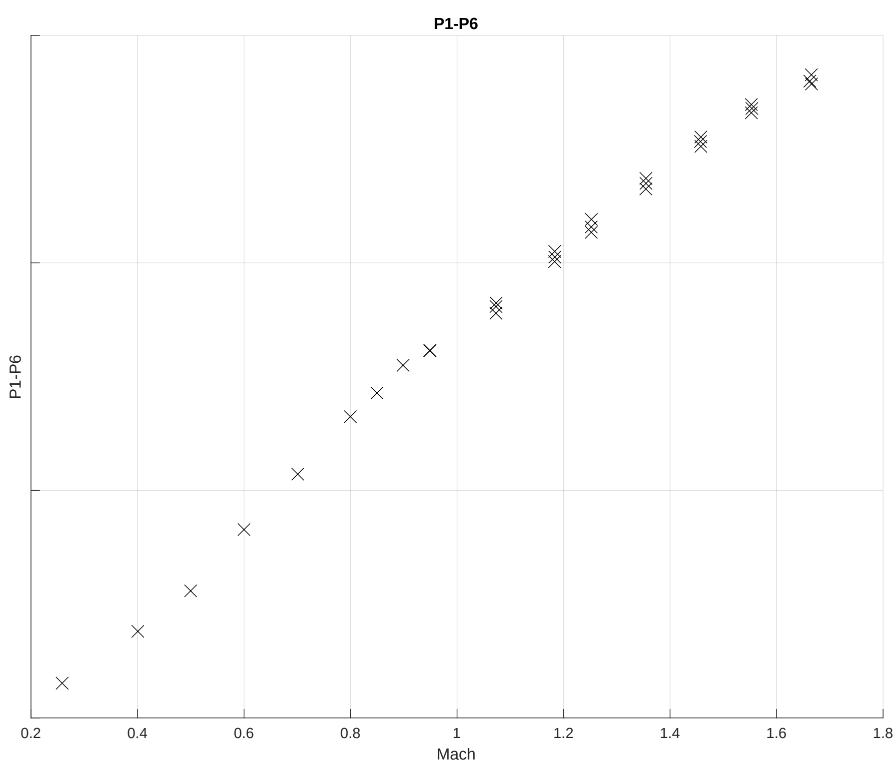


Fig. 36 Mach sweep, P1 - P6, Θ_{probe} 0°, ϕ_{SMRM} 0°.

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