# AERODYNAMIC TESTS OF THE SPACE LAUNCH SYSTEM FOR DATABASE DEVELOPMENT

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**The Aerosciences Branch (EV33) at the George C. Marshall Space Flight Center (MSFC) has been responsible for a series of wind tunnel tests on the National Aeronautics and Space Administration's (NASA) Space Launch System (SLS) vehicles. The primary purpose of these tests was to obtain aerodynamic data during the ascent phase and establish databases that can be used by the Guidance, Navigation, and Mission Analysis Branch (EV42) for trajectory simulations. The paper describes the test particulars regarding models and measurements and the facilities used, as well as database preparations.**

## Nomenclature

*ACB* = Advanced Concept Booster
*ARF* = Aerodynamics Research Facility
*BSM* = Booster Separation Motors
*CFD* = Computational Fluid Dynamics
*DAC* = Design Analysis Cycle
*GN&C* = Guidance, Navigation, and Control
*ICPS* = Interim Cryogenic Propulsion Stage
*LaRC* = Langley Research Center
*LAS* = Launch Abort System
*MPCV* = Multi-Purpose Crew Vehicle
*MPS* = Main Propulsion System
*MSA* = MPCV Spacecraft Adapter
*MSFC* = Marshall Space Flight Center
*NASA* = National Aeronautics and Space Administration
*OML* = Outer Mold Line
*SLS* = Space Launch System
*SRB* = Solid Rocket Booster
*TWT* = Trisonic Wind Tunnel
*UPWT* = Unitary Plan Wind Tunnel

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# I. Introduction

The Space Launch System (SLS) is currently under development by the National Aeronautics and Space Administration (NASA) and consists of a family of evolvable heavy-lift launch vehicles (Figure 1) that will carry both humans and cargo beyond low earth orbit. Ongoing is the third design analysis cycle leading to refinements of the ascent aerodynamic database developed during Design Analysis Cycle (DAC) 1 and 2 for the Block 1 crew SLS-10003 vehicle. Additionally, initial databases based on experimental data, rather than Computational Fluid Dynamics (CFD), were created for the configurations in the Block 1A and Block 1B family of vehicles using five-segment Solid Rocket Boosters (SRBs).

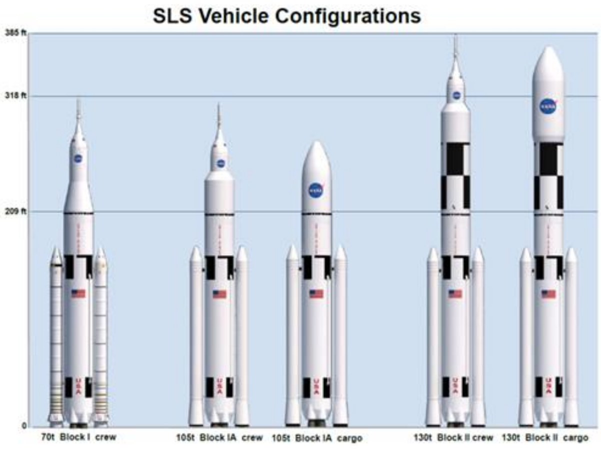


Figure 1. SLS Family of Vehicles

The Orion spacecraft from the Constellation program continues as the Multi-Purpose Crew Vehicle (MPCV). The core stage of the SLS is common to all of the vehicle configurations, essentially consisting of a modified Space Shuttle external tank with the aft section adapted to accept the rocket's Main Propulsion System (MPS) and the top converted to host an interstage structure. The stage will utilize varying numbers and versions of the RS-25 engine depending on the configuration to be used. In addition to the thrust produced by the engines on the core stage, first stage flight will be aided by two booster rockets, mounted on either side of the core stage, for the first two minutes. Early configurations of the SLS will use five-segment versions of the Space Shuttle Solid Rocket Boosters (SRBs). Later configurations are expected to employ an Advanced Concept Booster (ACB) utilizing either solid or liquid rocket engines.

# II. Test Summary

Aerodynamic wind tunnel tests were conducted by the Marshall Space Flight Center (MSFC) Aerosciences Branch (EV33) early within the SLS design cycles at the MSFC Aerodynamic Research Facility (ARF) on a variety of sub-scale SLS test articles using a six-component force and moment, internal strain gage balance. These tests encompass both full stack configurations with the SRBs mounted, center-body alone, and a special arrangement in which proximity aerodynamics were obtained during booster separation. These tests provide integrated force and moment aerodynamic data for first and second generation database development and complement other wind tunnel test programs. In addition, wind tunnel tests have also been performed on selected configurations to provide lift off transition aerodynamics, buffet loads, and aeroacoustic environments. Discussion of these experimental test programs are not part of this paper, but may be addressed by other authors.

Table 1 contains pertinent information regarding the test programs performed by EV33, highlighting the three main test entries used in the development of the first and second generation aerodynamic databases. The primary facility used for the test programs conducted by the MSFC Aerosciences Branch (EV33) was the MSFC ARF 14”

Table 1. Aerodynamic Tests conducted by the MSFC Aerosciences Branch

| PRODUCT ID | | | | | | | | | | | | CONFIG | TEST TITLE | TEST LOCATION | FACILITY | MODEL SCALE, % | FACILITY ID |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SLS | - | 10 | - | T | - | A | F | A | - | 001 | | 10000 | SLS DAC1 F&M TEST | MSFC | 14" TWT | 0.4 | TWT XP1.1 |
| SLS | - | 21 | - | T | - | A | F | A | - | 001 | | 21000 | SLS DAC1 F&M TEST | MSFC | 14" TWT | 0.4 | TWT XP1.1 |
| SLS | - | 10 | - | T | - | A | F | A | - | 002 | | 10000 | 0.004-scale msfc sls 10000 f&m model | LaRC | UPWT/TS1 | 0.4 | UPWT 2000 |
| SLS | - | 10 | - | T | - | A | F | A | - | 003 | | 10000 | 0.004-scale msfc sls 10000 f&m model | LaRC | UPWT/TS2 | 0.4 | UPWT 1871 |
| SLS | - | 10 | - | T | - | A | F | A | - | 006 | | 10003 | SLS DAC2 F&M TEST | MSFC | 14" TWT | 0.4 | TWT XP1.4 |
| SLS | - | 27 | - | T | - | A | F | A | - | 003 | | 27000 | SLS DAC2 F&M TEST | MSFC | 14" TWT | 0.4 | TWT XP1.4 |
| SLS | - | 28 | - | T | - | A | F | A | - | 003 | | 28000 | SLS DAC2 F&M TEST | MSFC | 14" TWT | 0.4 | TWT XP1.4 |
| SLS | - | 10 | - | T | - | S | F | A | - | 009 | | 10003 | SLS DAC2 PROXIMITY AERO | MSFC | 14" TWT | 0.4 | TWT XP1.5 |
| SLS | - | 10 | - | T | - | A | F | A | - | 013 | | 10003 | Transonic Case Study | MSFC | 14" TWT | 0.4 | TWT XP7.12 |
| SLS | - | 10 | - | T | - | A | F | A | | 014 | | 10003 | High Speed Schlieren | MSFC | 14" TWT | 0.4 | TWT XP1.12 |

Trisonic Wind Tunnel (TWT). However, the ARF's 0.4%-scale model was taken to the Langley Research Center (LaRC) Unitary Plan Wind Tunnel (UPWT) to obtain tunnel-to-tunnel comparisons. The results of the tunnel-to-tunnel comparisons were very favorable and provided an assessment of the wind tunnel test program being conducted during the early design process. A quick look tunnel-to-tunnel comparison can be seen in Figure 2.

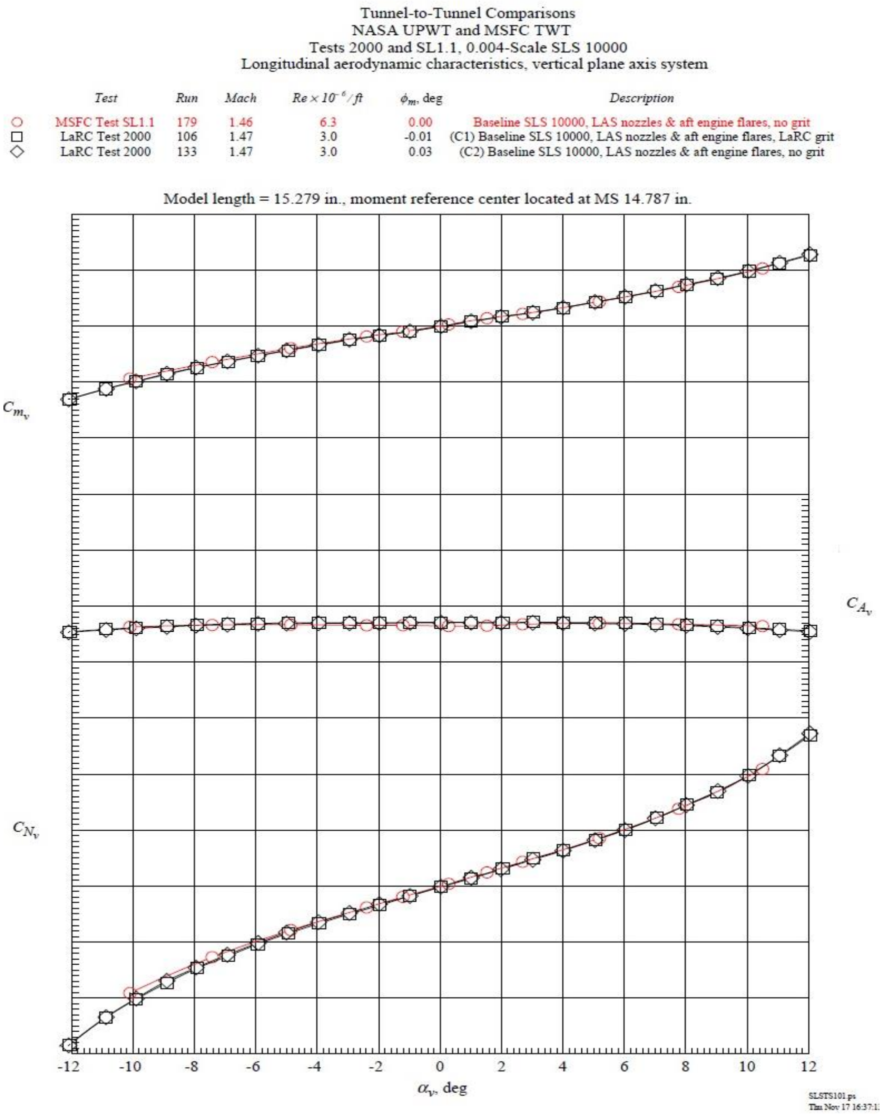


**Figure 2. Quick Look Tunnel-to-Tunnel Comparisons**

The initial ARF testing used relatively low fidelity scale models, but as the design matured, increased fidelity models were manufactured and captured vehicle protuberances as they evolved. One should note that due to model scale, some compromises are necessary from a manufacturability standpoint. This will be better defined in Section IV.

The early design test program consisted of more than 1650 wind tunnel runs equivalent to approximately 1100 tunnel occupancy hours. Six-component force and moment data were obtained at Mach numbers from 0.5 to 5 for total angles of attack ranging from ±10 degrees and selected roll angles between ±180 degrees. The measured force and moment data were used to populate a 16 x 16 "square" matrix of nominal points representing model attitudes between angles of attack and angles of sideslip of ±8 degrees. Some of this was accomplished directly via test data. In other instances interpolation between points or extrapolation beyond the data set were required to complete the matrix. In areas in which test data were not obtained, a mirroring logic was utilized based on the acquired data. The development of the first and second generation databases will be discussed in more detail in Section V.

## III. Test Facility Description

The NASA MSFC ARF TWT (Figure 3) is an intermittent, blow-down tunnel that operates from high-pressure storage to either vacuum or atmospheric exhaust. Each of its two interchangeable test sections measures 14 x 14 inches. The transonic section provides Mach numbers ranging from 0.2 to 2.5; and the supersonic section provides Mach numbers ranging from 2.74 to 4.96. [1] Air speed is varied in the subsonic range (Mach 0.2 to 0.9) by a controllable diffuser and in the transonic range (Mach 0.95 to 1.3) by auxiliary plenum suction and perforated tunnel walls, which allow for reflected shock wave cancellation. In the lower supersonic range, air speed is varied using interchangeable nozzle blocks to achieve discrete Mach numbers, namely 1.46, 1.68, 1.96, and 2.5. In the higher supersonic range (Mach 2.74 to 4.96), air speed is varied in approximately 0.25 increments by tilting fixed contour plates positioned by hydraulic screw jacks to control the nozzle throat and test section areas.

A hydraulically-controlled pitch sector located downstream of the test section provides angles of attack between nominally ±10 deg. Various offsets are used to achieve higher angles of attack while still remaining within sector limits. There is no remote roll capability. The sector assembly and diffuser telescope to allow access to the model and test section in order to more easily make roll and configuration changes.

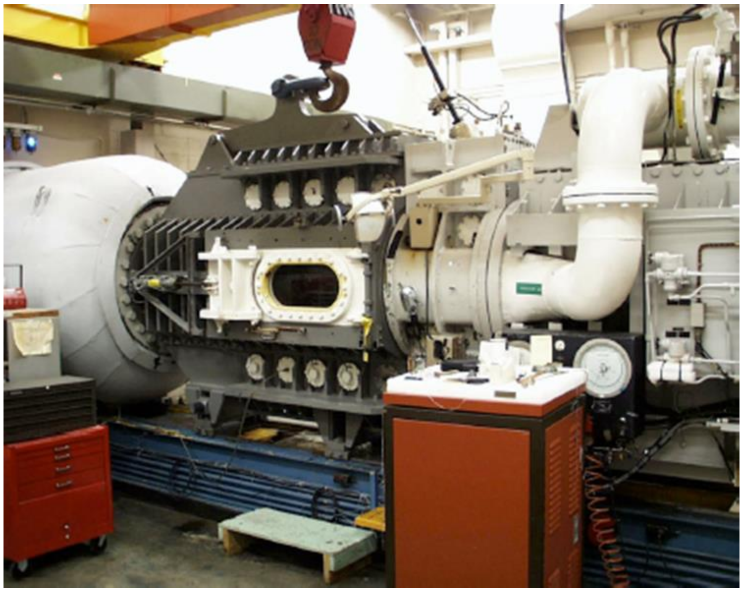


**Figure 3. The MSFC Aerodynamic Research Facility's 14" Trisonic Wind Tunnel**

Tunnel conditions are measured and recorded during each wind tunnel run using various transducers, thermocouples, and other instrumentation. Tunnel stilling chamber temperature is measured using a thermocouple connected to a Phoenix Contact MCR-E-UI-E Thermocouple Signal Conditioner resulting in an uncertainty of approximately 0.5 °F. Tunnel stilling chamber pressure is measured using a Druck PMP4070 transducer with a range from 0 to 100 psia and an accuracy of ±0.04% of full scale. Atmospheric pressure is measured using a Honeywell precision barometer, model HPA200, with a range from 0 to 911 mmHg (0 to 17.6 psia) and an accuracy of ±0.3 mmHg (0.006 psia). The model pressures are measured using a Scanivalve brand DSA3217/16Px array with a range of ±15psid and an accuracy of ±0.05% full scale. Sector angle of attack is measured using a Dynapar AI2500 encoder with an uncertainty of approximately ±0.01 deg.

## IV. Test Articles & Procedure

The test articles used for the three primary tests utilized in the development of the aerodynamic databases at MSFC are described in detail below. The first and second generation aerodynamic databases were developed using the data from three primary wind tunnel tests. Although several additional investigative tests have been completed at the MSFC and LaRC wind tunnels during the early design development of SLS, the discussion in this paper will be primarily focused on the testing of the initial SLS configurations, XP1.1, the higher fidelity SLS configurations, XP1.4, and the booster separation wind tunnel test, XP1.5.

### A. TWT XP1.1

The wind tunnel test XP1.1 was the first entry under the SLS wind tunnel test program. Testing took place in the NASA MSFC ARF 14-inch TWT between 13 September and 5 October 2011. Two SLS configurations were modeled during the test. The first configuration, the SLS-10000, included two SRBs, a core stage, an upper stage on which the MPCV is mounted, and the LAS tower. The second configuration tested, designated the SLS-21000 at the time, was the heavy lift configuration on which a large payload shroud was mounted. The SLS-21000 included two SRBs, a core stage, and a large second stage payload shroud. Both models utilized common hardware, which included the two SRBs, a core stage, and a 25.6 degree boat-tailed aft body. The SLS-10000 configuration was initially tested while the LAS tower nozzles and base engine fairings were being fabricated, and then tested later once they were completed. Full-scale sketches of both vehicle configurations highlighting the common core, boosters, and MPCV are illustrated in Figures 4 (Reference [2]). Each test article was instrumented with the MSFC ARF ½-inch six-component, open flexure, internal strain gage balance with a calibration uncertainty of 0.1% of the full scale load. The balance was contained within the common center-body. Each test article was mounted using the straight sting and extension which afforded an angle of attack range of ±10 degrees with a 360 degree manual roll capability. Static pressure was measured with sting-mounted tubes at six locations in the base of each model. Four locations were at the base of the core oriented in a cruciform arrangement, and the remaining two were centered at the base of each booster (Figure 5). Base pressure data were obtained to adjust the axial force and yawing moment

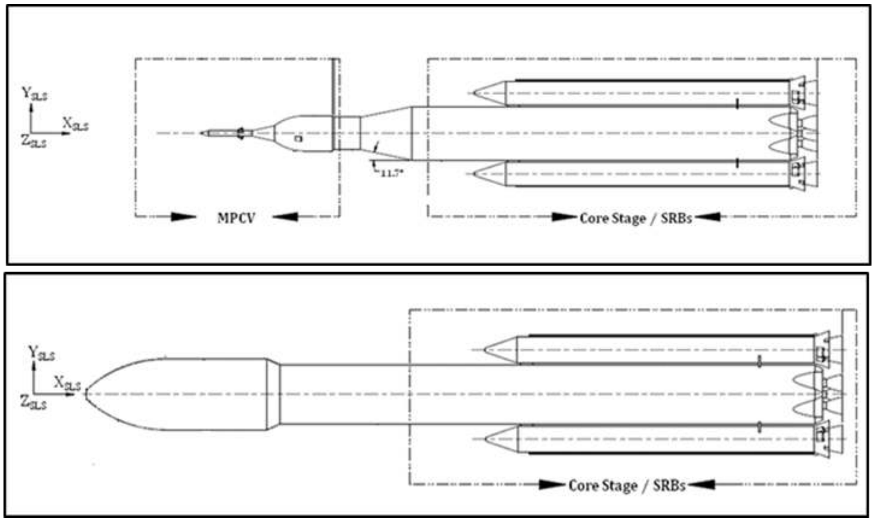


**Figure 4. Sketch of the SLS-10000 (top) and SLS-21000 (bottom) vehicles modeled for XP1.1**

coefficients for base drag. The models were tested over a Mach number range of 0.3 through 4.96 at angles of attack between ±8 degrees and discrete roll angles between -45 and 90 degrees.

Similar to the actual full-scale vehicle design, only the upper/second stages (forward bodies) of the two test articles varied. The upper/second stages were interchanged with a single center-body, boat-tailed aft end, and the two SRBs in order to fully assemble the stack. An aft and a forward pair of stand-off posts were used to attach the SRBs to the core. The attach points were centered equivalent to the axial stations of the full-scale vehicle, though the dimensions of the posts were not scaled. The common center-body with balance adapter was fabricated of H950 heat-treated 17-4 stainless steel. The remaining components were composed of 6061-T6 aluminum alloy.

**Figure 5. Base Pressure Tube Arrangement**

Grit was added on the SLS-10000 test article without the LAS nozzles in order to transition the boundary layer from laminar to turbulent flow. The grit was #180 silicon carbide grain and applied in a band approximately 0.1 inch wide just aft of the LAS tower and forward of the common core stage as shown in Figure 6.

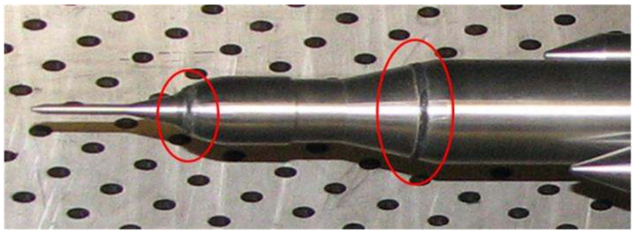


**Figure 6. Grit Applied to the SLS-10000 Model without LAS Nozzles**

Grit was not applied to the SLS-10000 test article with LAS nozzles, since it was assumed that the nozzles served as a transition mechanism (Figure 7). Similarly, grit was not added to the SLS-21000 because the spherically-blunt ogive nose was inadvertently machined with a flaw that was assumed to serve as a transition mechanism. The groove is approximately 0.03 in. wide and located 0.5 inches from the nose tip (Figure 8).

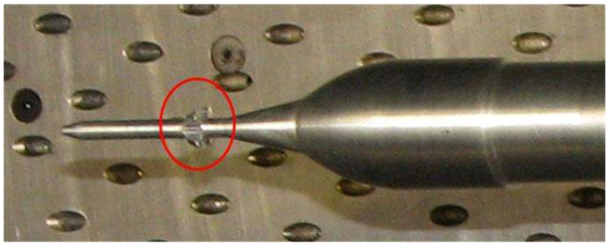


**Figure 7. No Grit Applied to the SLS-10000 Model with LAS Nozzles**

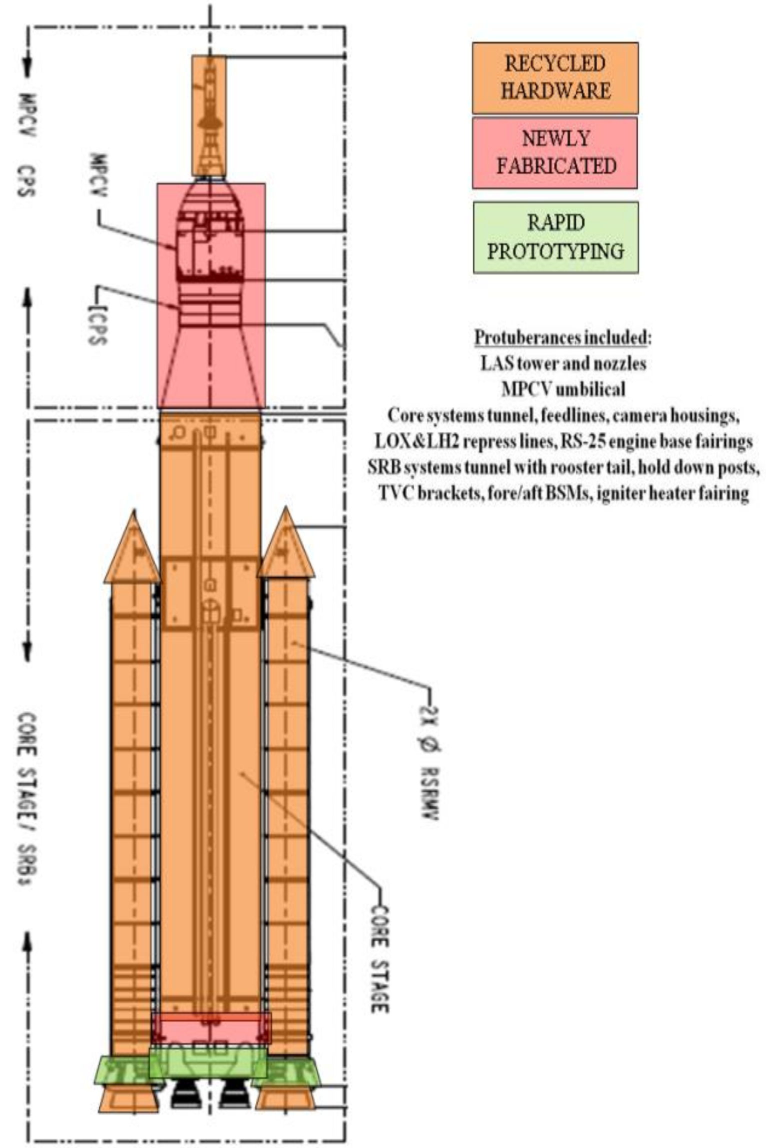
**Figure 8. Machined Flaw on SLS-21000 Model**

### B. TWT XP1.4

The primary test objective of the second main SLS test entry in the MSFC ARF, designated XP1.4, was to acquire six-component force and moment data on 0.4%-scale models with increased fidelity in order to update and/or develop the aerodynamic databases for the current configurations. This test complemented the previously discussed entry (XP1.1) for the DAC-1 version of the SLS-10000 configuration. In addition, a companion test utilizing 0.8%-scale models was also conducted in the LaRC UPWT supersonic test sections. Testing for XP1.4 was performed between 15 May and 25 July 2012. Priority was given to the SLS-10003 configuration and all runs, excluding transonic center-body alone, were acquired before any testing occurred with any other configuration. The test articles utilized the same 6-component strain gage balance, sting hardware, and base pressure arrangement as discussed in the previous section. The models were tested over a Mach number range of 0.3 through 4.96 at angles of attack between ±9.5 degrees and discrete roll angles between 0 and 180 degrees in 22.5 degree increments.

Three 0.4%-scale Space Launch System configurations were tested during the XP1.4 wind tunnel test which included: SLS-10003, SLS-27000, and SLS-28000. Model design was based on early release drawings of the vehicle full scale outer mold lines (OML), although there were some changes prior to completing the model fabrication that were incorporated. These changes will be addressed subsequently. The models are described as increased fidelity from that of the DAC-1 test article because of the addition of protuberances. Typically, a model of this scale would have only modeled protuberances and other external features of a size of ~10 inches or greater in vertical height full scale (0.040-inch model scale). However, in order to have more representative components of the vehicle geometry, smaller parts that were less than 10 inches full scale were fabricated and included on the model where possible.

The models utilized common hardware which included the center-body and two SRBs. The upper stage was interchangeable between the three configurations forward of the separation plane at vehicle STA 2332.01. For the SLS-10003 and SLS-28000 configurations, the LAS tower with nozzles and the MPCV were also used in common and only the Interim Cryogenic Propulsion Stage (ICPS) or the MPCV Spacecraft Adapter (MSA)/forward skirt and interstage were varied. The SLS-27000 configuration simply replaced the upper stage with the payload fairing shroud. In order to expedite the schedule, several components utilized existing hardware, with or without modification, as well as employing the use of rapid prototyping of several parts, particularly in the case of the SRB aft skirt. A summary of the protuberances modeled, new fabrication, existing hardware, and rapid prototyped pieces is shown in Figure 9.



**Protuberances included:**
LAS tower and nozzles
MPCV umbilical
Core systems tunnel, feedlines, camera housings,
LOX&LH2 repress lines, RS-25 engine base fairings
SRB systems tunnel with rooster tail, hold down posts,
TVC brackets, fore/aft BSMs, igniter heater fairing

**Figure 9. SLS Test Article Parts Identification used during XP1.4**

The main portion of the center-body was fabricated of 17-4 Ph stainless steel. This center-body piece was fabricated following the test in Reference [2] in order to move the balance center forward and improve the load distribution. The forward face of the center-body was designed to be equivalent to the separation plane between the core and upper stage (i.e., vehicle STA 2332.01). Other legacy hardware included the LAS tower with four nozzles and the two, five-segment SRBs, all fabricated of 6061-T6 aluminum.

The aft skirt on each of the existing SRBs was machined down to a cylindrical stub onto which a new, rapid-prototyped aft skirt was made to fit and sandwiched in place between the body and the nozzle extension affixed by a #10-24 socket head cap screw. All aft skirt protuberances were incorporated into the new aft skirt comprised of an epoxy resin. These protuberances consisted of the systems tunnel shroud, also commonly referred to as the rooster tail, 4 aft Booster Separation Motors (BSMs), hold down posts (4), Thrust Vector Control (TVC) brackets (2), and a Range Safety System (RSS) antenna. The SRB systems tunnels utilized the epoxy resin, as well. The SRB forward assembly and aero shells were also modified to accommodate the forward BSMs which were made from 1-mm diameter x 5-mm long stainless steel dowel pins. The pins were filed down to the appropriate protrusion height from the nose cone. It should be noted that the booster attachment geometry, including the attach ring, was not modeled for this test. Instead, previously used stand-offs were employed to provide the correct separation distance between the core and the SRBs when mated. Also, the aft attach point was not representative of the current vehicle location, but rather was upstream by 0.972 inches (model scale).

The MPCV umbilical, two core stage camera housings, LO2 and LH2 re-pressurization line forward fairings, and the core stage systems tunnel were manufactured with epoxy resin and glued to the test article. The two LO2 feedlines were constructed of 0.065-inch outer diameter stainless steel tubing, cut to length and epoxied to the core stage. A large LO2 feedline fairing had been made of the epoxy resin, but subsequent vehicle design changes from the early release drawings had removed this feature and re-oriented the radial positioning of the feedlines. The fairing was not used. The LO2 and LH2 re-pressurization lines were constructed of 0.014-inch diameter 304 stainless steel single strand wire, cut to length and glued to the model. The core stage boat tail aft body with four engine fairings arranged in an "x" configuration was also made via rapid prototyping using a polycarbonate material. This 0.202-inch long piece was affixed to a 6061-T6 aluminum aft core cylindrical extension with four #4-40 flat head cap screws. The four core stage RS-25 nozzles were not modeled.

Testing was primarily performed with boundary layer trips installed. Carborundum grit (no. 90, or an average height of 0.0057 inches) was applied for transonic Mach numbers less than M=1.96. Thereafter, the grit was removed and vinyl trip dots were used. A single grit band, approximately 0.1-inch wide, was applied to the core stage with a cyanoacrylate adhesive (i.e., superglue) at the ogive-cylinder tangency point. The self-adhesive trip dots, also applied at the ogive-cylinder tangency point, were 0.050 inches in diameter and 0.0056 inches high on 0.1-inch centers. Trips were not applied to the SRBs.

## C. TWT XP1.5

The wind tunnel test conducted under the facility test number XP1.5 took place in the MSFC ARF 14 x 14-inch TWT between 1 November 2012 and 9 January 2013. The primary objective of the wind tunnel test was to acquire proximity, dual-body, six-component force and moment aerodynamic data for power-off conditions on a 0.4% scaled SLS-10003 model in order to compile a separation aerodynamic database. The separation database was delivered during the SLS DAC-2 cycle to Guidance, Navigation and Control (GN&C) in order to improve their separation trajectory analysis. A secondary objective was to provide overlapping conditions for CFD comparisons. During the XP1.5 test entry, 275 runs were obtained for 200 configurations. Each configuration established linear and angular displacements between the SLS center-body and the five-segment SRBs in order to capture the predicted GN&C separation trajectory conditions. All configurations were tested at Mach 4.25 (the nominal separation Mach number) at angles of attack between either ±2 degrees or ±4 degrees, with select configurations also tested at Mach 4 and 4.45.

Existing installation hardware, most of which were fabricated for a Space Shuttle Orbiter aerodynamic separation test in the MSFC ARF, was repurposed for this test. It was designed to adjust the metric SRBs' linear positions and/or angular orientations relative to the center-body. The SRB positions were varied symmetrically for each rig configuration. Two six-component internal strain gage balances and a single dummy balance were used during the XP1.5 wind tunnel test. The center-body was instrumented with the MSFC ARF ½-inch balance designated 250D, the left booster was instrumented with the MSFC ARF 0.375-inch balance designated 241B, and the right booster was instrumented with a 0.375-inch dummy balance comparable to 241B. The booster installation and instrumentation setup is illustrated in Figure 10.

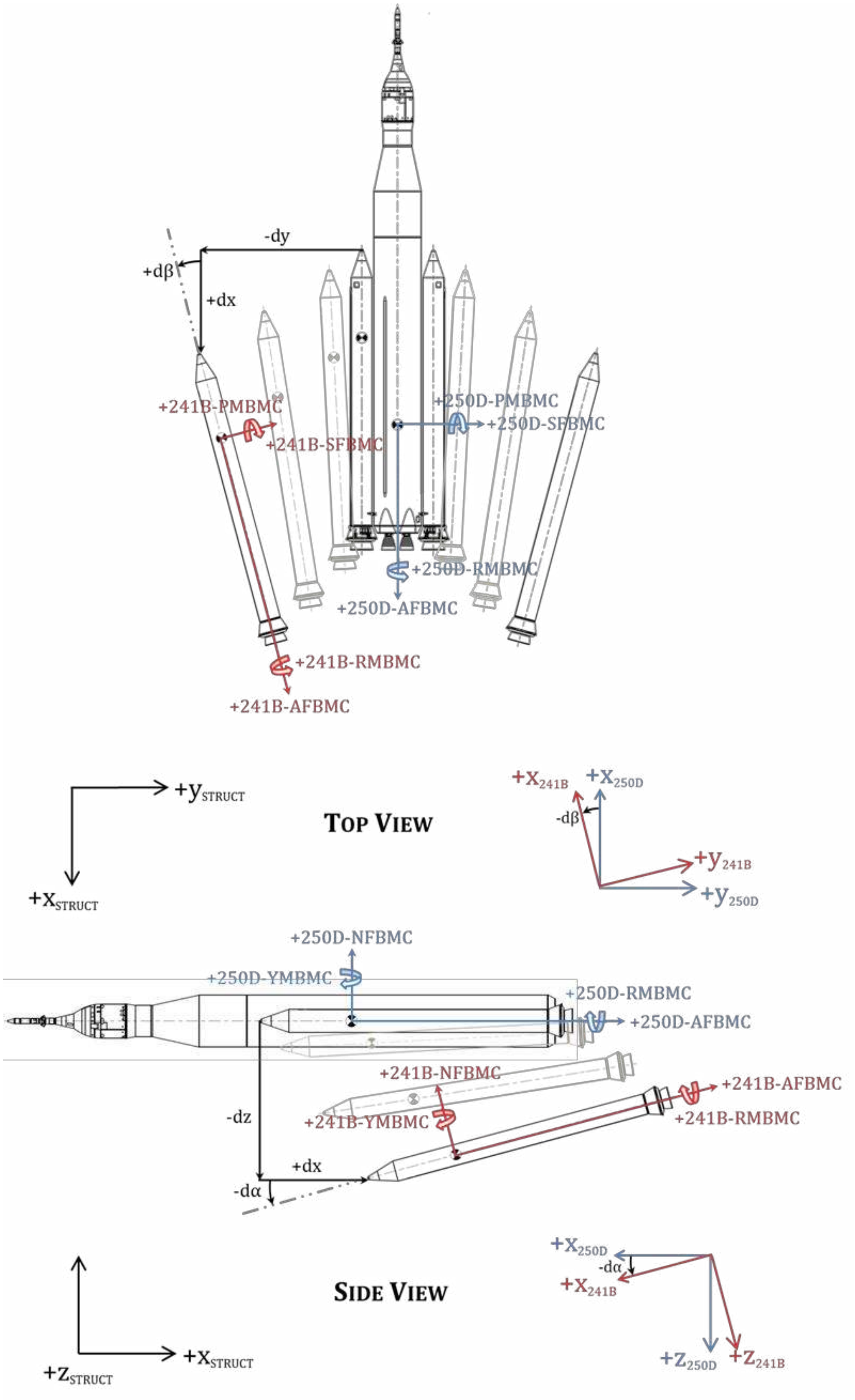


**Figure 10. SLS Booster Separation Setup and Installation on Test Article used during XP1.5**

The model used for the XP1.5 wind tunnel test consisted of a full-stack 0.4% scale SLS-10003 test article assembled using a center-body and either a metric (capable of being instrumented with a balance) or non-metric pair of solid rocket boosters. The center-body (Figure 11) was mostly comprised of pre-existing parts fabricated of aluminum or steel. These pre-existing parts included the LAS with nozzles, machined from aluminum; the MPCV, machined from aluminum and including the umbilical; the ICPS, also machined from aluminum; and a 4.9-inch long cylindrical segment that housed the balance and its adapter, machined from steel and modified to accommodate a new center-body base. The newly fabricated parts included a 0.5-inch high center-body boat tail with engine fairings fabricated of polycarbonate, the center-body systems tunnel, also fabricated of polycarbonate, two liquid oxygen feed lines with fairings modeled with 0.065-inch outer-diameter stainless steel tubing and polycarbonate, and a 4.6-inch cylindrical extension machined of aluminum and placed between the ICPS and balance segment so that the center-body was the proper scaled length.

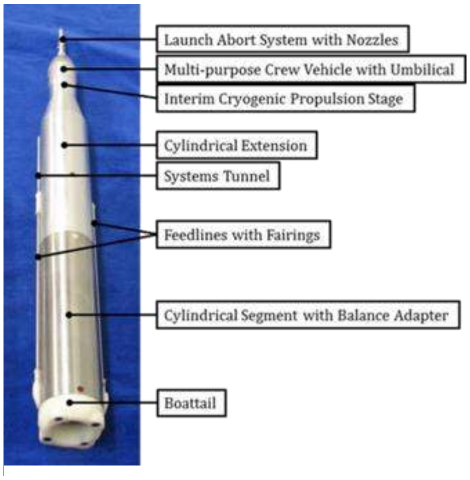


**Figure 11. SLS Center-Body**

The non-metric boosters (Figure 12, right) were also pre-existing. They were modified to accommodate a shorter center-body base and better model the locations of the aft attach points. These boosters were machined primarily of aluminum and included the nozzle extensions, aft skirts modeled with aft BSMs and rooster tails fabricated of epoxy resin, systems tunnels fabricated of epoxy resin, and nose cones with forward BSMs modeled using 1-mm diameter stainless steel dowel pins. The non-metric boosters were used for only integrated full stack runs during the test.

The second set of boosters (Figure 12, left) were newly fabricated in order to accommodate a 0.37-inch diameter balance located in the pilot's left-hand SRB or a similar-sized dummy balance located in the pilot's right-hand SRB. These boosters were machined primarily of an aluminum body and included the aft skirts, systems tunnels, and nose cones. The 0.4-inch long aft skirts, modeled with aft BSMs and rooster tails, along with the systems tunnels were fabricated of polycarbonate and attached to the aluminum body using epoxy. The nose cones with forward BSMs were fabricated of Inconel using a rapid prototype machining technology, sanded smooth, and attached to the aluminum booster body using screws. The metric boosters were used for all the proximity configurations.

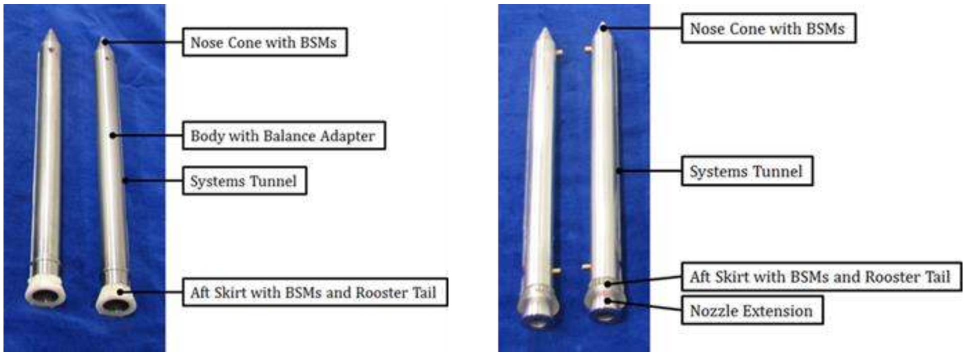


**Figure 12. Metric (left) and Non-Metric (right) Boosters**

## V. Database Preparation

The testing described was used to generate a first and second generation force and moment aerodynamic coefficient database for use by the GN&C community for ascent trajectory analysis. The second generation database improved on the previous first generation with the addition of vehicle protuberances on the wind tunnel model and thus increasing the fidelity of the database. The full stack database was generated using wind tunnel test data from the NASA MSFC ARF. While a predominance of the database was populated directly with wind tunnel test data, there were a few points that were analytically generated using interpolation or extrapolation from the wind tunnel data.

The first step in utilizing the wind tunnel test data was to examine all test data for adherence to expected trends and for the existence of data points that might lie outside the bands of expected test uncertainty. This process was completed "real time" during the wind tunnel testing by test personnel. After this was completed all test data were interpolated to even increments at cardinal values of total angle of attack. This step was necessary because the raw wind tunnel test data were not taken at integer values of total angle of attack. The final database requires the values of angle of attack and angle of sideslip to be even incremented, so a linear interpolation scheme was used to adjust the wind tunnel test values. These adjustments were very minor in nature as the angle of attack data measured during testing were close to the required evenly incremented values. The linear interpolation was performed on each wind tunnel test run individually. The interpolation was done using the two closest recorded test points to a given even value of total angle of attack to minimize error and to account for a small non-linearity in the aerodynamic coefficients. The resultant points are represented by the black squares in Figure 13. Next, the total angle of attack and roll angle combinations were converted to angle of attack and angle of sideslip values. For orientations not at a value of 0° for angle of attack or angle of sideslip, the angles of attack and angles of sideslip required even incrementing to cardinal values. Because the wind tunnel test data was collected for a constant roll orientation, a linear interpolation method was used. The “distance” of an even incremented point between measured points was used to determine the aerodynamic coefficient values at the evenly incremented values of angle of attack and angle of sideslip. The details of this interpolation method are given in Eq. (1):

$$C_x = \frac{\sqrt{(\beta_x - \beta_1)^2 + (\alpha_x - \alpha_1)^2}}{\sqrt{(\beta_2 - \beta_1)^2 + (\alpha_2 - \alpha_1)^2}} * (C_2 - C_1) + C_1 \tag{1}$$

where C represents any one of the six aerodynamic coefficients being interpolated, α represents the angle of attack, β represents the angle of sideslip, and the subscripts 1 and 2 denote the points closest to the point being interpolated, x. The resultant points are represented by the red circles in Figure 13. This methodology is NOT used for any points other than the red points in Figure 13. For the special cases along either a line of 0 degrees angle of attack or 0 degrees angle of sideslip, the values at the already evenly incremented total angle of attack were able to be used.

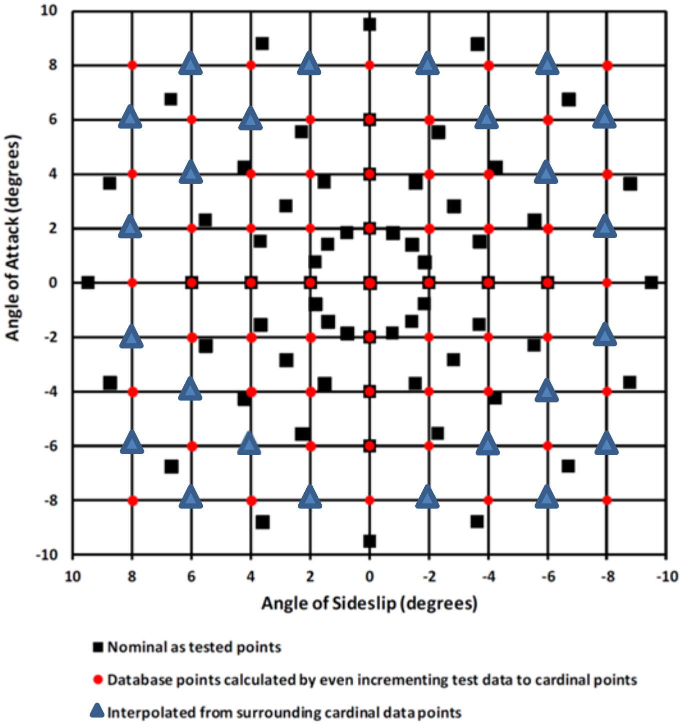


**Figure 13. Database Population Matrix**

Due to the nature of how wind tunnel testing is conducted in the ARF (i.e., total angle of attack sweeps at constant roll angles) there were some data points that required two-dimensional interpolation or extrapolation to complete the square database space. The points needing to be interpolated or extrapolated are denoted in blue in Figure 13. The points along the edge of the database space were calculated using the two closest points in the matrix. For example, to obtain data at (α, β) = (8,6) the data points at (8,8) and (8,4) were used. Points on the interior of the database space used the closest surrounding four data points to interpolate for the missing values. For example to obtain data at (α, β ) = (4,6) the data points at (2,6), (6,6), (4,4) and (4,8) were used. The resultant points are represented by the blue triangles in Figure 13.

Because testing was done at roll angles ranging from 0 to 180 degrees and at total angles of attack from ± 9.5 degrees, no mirroring was needed to populate all four quadrants of the database space for the second generation database as was done in the prior first generation database. Because no mirroring was utilized, the effects of all protuberances are represented accurately at all combinations of angle of attack and angle of sideslip and, as such, the database was able to be completely populated. Table 2 outlines the complete aerodynamic realm that the second generation SLS-10003 full stack database covers. Figure 14 provides a coordinate axis system definition for the database.

**Table 2. Full Stack Database Aerodynamic Parameters**

| Test Parameter | Values |
|---|---|
| Mach Number (M) | 0.30, 0.60, 0.80, 0.90, 0.95, 1.05, 1.10, 1.20, 1.30, 1.46, 1.96, 2.99, 4.00, 4.96 |
| Angle of Attack ($\alpha$) | -8, -6, -4, -2, 0, 2, 4, 6, 8 degrees |
| Angle of Sideslip ($\beta$) | -8, -6, -4, -2, 0, 2, 4, 6, 8 degrees |

The axial force coefficient values in the second generation database were increased by 3.0% over the values measured in the wind tunnel. This increase is to account for axial force coefficient increases due to external protuberances being added to the vehicle OML as the design matures. The 3.0% value was based on historical data for a number of launch vehicles. No increases were made to any other aerodynamic coefficients to account for OML changes. Similarly, the dispersions provided accounted for experimental and database generation errors only. Dispersions do not take into account changes in OML and associated changes in the aerodynamic coefficients.

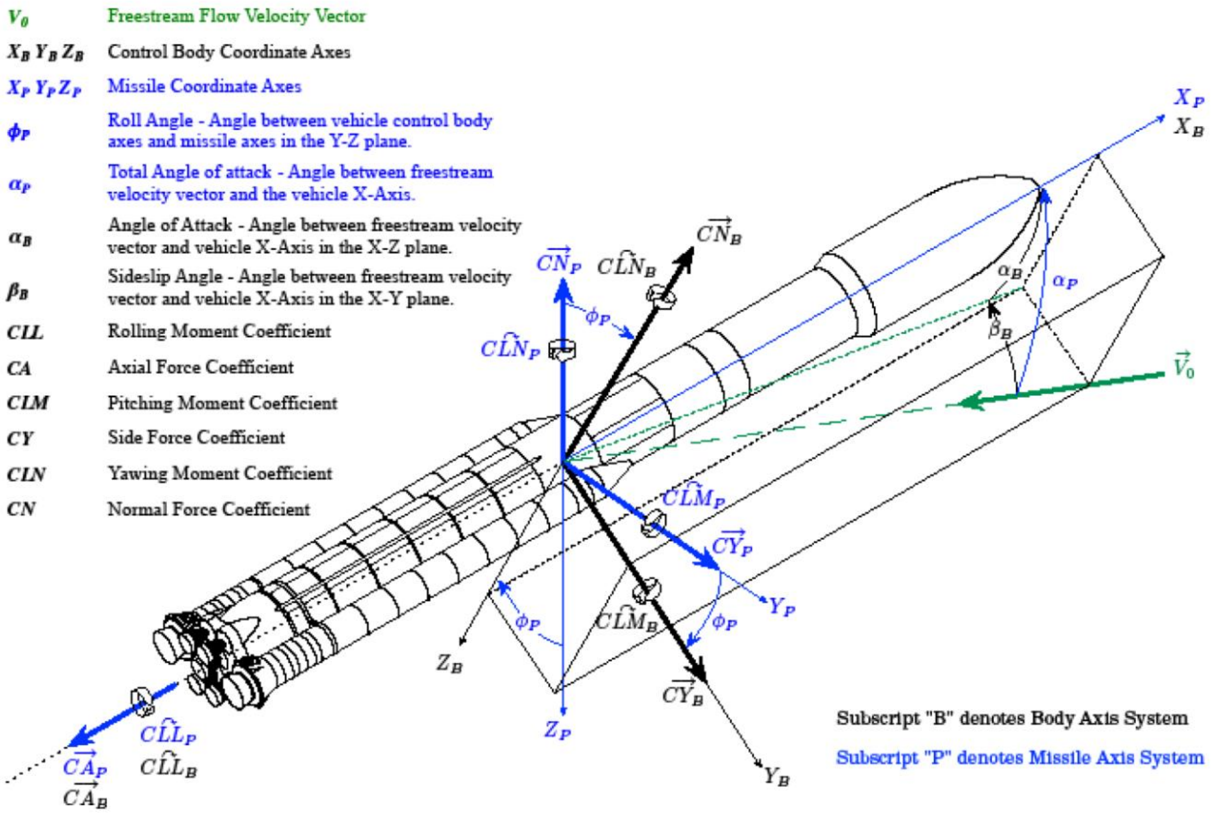


**Figure 14. Database Coordinate System Definition**

## VI. Summary & Future Work

A variety of sub-scale wind tunnel tests have been conducted at the MSFC ARF in support of the DAC-1 and DAC-2 milestones for SLS test program. The tests were designed and conducted in order to collect six degree of freedom integrated force and moment aerodynamic data for first and second generation database development and complement other wind tunnel test programs. These tests encompass full stack configurations with the SRBs mounted, center-body alone, special parametric and investigative studies, and proximity aerodynamics during booster separation. All test articles and hardware were designed and built at MSFC or modified for the SLS wind tunnel test programs. Data were collected with six-component force and moment, internal strain gage balances. The MSFC Aerosciences Branch led the development of these aerodynamic wind tunnel tests within the first two SLS design cycles in order to support the early design work by other disciplines. The data acquired through these tests were used to develop wind tunnel based aerodynamic force and moment databases for trajectory analysis. Special techniques were used in the development of the first and second generation databases in order to provide a square database that encompasses the flight envelope and provides data at cardinal angles of attack and angles of sideslip.

As the SLS program and design matures, additional wind tunnel testing will be required to meet the milestones of the program. A large portion of that experimental work is already underway while other milestones have yet to be reached. As with the development of any launch vehicle, years of hard work by a dedicated and talented workforce across the agency and country are required to reach the ultimate goal of a successful flight. In order to reach that point, the early design work and the early definition of the aerodynamic environments are crucial to the start of a successful program.

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## References

[1] Simon, Erwin, "The George C. Marshall Space Flight Center's 14x14-inch Trisonic Wind Tunnel Technical Handbook", NASA TM X-64626, November 1971

[2] Mayle, Melody N. et al, "Force and Moment Testing of Configurations 10000 and 21000 in the Marshall 14-inch Trisonic Wind Tunnel," EV33-12-001, December 2011

[3] Crosby, William A. et al, "Force and Moment Testing of the Space Launch System (SLS) Design Analysis Cycle 2 (DAC-2) in the MSFC 14-inch Trisonic Wind Tunnel," EV33-12-015, January 2013

[4] Mayle, Melody N. et al, "Proximity Aerodynamic Wind Tunnel Testing of the Space Launch System (SLS) 10003 Configuration in the Marshall 14-inch Tri-sonic Wind Tunnel in Support of the SLS Design Analysis Cycle 2 (DAC-2) Separation Database," EV33-13-018, June 2013

[5] Purinton, David C., "Aerodynamic Database SLS-10-D-AFA-002 Revision 2," Technical Memorandum, 26 July 2012