

# An Overview of the Characterization of the Space Launch Vehicle Aerodynamic Environments

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Aerodynamic environments are some of the first engineering data products that are needed to design a space launch vehicle. These products are used in performance predictions, vehicle control algorithm design, as well as determining loads on primary and secondary structures in multiple discipline areas. When the National Aeronautics and Space Administration (NASA) Space Launch System (SLS) Program was established with the goal of designing a new, heavy-lift launch vehicle first capable of lifting the Orion Program Multi-Purpose Crew Vehicle (MPCV) to low-earth orbit and preserving the potential to evolve the design to a 200 metric ton cargo launcher, the data needs were no different. Upon commencement of the new program, a characterization of aerodynamic environments were immediately initiated. In the time since, the SLS Aerodynamics Team has produced data describing the majority of the aerodynamic environment definitions needed for structural design and vehicle control under nominal flight conditions. This paper provides an overview of select SLS aerodynamic environments completed to date.

## I. Introduction

THE SLS architecture, being a chemically-propelled rocket launch vehicle, must pass through several phases of flight before reaching the desired target conditions in space. These phases of flight, outlined in Fig. 1, have unique modeling requirements that must be addressed by creating several different aerodynamic database products that address the specific needs of analysts modeling the launch system operating in a particular portion of flight. This paper attempts to summarize these select data products that model the aerodynamic response of the SLS geometry as it passes through nominal flight conditions. Although considerations for off-nominal flight (abort situations) are considered in the design of launch vehicles, and aerodynamic data describing those environments for SLS are produced, they will not be discussed here.

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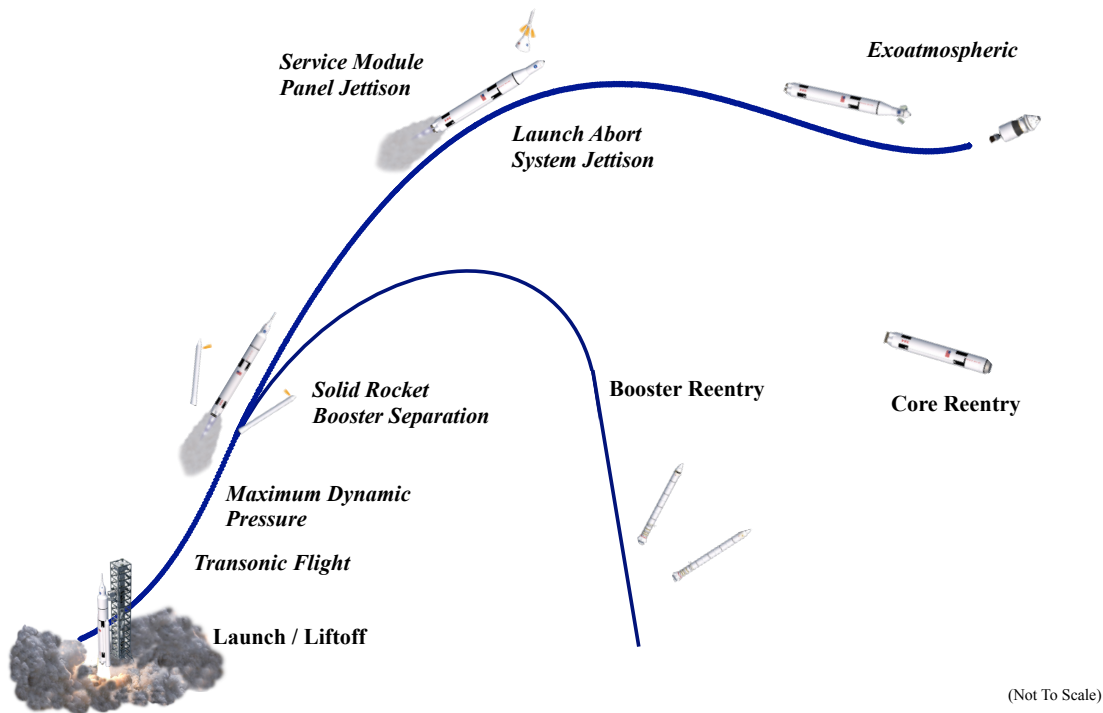


Figure 1. Phases of Flight for the SLS Launch Vehicle

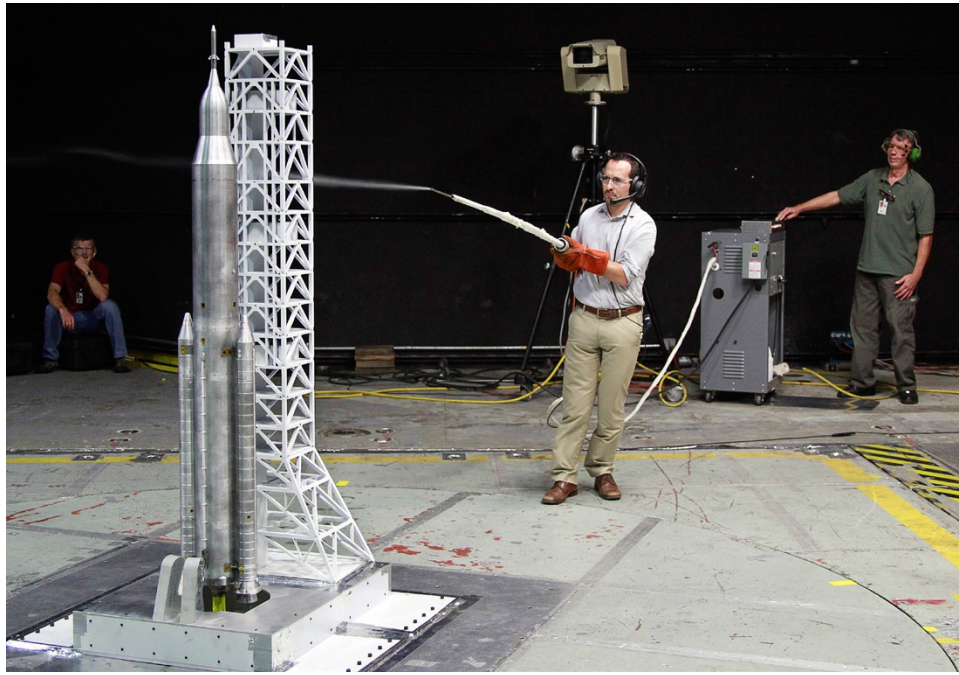
## II. Ground Winds / Lift-off Aerodynamics

This low-speed aerodynamic environment moves in a direction that is mostly perpendicular to the launch vehicle axis and modeled by measurements of the typical wind profiles experienced at the launch pad. Similar to the ground winds environment, the initial lift-off aerodynamic environment encountered by the launch vehicle behaves much like ground winds, but as the vehicle velocity increases, it transitions to the ascent aerodynamic environment in which the freestream air flow is mostly parallel to the launch vehicle axis within a few degrees. These ground wind and lift-off aerodynamic environments are needed to assess loads during roll-out and pad stay time, and vehicle trajectory and attitude control during lift-off and the initial seconds of flight. For SLS, computational fluid dynamics (CFD), analytical methods based on historical data, and wind tunnel testing have been employed to support the design and analysis activities of SLS.

Databases produced prior to conducting any wind tunnel tests were based on CFD while performing numerous checks against historical vehicle data<sup>1,2,3,4</sup> and using the NASA launch vehicle design criteria.<sup>5</sup> The CFD analysis was performed using best practices established in previous NASA launch vehicle programs.

The anchor for all ground wind loads and lift-off aerodynamics databases is the wind tunnel test data acquired in the Langley Research Center (LaRC) 14'x22' Subsonic Wind Tunnel. A photo of the flow visualization technique used during the wind tunnel testing is shown in Fig. 2. The testing determined integrated ground wind loads on the launch vehicle with and without the launch tower present and at various angles of attack and altitudes relative to the launch tower position to simulate the vehicle lifting off. In addition to integrated force and moment measurements, static pressure measurements were distributed spatially on the vehicle for observation, comparison to CFD, and for determination of distributed aerodynamic loading on external components and element interfaces.

## III. Ascent Force and Moment Aerodynamics



**Figure 2. Ground Winds & Lift-off Aerodynamics Testing at the Langley Research Center 14'x22' Subsonic Wind Tunnel**



**Figure 3. Force & Moment Aerodynamics Testing in the Marshall Space Flight Center 14 in. Tri-Sonic Wind Tunnel**

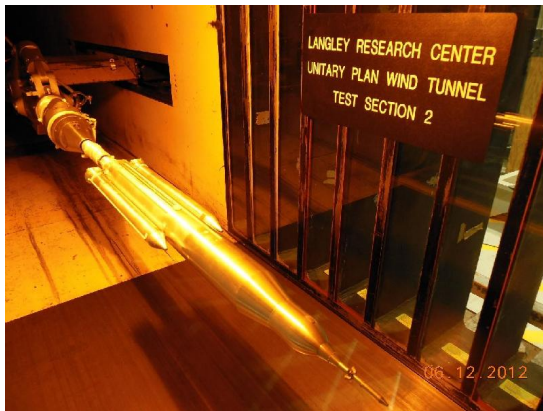
Aerodynamics-induced forces and moments for the integrated vehicle are one of the first aerodynamic products that engineers use to predict vehicle control, trajectories, and payload performance. Numerous methods of early prediction have been developed over the last several decades for different types of flight vehicles, most notably Missile DATCOM.<sup>6</sup> While these predictions are easy and quick to produce, they are insufficient for any analysis other than preliminary studies. As for most space access vehicles, the aerodynamic environment spans a large Mach range for which vehicle control must be maintained, and the aerodynamic inaccuracies are integrated through atmospheric flight and non-linearly affect performance.

The primary method used for developing SLS ascent aerodynamic data is wind tunnel testing, with select CFD simulations for comparison. Detailed de-

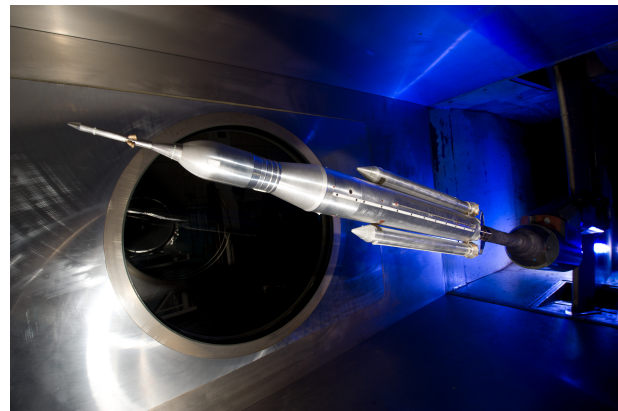
scriptions of these tests, and database development methodologies are provided as companion papers within this conference session.<sup>7,8</sup> As noted in these articles, in order to provide adequate flight envelope conditions for nominal flight, thousands of flight conditions that vary in Mach, angle-of-attack, and side-slip are required. These values are used for pertinent trajectory simulation and control system design. SLS tests during early, low fidelity 0.4% scale and medium fidelity 0.8% scale testing are shown in Fig. 3 and Fig. 4, respectively. These tests were accomplished at the Marshall Space Flight Center (MSFC) 14-inch Tri-Sonic Wind Tunnel (TWT) for low fidelity, and a combination of the LaRC Unitary Plan Wind Tunnel (UPWT) and the Boeing Poly-Sonic Wind Tunnel (PSWT) for medium fidelity.

The use of CFD has provided a unique capability in launch vehicle development and is an integral part of the aerodynamic environment definition process. However, the use of wind tunnels still provides the most cost-effective approach to accumulating the large amount data required for a highly-resolved ascent force and moment database. The SLS aerodynamics team compares select CFD cases to the integrated forces and moments measured in the wind tunnel. These comparisons provide confidence in using those CFD solutions

for distributed pressures and loads products.



(a) Langley Research Center Unitary Plan Wind Tunnel

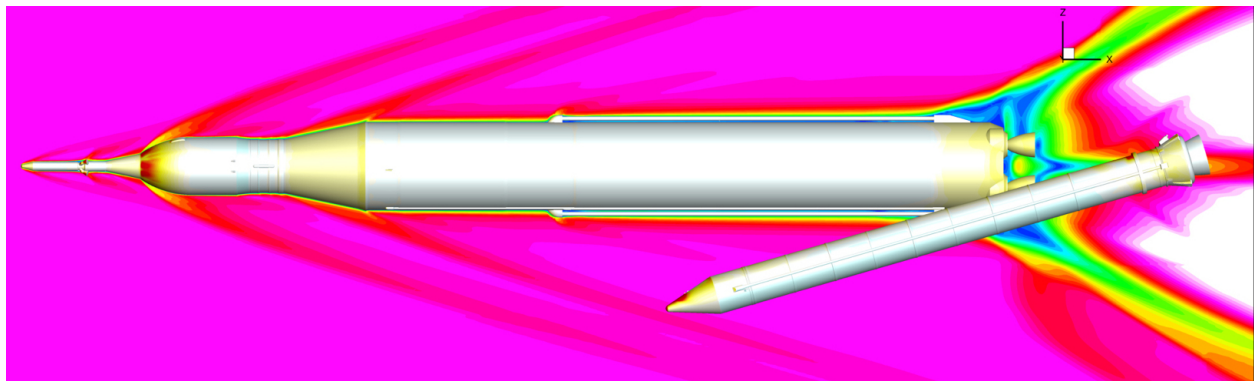


(b) Boeing Poly-Sonic Wind Tunnel

**Figure 4. Medium-Fidelity Force & Moment Aerodynamics Testing**

## IV. Booster Separation Aerodynamics

The SLS vehicle, similar to the Space Shuttle Launch Vehicle, has dual solid boosters to provide high thrust for lift-off through the flight regime where aerodynamic induced forces are greatest. These large vehicle components are jettisoned after their contribution to vehicle propulsion as a benefit to the performance of the launch vehicle, increasing the mass-to-orbit capability by a significant amount. As with the Space Shuttle, and illustrated in Fig. 1, the Solid Rocket Boosters (SRBs) must be safely separated from the core vehicle during ascent. For the separation event, the predominate force affecting motion of the launch vehicle components is provided by booster separation motors (BSMs), again, similar to the Shuttle system. This style of separation system produces complex flow interactions between freestream flow and the numerous supersonic exhaust plumes from the BSMs.



**Figure 5. CFD Simulation of SLS SRB Separation Showing the Flow Around the Vehicle and Boosters.**

In such a complex flight scenario, the aerosciences leadership (the authors of this paper) have chosen to rely on CFD (Fig. 5) to produce the anchoring data while depending on select wind tunnel testing of proximity aerodynamics and historical wind tunnel data for sub-model validation. Additionally, a planned separation wind tunnel test will obtain data while including BSM plumes simulated with cold gas nozzles. This test will provide additional validation data for the CFD-based database. This product necessarily includes complex jet-to-jet interactions for potential failure events, such as a single BSM no-fire condition. A wind tunnel test to cover all potential database requirements would be prohibitively expensive, and in this case leave considerable uncertainty due to the compromises needed to accurately model the exhaust plumes.



## V. SRB Decent Aerodynamics

The SLS SRB descent database is chiefly based on comprehensive reentry wind tunnel testing of the Constellation Program's Ares I First Stage which was based on the Space Shuttle SRB.<sup>9</sup> Because it was planned to recover and reuse the Ares I First Stage, extensive testing was conducted to verify that the stage would fall through the atmosphere in such a way that would not damage the structure or any components on the outer surface that were exposed to the atmosphere, as well as confirm that the stage orientation during reentry would allow for proper operation of the recovery system parachutes.

The SLS architecture, while using the same motor hardware, does not call for the recovery and reuse of the SRBs. However, the abundance of aerodynamic data generated for Ares I, as well as aerodynamic data from Space Shuttle Program testing of the SRBs allowed for the creation of a booster descent aerodynamic database in which there was plenty of confidence for use to certify that the falling SLS SRBs would fall and impact the Atlantic Ocean in a safe location.

## VI. Centerbody Ascent and Reentry

Regimes of flight that are particularly well-suited for CFD modeling are those with geometry traveling through high-altitude, low-density atmosphere and at very high velocities (greater than Mach 5) such as vehicle upper stage flight or obtaining stage reentry initial conditions for a hardware breakup analysis. Inviscid CFD codes can be used in regions where the contribution of viscous effects are minimal and can be ignored or covered with scaling factors based on empirical data or engineering judgement. Utilizing the less demanding inviscid CFD codes where appropriate is both fast and low-cost.

## VII. Vehicle Ascent Sectional Loads and Distributed Pressures

In addition to integrated aerodynamic force and moment testing, full vehicle CFD solutions are generated for many of the same conditions that were tested in the wind tunnel. The major application of the resultant data is as "line loads". These major inputs to structural loads analysis are developed by integrating the CFD solution data circumferentially along the length of the vehicle centerline axis. In this way, each of the aerodynamic coefficients of interest can be depicted not only as a function of the vehicle state, but also as a function of the location along the length of the launch vehicle. This distributed aerodynamic load data is a key component of the integrated vehicle loads analysis which in turn is used to design the rocket's primary structure.

The CFD solution data are also used as surface pressure maps that guide engineers in the placement of compartment aerodynamic vents. Once the vent locations are decided, this surface pressure data is used as an input to vent-sizing analyses and performance assessments.

Additional benefits of having both integrated force and moment data and CFD solutions is that test data can be used to anchor surface pressure and line loads databases, as well as the additional confidence in end results achieved by having two independently-derived sets of comparable data.

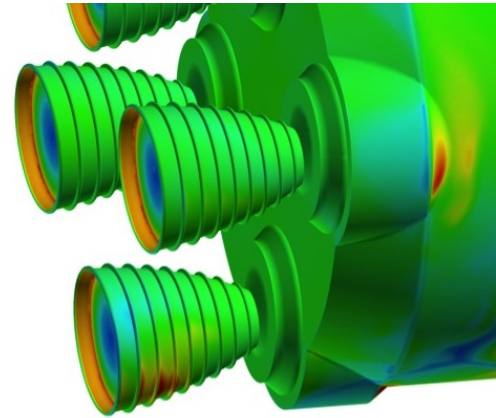
## VIII. Aerodynamics-Induced Protuberance Loads

Aerodynamic loading represents one major component of the forces experienced by the protuberances which must be accounted for in the localized design of launch vehicle structures. Accurate knowledge of protuberance loads is important for a number of reasons, including determining the size and spacing of fasteners, skin thicknesses, and underlying support structure. One of the unique challenges of this effort is that the protuberances are not subjected to a constant environment, but must be designed to withstand the entire ascent trajectory. The determination of these environments is one particularly well-placed application of CFD. For SLS, development of protuberance air loads utilized methods developed while designing Ares I during the Constellation Program. Each protuberance of interest was broken down into patches which represented the front, sides, back, and top of the shape before running CFD simulations. Maximum and minimum gauge pressures and force coefficients are then determined over the entire simulated flight envelope for each patch.<sup>10</sup>

## IX. Engine Nozzle Aerodynamic Hinge Moments

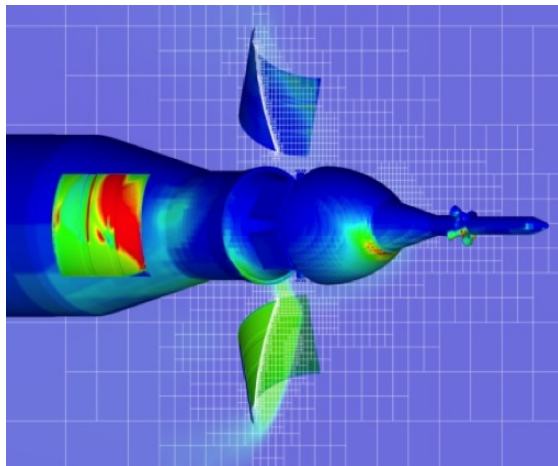
There are several very complicated and specialized aerodynamic environments for localized hardware that would both be very difficult to physically model in a wind tunnel and where testing would become rather cost-prohibitive due to facility constraints or piece-part fidelity requirements. One such environment is the modeling of engine nozzle hinge moments and aerodynamic surface pressure loads in the proximity of the engines' plumes at the base of the launch vehicle. This region of the vehicle exhibits complex flow fields that can dramatically change the environment as the engines gimbal or the vehicle attitude changes.

It had been demonstrated in previous analysis that neglecting exhaust plumes when predicting nozzle hinge moments resulted in overly conservative data. As a result, engine nozzle aerodynamic loading was determined with CFD by simulating engine plume flows as well as the freestream air for various combinations of engine gimbal angle and vehicle angle of attack and velocity as shown in Fig. 6. Additionally, it was examined whether or not the environment experienced after an engine failure (one main engine disabled out of the four available) would produce an increased engine nozzle hinge moment. Several more sets of CFD cases were performed while not simulating one of the engine plumes. Surprisingly, for this architecture, it was determined that the nozzle hinge moments were indeed bounded by the original cases where all four engine plumes were simulated.



**Figure 6. CFD Simulation of Nozzle Hinge Moments**

## X. MPCV Service Module Fairing Panel Jettison Aerodynamics



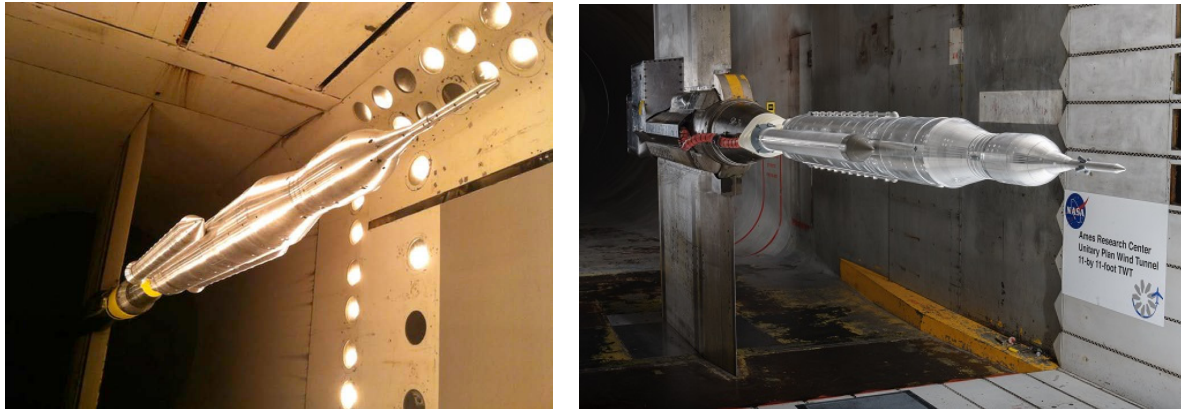
**Figure 7. CFD Simulation of the Multi-Purpose Crew Vehicle Jettison-able Service Module Aerodynamic Panels**

attitudes in relation to the main vehicle. A snapshot of one of these simulation cases is depicted in Fig. 7. Based on these predicted feasible variations in flight conditions, an aerodynamic force and moment database considering the proximity to the main launch vehicle body was constructed to model this complex regime of flight.

## XI. Unsteady Aerodynamic Environments

In addition to the force and moment testing, much larger models were utilized in testing to characterize the unsteady aerodynamic environment acting on the launch vehicle. The first of these environments is

aerodynamic buffet which manifests itself as a lower frequency cyclic fluctuating pressure over an area of the outer mold line (OML). Characterization of this environment is imperative, as this pressure fluctuation can manifest itself as a periodic force acting on the rocket, that can, especially when coupled with a vehicle bending mode of similar frequency, lead to catastrophic results during flight. The first rigid buffet testing for SLS occurred with a higher-fidelity, 3% scale model in the LaRC Transonic Dynamics Tunnel (TDT) (Fig. 8(a)). This test incorporated 360 dynamic pressure transducers in specific locations over the OML of the vehicle to collect gigabytes of data characterizing this dynamic aerodynamic pressure phenomena. An additional rigid buffet test is currently planned with the latest details of the vehicle configuration in the same wind tunnel in 2014.



(a) Rigid Buffet Testing at the Langley Research Center Transonic Dynamics Tunnel (b) Aeroacoustics Testing at Ames Research Center 11 ft. Transonic Wind Tunnel

**Figure 8. SLS Unsteady Aerodynamics Testing**

Another unsteady aerodynamic environment is higher frequency random noise. While not often having a systemic effect on the entire launch vehicle, flight aeroacoustic environments can drive the design of local structure, the placement of vehicle avionics system components, and is a primary input to the evaluation of vibration resonating through the vehicle structure. Aeroacoustics testing took place at the Ames Research Center (ARC) 11 ft. Transonic Wind Tunnel (shown in Fig. 8(b) and the 9'x7' Supersonic Wind Tunnel. While this testing is similar in concept to the rigid buffet testing, it utilizes instrumentation designed to measure much higher frequencies of fluctuating pressure and is often concentrated in different locations on the OML.

## XII. Conclusion

The SLS Aerodynamics Team has striven to meet data needs and requirements of the other SLS analytical teams developing the newest NASA launch vehicle by providing aerodynamic environmental models for all phases of nominal flight while remaining flexible and responsive to changes and performing duties in a cost-effective manner. The team took careful consideration before making decisions about how best to acquire environment data in both a timely and cost-effective way. This paper describes these development choices and explains why they were made in a particular way.

## Acknowledgments

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