

An Overview of NASA Langley Low-Speed CFD Contributions to the Space Launch System Program

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In this review paper, low-speed computational work from NASA Langley in support of the Space Launch System (SLS) is discussed. This information includes both historic and present efforts with the Kestrel CFD solver. The low-speed aerodynamics of SLS is highly complex and analysis of the unsteady flowfield requires significant computational efforts. The SLS mission profile varies from the vehicle static on the launch pad through high-speed ascent, and this paper focuses on the prelaunch as well as liftoff and transition portions of the flight both in proximity to the launch tower and in isolation. High-alpha conditions, as large as 90 deg, result in a flowfield dominated by massive, large-scale flow separation and asymmetric vortices. High-fidelity solutions require an unsteady computational formulation to accurately capture the aerodynamics of the vehicle. A detailed discussion of the computational approach is presented, followed by key efforts to support the program.

Nomenclature

C_A	=	axial force coefficient (missile axis coordinate system)
C_N	=	normal force coefficient (missile axis coordinate system)
C_Y	=	side force coefficient (missile axis coordinate system)
C_l	=	rolling moment coefficient (missile axis coordinate system)
C_m	=	pitching moment coefficient (missile axis coordinate system)
C_n	=	yawing moment coefficient (missile axis coordinate system)
D	=	diameter
dt	=	time step (sec)
dt^*	=	nondimensional time step
h	=	distance of the vehicle above the launch platform
h/L	=	vehicle liftoff ratio
L	=	tower height
L_{ref}	=	a reference length
ll	=	lineload
lm	=	line moment
$\hat{n}$	=	unit normal vector
Q	=	Q-criterion $Q \equiv (\omega^2 - S^2) / 2$
$\vec{r}$	=	moment arm
Re_D	=	Reynolds number based on core diameter
S	=	rate of strain

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u	=	velocity
x	=	Cartesian coordinate parallel to longitudinal centerbody axis
y	=	Cartesian coordinate orthogonal to longitudinal centerbody axis and pointed toward the solid rocket boosters
y^+	=	dimensionless wall distance
z	=	Cartesian coordinate orthogonal to longitudinal centerbody axis and the solid rocket boosters
z	=	(completes the right-hand rule)
z	=	elevation from the ground
α	=	angle of attack (wind axis coordinate system)
α_P	=	total angle of attack (missile axis coordinate system)
β	=	sideslip angle (wind axis coordinate system)
Δ	=	a difference
$\Delta C_A / (\Delta x / L)$	=	nondimensional axial force line load coefficient
$\Delta C_N / (\Delta x / L)$	=	nondimensional normal force line load coefficient
$\Delta C_Y / (\Delta x / L)$	=	nondimensional side force line load coefficient
ϕ	=	body circumferential angle (body axis coordinate system)
ϕ_P	=	roll angle (missile axis coordinate system)
ϕ_{azi}	=	freestream wind azimuth angle
θ	=	hatch deployment angle
$\vec{\sigma}$	=	stress tensor
τ	=	time
ω	=	vorticity

Acronyms

CAA	=	Crew Access Arm
CAD	=	Computer Aided Design
CFD	=	Computational Fluid Dynamics
CREATE-AV	=	Computational Research and Engineering Acquisition Tools and Environments Air Vehicles
CSFSU	=	Core Stage Forward Skirt Umbilical
CSITU	=	Core Stage Inter-Tank Umbilical
DDES	=	Delayed Detached Eddy Simulation
DES	=	Detached Eddy Simulation
DFROM	=	Data-Fused Reduced-Order Model
DNS	=	Direct Numerical Simulation
DOD	=	United States Department of Defense
DOE	=	Design of Experiments
DSNE	=	Design Specification for Natural Environments
EUSU	=	Exploration Upper Stage Umbilical
F&M	=	Force and Moment
HPCMP	=	High Performance Computing Modernization Program
ICPSU	=	Interim Cryogenic Propulsion Stage Umbilical
IDDES	=	Improved Delayed Detached Eddy Simulation
KCFD	=	Kestrel Computational Fluid Dynamics
LAS	=	Launch Abort System
LVSA	=	Launch Vehicle Stage Adapter
LaRC	=	Langley Research Center
MDDES	=	Modified Delayed Detached Eddy Simulation
ML	=	Mobile Launcher
ML-1	=	Mobile Launcher 1
ML-1E	=	Mobile Launcher 1 Extended
ML-2	=	Mobile Launcher 2
NASA	=	National Aeronautics and Space Administration
OML	=	Outer Mold Line

<i>OSMU</i>	=	Orion Service Module Umbilical
<i>PSP</i>	=	Pressure Sensitive Paint
<i>RANS</i>	=	Reynolds-averaged Navier-Stokes equations
<i>ROM</i>	=	Reduced-Order Model
<i>RC</i>	=	Rotation/Curvature Correction
<i>SA</i>	=	Spalart-Allmaras turbulence model
<i>SLS</i>	=	Space Launch System
<i>SRB</i>	=	Solid Rocket Booster
<i>TetrUSS</i>	=	Tetrahedral Unstructured Software System
<i>UQ</i>	=	Uncertainty Quantification
<i>VAB</i>	=	Vehicle Assembly Building
<i>VSS</i>	=	Vehicle Stabilizer System
<i>14x22</i>	=	NASA LaRC 14- by 22-Foot Subsonic Tunnel

Subscripts

<i>avg</i>	=	an average value
<i>centerbody</i>	=	relating to entire portion of the rocket including the core and anything above the core
<i>core</i>	=	relating to the vehicle core (center stack below the LVSA)
<i>inst</i>	=	an instantaneous value
<i>norm</i>	=	a normalized value
<i>port</i>	=	relating to the port SRB
<i>star</i>	=	relating to the starboard SRB

I. Introduction

The NASA Artemis program is a large-scale program that seeks to enable human-class deep-space exploration. Most of the Artemis program is supported by NASA with contributors from 15 unique NASA sites. In addition to key NASA/industry partnerships, a number of international organizations provide support to the program. A number of missions, both crew and cargo, are planned to develop the infrastructure and equipment necessary for sustained human presence on the Moon. A family of heavy-lift vehicles, the Space Launch System (SLS), will deliver individuals to the Moon via the Gateway, a small space station in orbit around the Moon. The Gateway, orbiting the Moon every nine days, will provide a base from which astronauts will be able to make routine trips to and from the lunar surface, allowing for extensive exploration not possible without a permanent presence on or near the Moon. The four-astronaut Orion capsule, with endurance of 21 days, will ferry astronauts to and from the Gateway.

Numerous missions are planned to construct the Gateway, and this hardware will be delivered to lunar orbit by the SLS and other commercial vehicles. With increasing capabilities, the Gateway will ultimately facilitate the construction of the permanent Artemis Base Camp, located near the lunar South Pole. This base will allow extended crewed exploration missions of the Lunar surface. Ultimately, the significant experience gained through sustained presence on and near the moon will provide the base infrastructure for human exploration of Mars.

A. Space Launch System

The SLS is a central element of the Artemis program that will provide the capabilities required for manned deep-space exploration. As currently planned, this family of heavy-lift vehicles will enable exploration of the Moon and Mars [1–4]. Three classes of the SLS configuration, each of which includes both a crew and cargo version, are shown in Fig. 1. While now obsolete, the Block 1 Cargo vehicle is shown in the image as it was part of the original family plan. In addition, the flowfield on this vehicle exhibits aerodynamic features of interest. The large propulsive force needed to propel the targeted payloads is provided by two solid rocket boosters (SRB) side-mounted onto a core stage that embodies four RS-25 engines. As seen in the figure, the core is defined as the components of the central body below the Launch Vehicle Stage Adapter (LVSA). Containing a common core, a number of stacks hold the fuel for the RS-25 engines that produce a total of 1.7 million pounds of thrust. A large cryogenic liquid hydrogen tank is located at the base of the core while a cryogenic liquid oxygen tank is located near the top of the core. Mounted on the side of the core, two five-segment, single-use SRBs each yield approximately 3.6 million pounds of thrust such that the desired mission profile can be achieved. The payload, whether the Orion crew capsule or a cargo compartment, is mounted atop

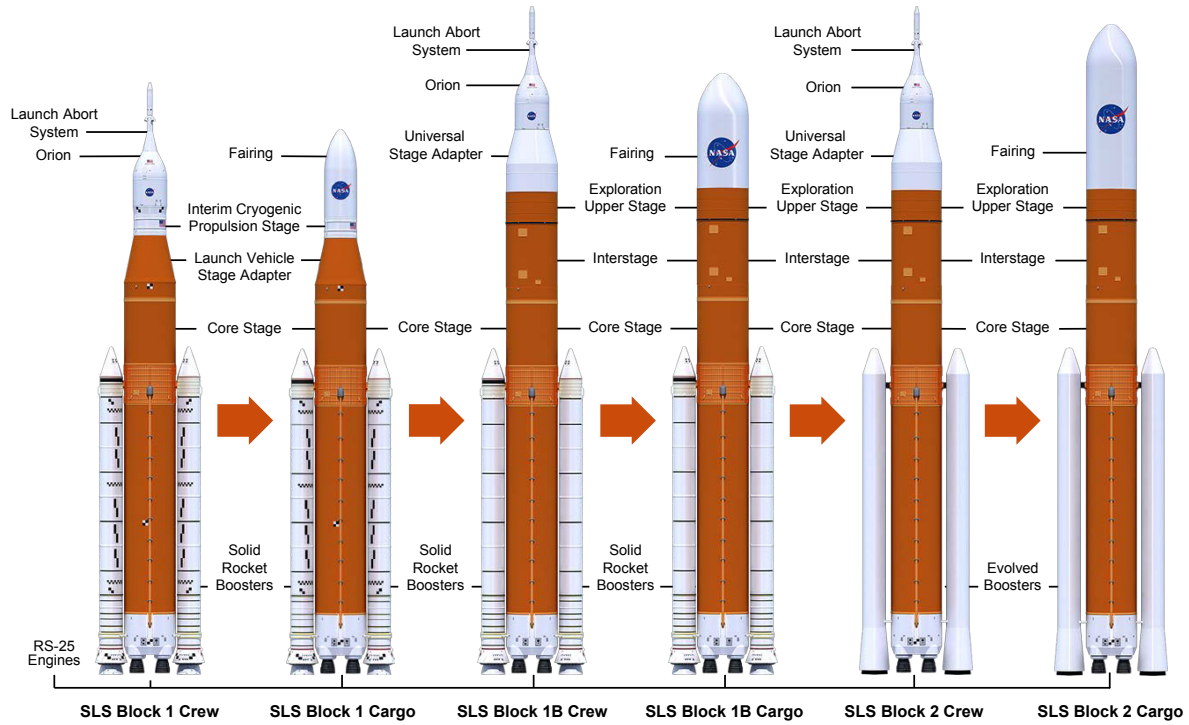


Fig. 1 Six vehicles in the Space Launch System family including three sizes of rockets with both crew and cargo versions.



Fig. 2 Artemis I mission with Block 1 Crew vehicle during launch [Photo: NASA].

the rocket. A photograph of the vehicle during the successful Artemis I flight on November 16, 2022 is shown in Fig. 2. The Block 1 Crew vehicle, which launched from Launch Complex 39B at Kennedy Space Center, achieved the desired mission objectives in which the Orion capsule was delivered to Lunar orbit. The capsule reached the desired distant retrograde orbit for six days as part of a 25-day mission.

Throughout the course of a flight, the SLS is exposed to a wide variety of flight regimes through the mission profile, as depicted in Fig. 3. While on the launch pad and during the early portions of liftoff, the rocket is subjected to low-speed flow with ground winds from any direction. Immediately after launch, the vehicle enters the liftoff and transition phase of flight with low subsonic Mach numbers and large angles of attack. Ultimately, the rocket leaves the liftoff and transition phase and enters the ascent phase in which it experiences subsonic, transonic, and high supersonic flight regimes. Jettison of the SRBs followed by jettison of the Launch Abort System (LAS) both occur at the end of the ascent phase of flight. The work in this paper, which captures computational work at the NASA Langley Research Center (LaRC), is focused on the prelaunch as well as the liftoff and transition flight regimes in which the vehicle is stationary on the launch pad through launch and up to a vehicle speed of Mach 0.3.

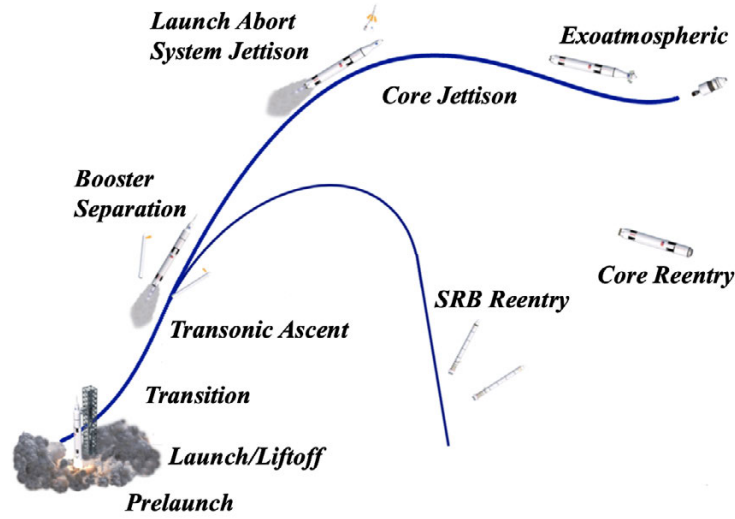


Fig. 3 SLS mission profile including launch, liftoff, ascent, Solid Rocket Booster (SRB) and Launch Abort System (LAS) jettison, and reentry.

B. Coordinate Systems

The baseline coordinate system, referred to as the Space Launch System Structural Coordinate System and defined in SLS-SPEC-048, was used for these analyses [5]. As plotted in Fig. 4(a), the x axis is pointed down the centerline of the body, and the y axis is orthogonal to the vehicle centerline and points toward the starboard, or right, solid rocket booster. The orientation of z completes the right hand rule. In addition, the body circumferential angle (ϕ) is defined in Fig. 4(b) [6]. As depicted, the freestream velocity is aligned with the z axis such that the systems tunnel is on the windward side of the vehicle for ϕ of 0 deg. The moment reference point for the SLS is also shown near the base of the core.

In addition to the structural coordinate system, SLS-SPEC-048 defines both the body and missile axis coordinate systems [5]. Seen in Fig. 5, aerodynamic data are calculated in these coordinate systems. Relative to Fig. 4, the directions of both the x and z axes are reversed. Shown in the figure, α_P is the angle between the freestream velocity

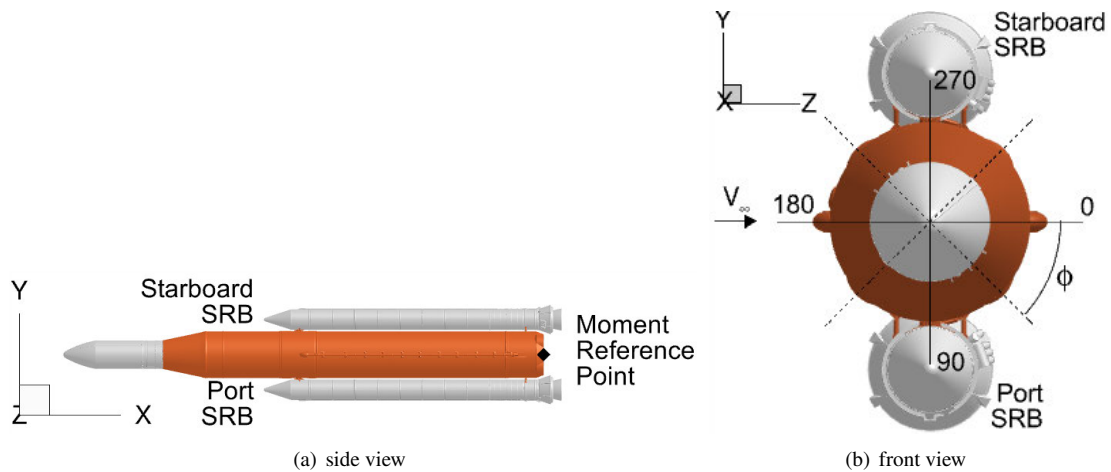


Fig. 4 SLS structural coordinate system showing core and SRBs in (a) side view and (b) front view depicting body circumferential angle (ϕ) and freestream velocity vector.

V_0 Freestream Flow Velocity Vector

$X_B Y_B Z_B$ Control Body Coordinate Axes

$X_P Y_P Z_P$ Missile Coordinate Axes

ϕ_P Roll Angle - Angle between vehicle control body axes and missile axes in the Y-Z plane.

α_P Total Angle of attack - Angle between freestream velocity vector and the vehicle X-Axis.

α_B Angle of Attack - Angle between freestream velocity vector and vehicle X-Axis in the X-Z plane.

β_B Sideslip Angle - Angle between freestream velocity vector and vehicle X-Axis in the X-Y plane.

C_l Rolling Moment Coefficient

C_A Axial Force Coefficient

C_m Pitching Moment Coefficient

C_Y Side Force Coefficient

C_n Yawing Moment Coefficient

C_N Normal Force Coefficient

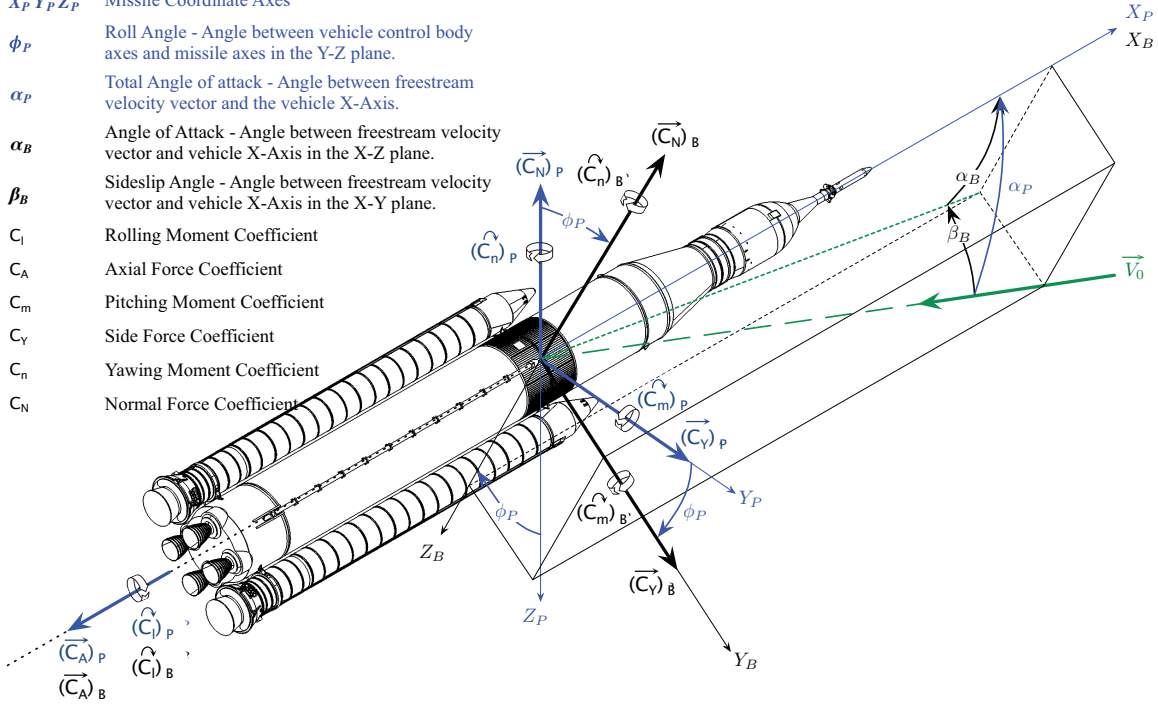


Fig. 5 SLS coordinate system for aerodynamic force and moment coefficients.

vector and the vehicle x axis and the roll angle ϕ_P is the angle between the vehicle control body axes and missile axes in the y - z plane. For situations in which the roll angle is 0 deg, the body and missile axis coordinate systems are coincident. In the missile axis coordinate system, the axial, normal, and side force coefficients are defined as C_A , C_N , and C_Y , respectively. The moment coefficients around the x , y , and z axes are defined as C_l for the rolling moment coefficient, C_m for the pitching moment coefficient, and C_n for the yawing moment coefficient.

When the vehicle is located in proximity of the tower, the coordinate system in Fig. 6 governs the vehicle. This is the same coordinate system as that for the isolated vehicle. In this case, a positive normal force acts to the south and a positive side force acts to the east. During the portion of flight in which the rocket is in proximity to the tower, the vertical location of the vehicle can be quantified as the nondimensional h/L in which h is the distance from the launch pad and L is the height of the tower. The bottom of the vehicle is defined as the SRB nozzle exit plane. As shown in Fig. 6(b), prelaunch is the case in which the vehicle is located on the launch pad. When on the pad, the nozzle exit plane is slightly below the mobile launcher platform such that $h/L = -0.003$ prior to launch. By definition, the vehicle clears the tower at $h/L=1$, shown in Fig. 6(c).

C. Liftoff and Transition in Free Air

Significant computational efforts and detailed analysis has been performed on the Block 1 Crew, Block 1 Cargo, Block 1B Crew, and Block 1B Cargo vehicles. These analyses include both the prelaunch as well as the liftoff and transition phases of flight, as depicted in Fig. 3. During these portions of the mission, the total angle of attack (α_P) ranges from 90 deg at the beginning of the phase through nearly 0 deg at the beginning of ascent (i.e., Mach 0.3). The roll angle during the liftoff and transition phase ranges from 0 to 360 deg. At the moderate to large α_P usually experienced during liftoff and transition in free air ($\alpha_P > 20$ deg), significant separation is observed on the leeward side of the rocket. The wake in this region is extremely unsteady, and the large-scale separation dominates the flowfield. Due to the complex flowfield, it can be difficult to accurately capture this wake using computational methods using traditional computational schemes.

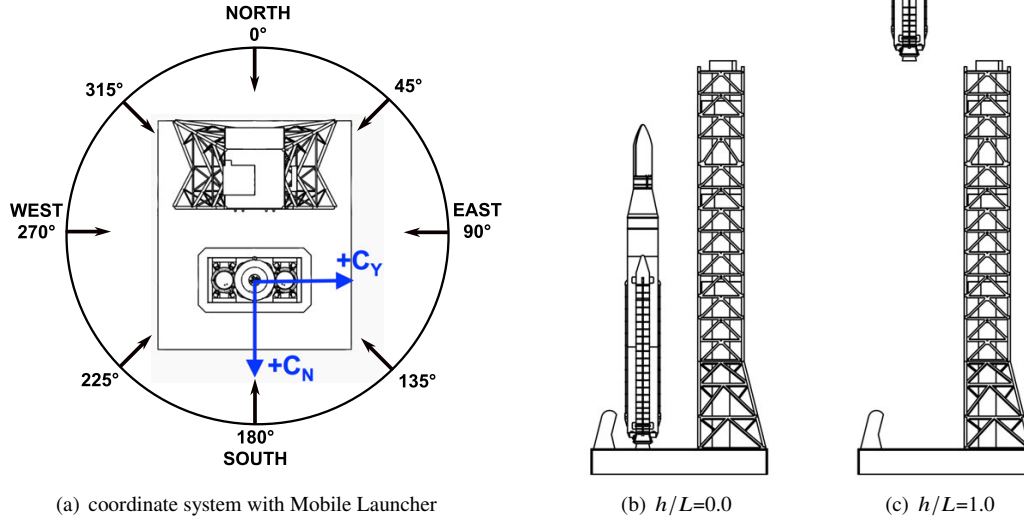


Fig. 6 SLS coordinate system with the launch tower including (a) normal and side force coefficients as well as (b) vehicle on launch pad corresponding to $h/L=0.0$ and (c) vehicle at top of tower ($h/L=1.0$).

1. Large-Scale Flowfield Separation

Due to the high- α_P flowfield, significant separation is present on the leeward side of the vehicle. This massively-separated wake, originating from separation over the SRBs and centerbody, exhibits significant unsteadiness for a large distance downstream of the vehicle. The wake, quantified by ω , downstream of an SLS-type vehicle is shown in Fig. 7. For this configuration, the offbody grid was refined a large distance downstream, which allowed the small-scale features to be visualized through the wake. This simulation was executed at a freestream Reynolds number based on the core diameter of 600,000, $\alpha_P=50$ deg, and $\phi_P=0$ deg. While broadband separation is evident for this simulation, it is possible that the wake will exhibit different topological flow features at lower or higher Reynolds numbers.

2. Asymmetric Vortex

Vehicles with slender forebodies, such as the SLS, can generate two large, stable asymmetric vortices at moderate to high α_P ($20 < \alpha_P < 70$ deg), as extensively documented in the literature [7–14]. Typically, the vortex on one side of the body will be small and stay close to the body while the opposite vortex will be larger and further off the surface, as seen in Fig. 8. Both primary vortices may generate a secondary vortex, also shown in the figure. Despite the unsteady nature of the wake over part of the rocket, these vortices vary little with time. Because of the asymmetric nature of the flowfield,

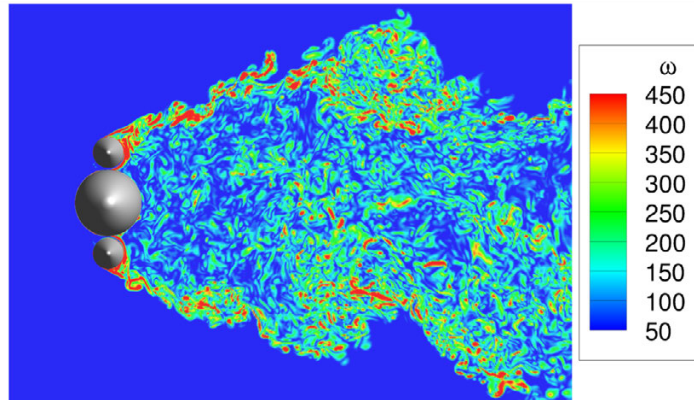


Fig. 7 Unsteady, separated wake downstream of an SLS-like vehicle.

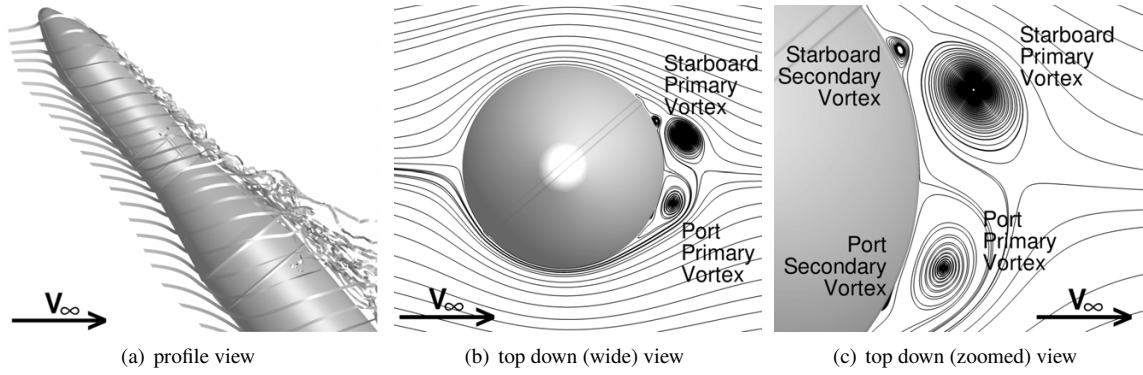


Fig. 8 Separated flowfield showing primary and secondary asymmetric vortices in (a) profile, (b) top down (wide), and (c) top down (zoomed) views.

a significant side force may be exerted on the body. It was observed through wind-tunnel testing that this asymmetric vortex may switch from side to side of the body at different instances of the same condition. With increased downstream distance, the vortices will either experience vortex break down or simply decompose into a massively-separated flowfield. The point at which a vortex devolves is dependent on many factors including freestream conditions, the construction of the vehicle or model, and the fidelity of the computational simulation. Even with high-fidelity computational solvers, it can be extremely difficult to accurately predict the asymmetric vortex as a stable state exists with the largest vortex on either side of the slender body. The schematic in Fig. 8 is from the Block 1 Cargo vehicle in which a seam is present on the cargo fairing. While the seam does not exist on other configurations, similar asymmetric vortex formation can occur.

3. Representative SLS Forebody Flowfields

As an asymmetric vortex can form at moderate angles of attack, it is prudent to discuss a representative flowfield for an SLS vehicle. Figure 9 depicts the instantaneous flowfield around the forebody of the SLS Block 1 Cargo vehicle for $\alpha_P=50$ deg and $\phi_P=0$ deg. In the figure, an isosurface of constant total pressure is shown in gray with body station slices of vorticity blanked below a certain threshold such that the vortex cores can be easily visualized. As seen in the figure and previously demonstrated for the SLS vehicle, the asymmetric vortex near the forward end of the vehicle is quite stable with minimal temporal variations in the structure [9, 15, 16]. In this image, the starboard vortex is observed to lift off the surface and out of the boundary layer while maintaining a clear, well-defined vortex core as it departs from the surface of the Launch Vehicle Stage Adapter (LVSA). The port vortex remains in tact until it eventually devolves into the separated flowfield. In both vortices, a vortex sheet is observed to be entrained from the windward side of the vehicle.

The flowfield presented in Fig. 9 is for one vehicle at one freestream condition. It is known that the flowfield features are dependent upon both the vehicle geometry and freestream conditions, especially the total angle of attack, roll angle, and Reynolds number. At moderate α_P , the forebody geometry of a cargo vehicle leads to clean, well-defined asymmetric vortices. However, this is not the case with a crew vehicle in which the Launch Abort System (LAS) near the front of the vehicle disturbs the flowfield such that clean, well-behaved vortices are not present. This behavior is seen in Fig. 10(a) in which the Block 1 Crew vehicle was simulated at $\alpha_P=50$ deg, the same as the Block 1 Cargo Fig. 9. In this figure, two asymmetric vortices form over the extreme forward portion of the LAS. The starboard asymmetric vortex lifts off the surface and devolves in a short distance. However, the port asymmetric vortex, albeit small, remains intact for a large distance off the surface. Contrary to the Block 1 Cargo rocket shown in Fig. 9, the asymmetric vortices on the Block 1 Crew vehicle are smaller than the cargo vehicle as these vortices depart from the surface on the upper portion of the LAS and do not extend over the upper stage or to the LVSA. The flow over the Block 1 Cargo vehicle at an angle of attack of 90 deg is shown in Fig. 10(b) such that the flow is from the bottom of the page toward the top. Topologically, the flowfield looks quite different than that in Fig. 9. At 90 deg, no asymmetric vortices are observed. Instead, a large, separated wake is seen to exist over the entire vehicle.

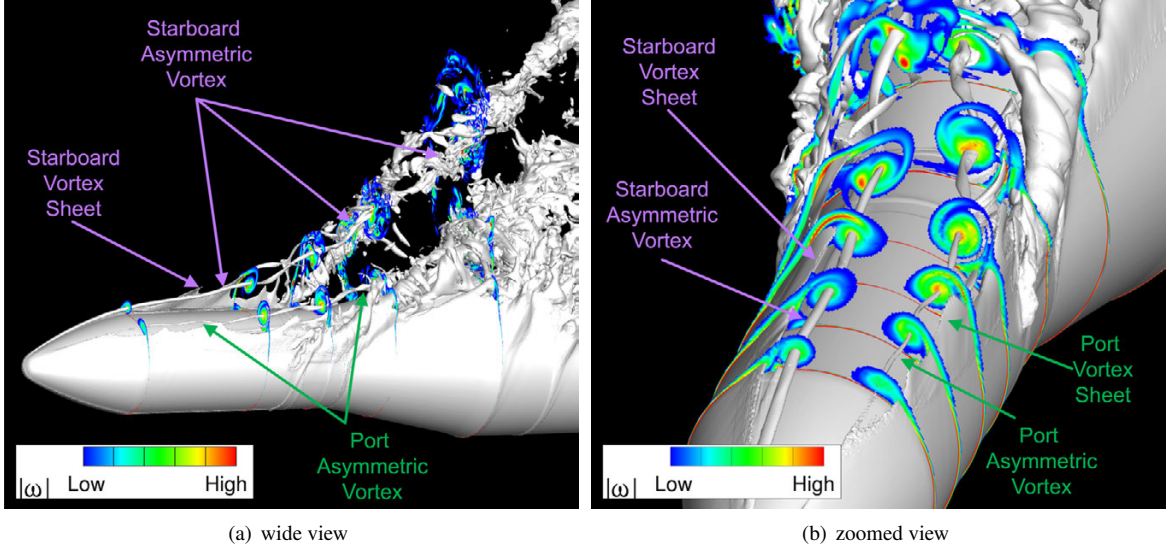


Fig. 9 Forebody flowfield on the SLS Block 1 Cargo at $\alpha_P = 50$ deg showing (a) wide view of asymmetric formation and dissipation of asymmetric vortices and (b) zoomed view of asymmetric vortex formation.

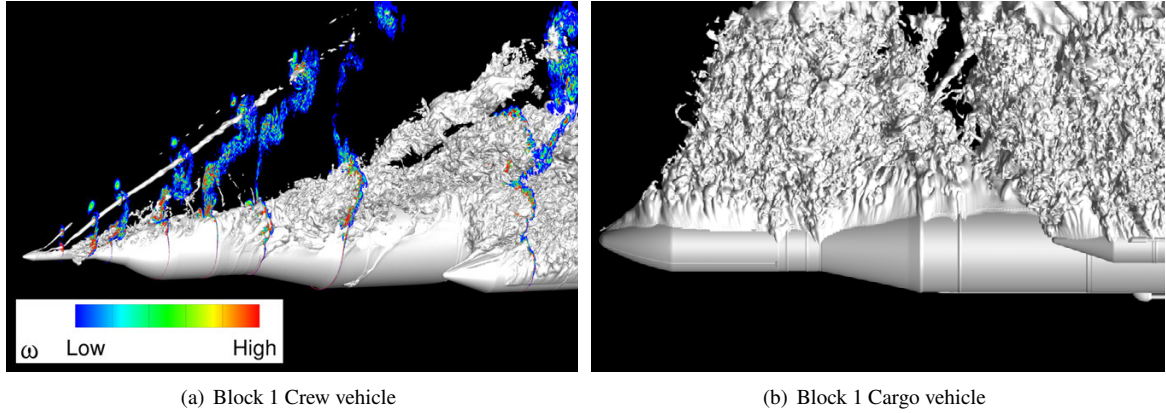


Fig. 10 Forebody flowfield on the SLS (a) Block 1 Crew at $\alpha_P = 50$ deg and (b) Block 1 Cargo at $\alpha_P = 90$ deg.

4. Coanda Effect

In addition to smooth-surface separation, the flow behind the SRBs is further complicated by the complex flow through the gaps between the SRBs and core. As documented in the literature, this region can be subjected to the presence of the Coanda effect, which is the tendency of the flow emanating from a jet to remain attached to a curved surface longer than if the surface were in isolation [7, 9, 15, 17–19]. The Coanda effect is particularly prominent when the rocket is sitting on the launch pad or in the early portions of liftoff/transition as it is a high- α_T phenomena.

While the asymmetric vortices can dominate the flowfield at moderate angles of attack, a Coanda effect is most prominent at very high angles of attack. The gaps between the SRBs and core accelerate the flow in the same manner as a jet around the highly-curved surface of the SRBs and core. Consequently, the vehicle is subjected to the Coanda effect. For the SLS, the Coanda effect is a function of the gap size between the SRBs and core and also the diameter of the bodies. It has been shown that, with slight changes in freestream condition or geometry, the flow may exhibit different attachment characteristics through the SRB/core gaps. Similar to the asymmetric vortices, this feature can be difficult to capture computationally, thus adding to uncertainty of the simulations. For the case at α_P of 90 deg and roll angle of 0 deg, there are four potential different Coanda modes, seen in Fig. 11, including:

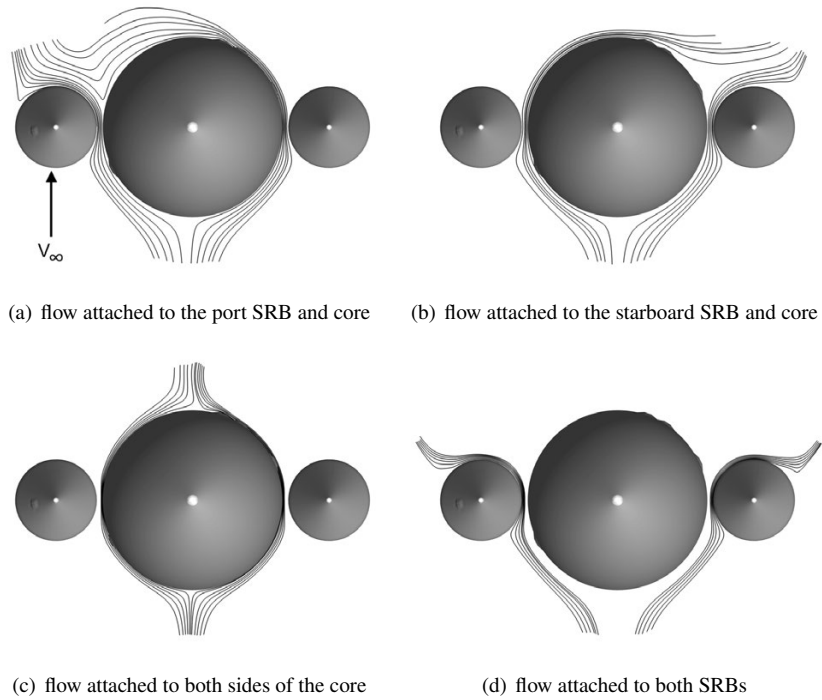


Fig. 11 Four different Coanda modes depicting flow attached to (a) the port SRB and core, (b) the starboard SRB and core, (c) the core, and (d) both SRBs.

- Fig. 11(a); flow bends to the left and attaches to the port SRB and core
- Fig. 11(b); flow bends to the right and attaches to the starboard SRB and core
- Fig. 11(c); flow bends around and attaches to neither SRB and both sides of the core
- Fig. 11(d); flow bends around and attaches to both SRBs and neither side of the core

While the figure shows the possible Coanda states at a roll angle of 0 deg, more variations exist for nonzero roll angles. For example, roll angles near 90 deg yield flowfields with minimal flow through either of the two SRB/core gaps. However, a roll angle of about 60 deg yields some flow through the windward SRB gap but minimal flow through the leeward SRB gap, which is in the separated wake behind the core. Due to the multiple combinations, the Coanda effect can add significant uncertainty to the numerical simulation.

As all four Coanda modes are stable, aerodynamic states, it is possible to computationally capture different states. This behavior is visualized in Fig. 12 as the flowfield depicts three different Coanda states. Similar to Fig. 11, the freestream flow points toward the top of the page. This particular image depicts the effect of turbulence model on the flowfield. In this figure, the standard SA model yields flow attached to the port side of the vehicle. Addition of the rotation/curvature correction (RC) causes flow attachment to the centerbody, while the modified DDES (MDDES) model causes the flow to be attached to both SRBs.

D. Liftoff and Transition in Proximity of Tower

In addition to the complex aerodynamic features and considerations discussed in Sec. I.C, the addition of the launch tower yields additional complications. The coupled effect between the vehicle and tower significantly affect not only the flowfield but also the vehicle integrated aerodynamic force and moment quantities. Figure 13(a) depicts a photograph of the Block 1 Crew vehicle mounted on the mobile launch platform in preparation for the Artemis I launch, and Fig. 13(b) shows a sample computational model for the launch pad, vehicle, and tower. The computational outer mold lines (OML) do not include every small protuberance on the vehicle, but it does maintain many small features such as the cameras, latches, brackets, and feed lines. Additionally, while the computational fluid dynamics (CFD) model does not include

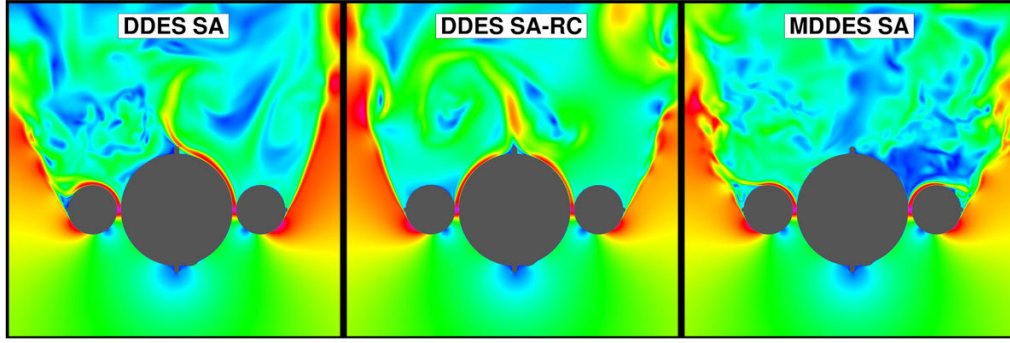
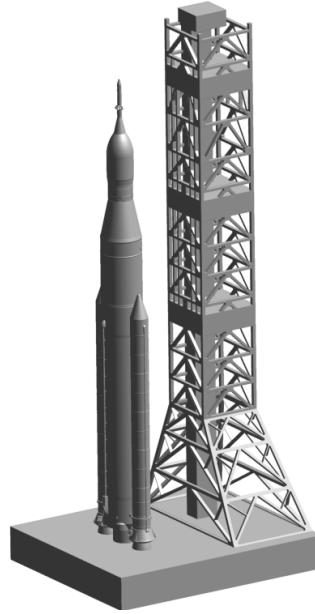


Fig. 12 Solutions with three turbulence models exhibiting differing Coanda states.



(a) photograph of the vehicle and tower



(b) computational model of the vehicle and tower

Fig. 13 SLS Block 1 Crew vehicle in proximity of launch tower including (a) a photograph of the vehicle and (b) computational model used for the vehicle and tower analyses [Photo: NASA].

all the fine-scale details of the true mobile launcher, key features of the tower were retained. These features include the skeleton of the support structure, elevator shaft, and equipment rooms.

During the prelaunch and also the early portions of the liftoff and transition flight segments, the location of the vehicle ranges from h/L values, the nondimensional vehicle liftoff ratio, of 0 through 1.5, as defined in Fig. 6. While the vehicle clears the tower by $h/L=1.0$, significant tower effects are present as high as $h/L=1.5$. Consequently, to ensure the aerodynamics of the vehicle in presence of the tower was accurately captured, databases with the launch tower were generated up to $h/L=1.5$.

Computational simulations for flight in proximity to the tower are complex due to the large wakes on the leeward side of the vehicle and tower. It has been shown that these large wakes are insufficiently captured with Reynolds-averaged Navier Stokes (RANS) schemes [7, 9, 15, 16, 20]. Consequently, it is necessary to implement scale-resolving methods such as Large Eddy Simulations (LES) or a Detached Eddy Simulation, a hybrid RANS/LES method. In each of these approaches, regions of fine grid density permit the appropriate modeling of large-scale flow features.

II. Program Needs

Support for the Artemis Program, and SLS, requires advanced aerodynamic analysis with both experimental and computational methods. The main users of aerodynamic data are the Structural Loads and Dynamics groups as well as Guidance, Navigation, and Control. A summary of program requests are discussed in this section.

A. Computational Challenges

The computational databases for low-speed liftoff and transition SLS calculations are complicated due to numerous different considerations. To ensure the integrity of the computational results, methods must be employed that capture sufficient geometric details, accurately calculate the flowfield, and are simulated at a sufficient number of conditions to yield a high-quality database. Each of these pose independent complications, as shown in the Fig. 14 schematic. With each successive overlap between ovals, the computational problem yields additional complications. The SLS liftoff and transition IDDES database work, shown in shaded green in the middle of the figure, is particularly challenging. Extensive experimental and computational efforts, both historic and current, have been undertaken in an effort to accurately capture the requisite liftoff and transition data [3, 6–10, 15, 16, 19–26].

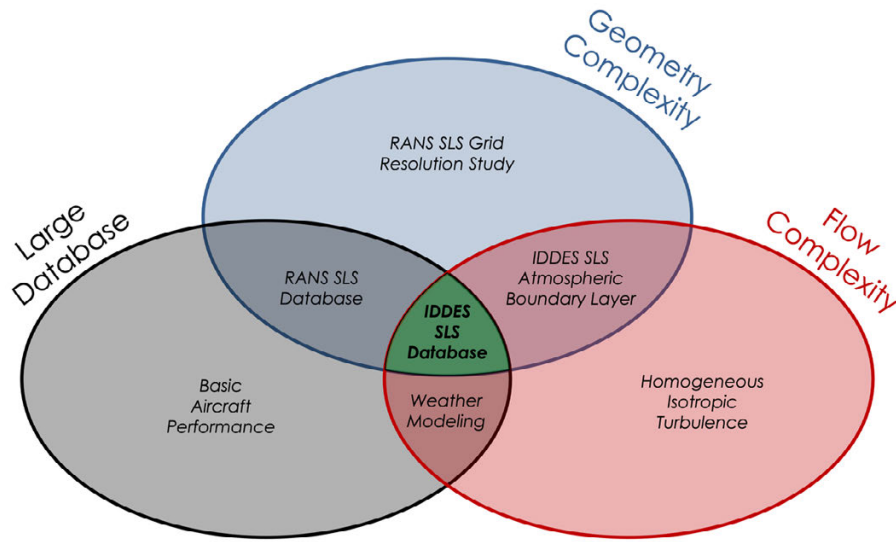


Fig. 14 Venn diagram capturing challenges to various computational applications.

B. Databases

Aerodynamic support for the SLS requires the use of both wind tunnel tests and computational simulations to develop aerodynamic databases across the flight mission profile. Due to the wide range of flight conditions experienced during the trajectory of a flight, numerous tools are required to accurately capture the properties of the complex flowfields that evolve over time. Experimental results, which are useful and necessary, are essential to the construction of the databases and validation of computational results. These computational simulations yield results at flight conditions not easily tested in a wind tunnel facility. In addition, the computational flowfield can be easily interrogated on the surface and in the volume, thus revealing fine-scale details that are not measurable, or at least not easily measured, in a wind tunnel.

Databases of aerodynamic forces and moments acting on the vehicle throughout the flight regime are provided to a number of different SLS subteams, with the most prominent being the Loads and Guidance, Navigation, and Control groups. While integrated forces and moments on the different components of the vehicle are captured in both computations and experiments, it is not easy to measure distributed loads in an experimental environment. The longitudinal load distribution, referred to as the lineload, is of particular interest [6–9, 15, 16, 20, 22, 27–29]. Complex pressure sensitive paint (PSP) experiments for low-speed flows is not possible with current state-of-the-art methods. In addition, PSP does not capture the skin friction coefficient distribution (C_f), which is a contributing factor to the lineloads. Due to the limitations of PSP experiments, computational simulations serve a vital purpose to generate these lineload data.

C. Mobile Launcher

The Mobile Launcher (ML) is a ground structure used to assemble, process, transport, and launch the SLS rocket and Orion spacecraft. This system, shown in Fig. 15 is comprised of the crawler-transporter and the launch tower. While on the Mobile Launcher, many umbilicals provide power, communication, coolant, propellants, and stabilization of SLS prior to vehicle launch. Construction of SLS is done inside the large Vehicle Assembly Building (VAB). The Mobile Launcher slowly crawls from the VAB to the Kennedy Space Center Launch Complex-39B, a journey of 4.5 miles that takes approximately eight hours. The ML with SLS is subsequently lowered onto the launch pad and the crawler-transporter moves safely away from the launch pad prior to launch. As seen in Fig 15(b), limited infrastructure exists at the launch complex with the most notable system being the large lightning-protection system. The majority of the systems needed to launch SLS are integrated into the mobile launcher.

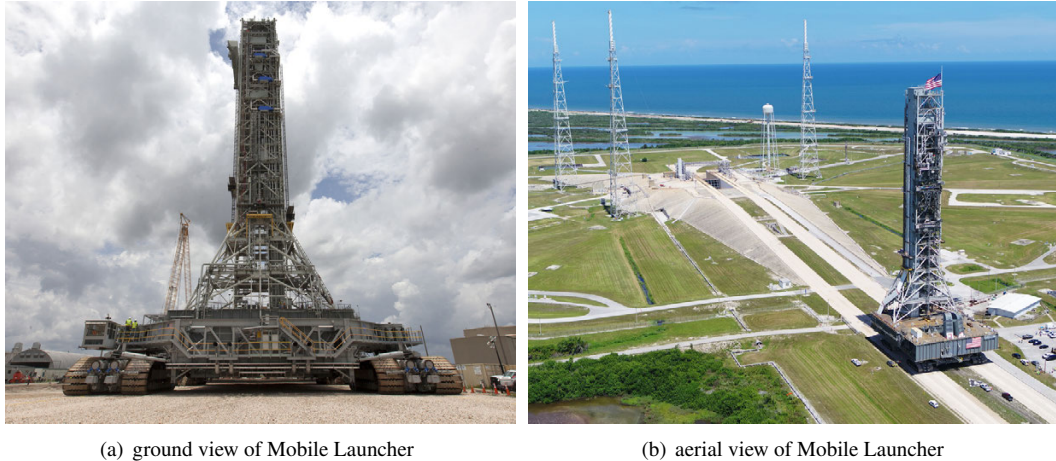


Fig. 15 Mobile Launcher including both (a) ground and (b) aerial views [Photos: NASA].

D. Atmospheric Boundary Layer

Most simulations in this project were executed with uniform freestream conditions, which closely approximates the boundary conditions imposed in a wind-tunnel test. However, in actuality, the vehicle is subject to an atmospheric boundary layer when the rocket is in close proximity to the ground. This boundary layer, which may be hundreds of feet tall, can have a significant effect on the SLS configuration, which is also hundreds of feet tall. The vehicle is subject to an atmospheric boundary layer when the vehicle is static on the launch pad and for a short time after the rocket clears the tower. Databases provided to the SLS program include data with differing vehicle geometry, tower geometry, vehicle height relative to the tower, angles of attack, roll angles, freestream velocities, and Reynolds numbers. In general, simplifications and assumptions of the database structure have been made such that computational resources are not excessive relative to the fidelity of data that is required. The data from these efforts help augment the databases with a constant-velocity profile to a database, which is subject to an atmospheric boundary layer profile. In addition, the information informs the uncertainty of the Ground Force Loads databases.

E. Crew Access Arm

Access from the tower to the vehicle is provided by the Crew Access Arm (CAA). Located near the top of the launch tower, the CAA can deploy and retract to provide astronaut and support crew access to the vehicle. Approximately one hour prior to launch, the CAA retracts into proximity of the tower. Two photographs of the CAA, in both the stowed and deployed configurations, are shown in Fig. 16. Emergency egress procedures require that the CAA can serve astronaut egress in a wide range of conditions. In addition to exhibiting favorable and stable behavior in the deployed position, the CAA must be able to deploy from the tower to the vehicle in no more than 45 sec. Consequently, the coupled effects of the tower, CAA, and rocket must all be considered simultaneously. As the safety of the astronauts is of utmost importance, detailed CFD analysis of the CAA is necessary to ensure robust design of the system in the presence of wind at a variety of speeds and from any direction.

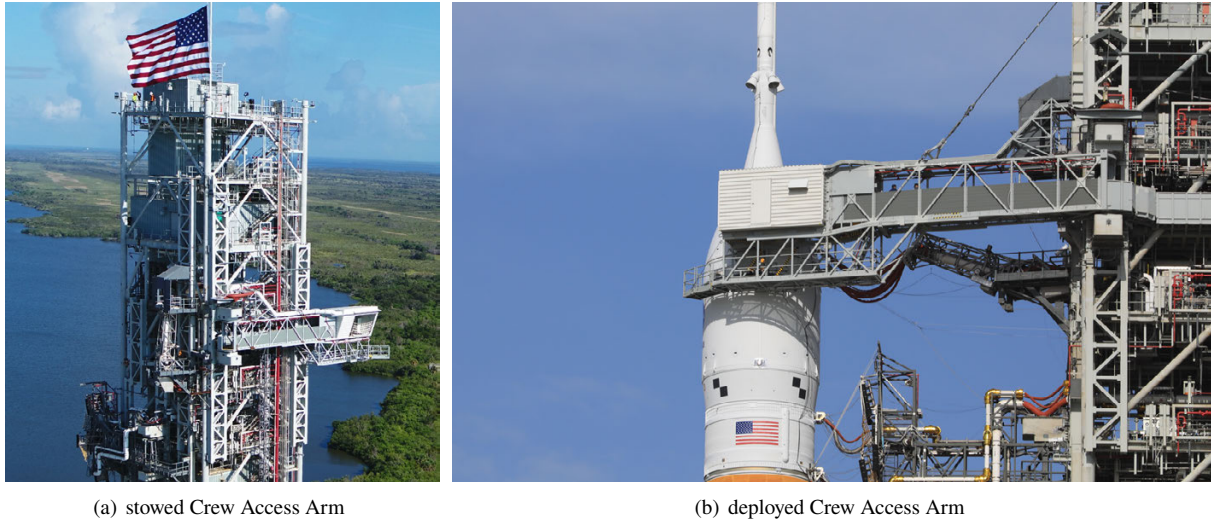


Fig. 16 Crew Access Arm on launch tower in (a) stowed and (b) deployed positions [Photos: NASA].

F. Launch Abort System Hatch

In addition to aerodynamic databases for the standard configuration, CFD simulations were executed to develop aerodynamic loading databases in support of emergency egress analysis for the Orion program. Two access hatches exist on the vehicle, including both an Orion hatch and a LAS hatch. An opening mechanism couples the Orion hatch to the LAS hatch such that the Orion hatch pushes on the LAS hatch when opening. The LAS hatch must be able to deploy from a fully-closed position to a fully-deployed position in less than a specified amount of time under a given load limit. Figure 17 shows both a photograph and CAD representation of the system. This work is critically important to ensure the safety of the crew in an emergency event in which the crew must exit the vehicle on the launch pad.

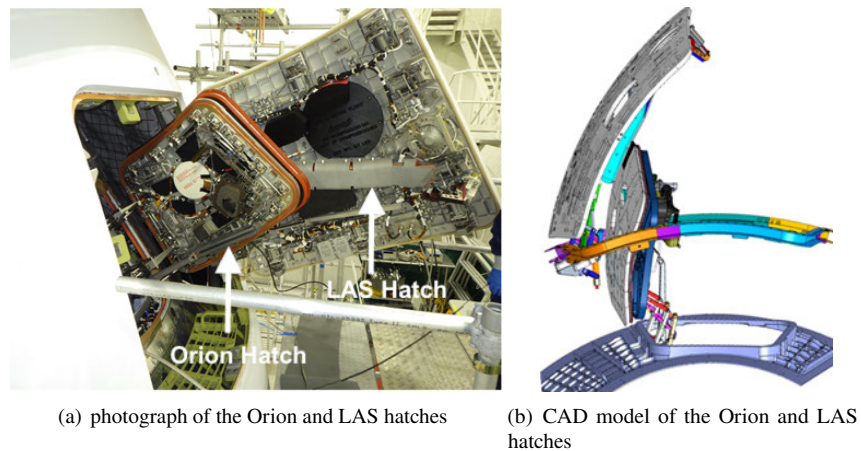


Fig. 17 Orion and LAS hatches showing (a) a photograph and (b) a CAD model [Photo: NASA].

III. CFD Tools

Analyses of the complex flowfield surrounding the SLS vehicle require numerous tools to both calculate the flowfield and postprocess these data to provide information to other groups supporting SLS. In particular, the massively-separated wakes at large α_P must be calculated with complex, unsteady computational solvers using large-scale high-performance-

computing tools. As database level analysis is performed on the vehicle, both integrated loads and also load distributions are calculated and delivered. An overview of these tools is presented in this section.

A. Uncertainty Sources

Myriad uncertainty sources manifest within this, as any, computational framework. A combination of mitigation and quantification of these uncertainties comprises the current state of the practice for SLS computational data generation. In general, the CFD framework can be organized into four very broad steps:

- 1) geometry simplification,
- 2) grid generation,
- 3) solution setup and iteration, and
- 4) solution reporting.

Within each of these steps, multiple factors contribute to the resultant quantities of interest differing from those experienced by the real vehicle.

The most significant source of uncertainty during geometry simplification is the removal of features deemed both too complicated to model and not significant enough to retain. It is evident from Fig. 13 how liberal this feature removal process can be. This practice takes a great deal of engineering expertise; information gleaned from data taken throughout the iterative design process informs the estimated significance (or lack thereof) of different features, which appeared and disappeared as the vehicle configuration evolved. In general, any surface feature smaller than the accepted grid scale is removed; other larger structures may undergo simplification but not outright removal, as is the case with the booster attachment hardware.

The generated grid structure can be broadly split into three components: that of the surface grid, the near-body grid, and the off-body grid. The surface grid's uncertainty lies primarily in the selected resolution of small features, but other factors like artificial surface roughness must also be accounted for. Likewise, the near-body grid can greatly influence the resulting quantities of interest based on the height of the initial cell layer, the layer growth rate, and the total number of layers. The near-body grid is often structurally different from the off-body grid, and often less adaptable during a simulation. The off-body grid determines crucial aspects like how well the wake is resolved and how far downstream convecting structures can propagate. In Kestrel, the off-body grid is adaptively refined via flow gradient criteria; this adaptive refinement adds an additional layer of complexity to grid generation-propagated uncertainty. Grid resolution studies and comparison to other data sources are the current best practice by which the grid generation uncertainty is addressed. Section IV.A discusses the grid generation procedure in more detail.

The form of the flow solution is perhaps the most significant source of variation within the computational framework, but this does not necessarily translate to it being the largest source of uncertainty. Although the computationalist can adjust numerous aspects of the simulation – the formulation itself, time accuracy, iteration resolution, compressibility limiters, derivative schemes, subgrid and turbulence modeling choices, and relaxation factors just to name a few – there are regular flow prediction workshops and rigorous internal reviews, which establish and monitor recommendations for how to assign these parameters such that they do not confound the final answer or its fidelity. Section IV.D presents examples of how even different versions of the same CFD code can present different final averaged values. In the context of SLS CFD, certain more case-specific uncertainty sources require more specific attention: whether the engine plumes affect the aerodynamics enough to be modeled, whether the freestream wind profile can be uniform when simulating the rocket and tower prior to liftoff, etc. Discussing these sources in detail is beyond the scope of this paper, but are themselves nuanced and active areas of research.

There is also uncertainty introduced as computationalists reduce their flow simulations to tabulated quantities of interest. If the flow is simulated to be time-accurate, then the delivered value can differ based on the number of preliminary iterations that are performed, as well as how large the averaging window is set to be. Solution convergence criteria can themselves vary from code to code and from application to application. What is more, if the flow exhibits multistable flow states, it is not always clear how those states can be reconciled into a single datum or which state should be solely represented in the delivered database. Again, the CFD community has endeavored to establish norms by which these kinds of decisions are made. In the SLS program, presentation of multi-stable states has even altered the structure of delivered data to ensure that the physics are most reasonably communicated and database users have access to the likely gamut of flow physics experienced by the rocket.

B. Kestrel

The Kestrel CFD package is a suite of programs that enable solution preparation, adaptive grid generation, computational calculation, and simple postprocessing of both Reynolds-averaged Navier-Stokes (RANS) and Improved Delayed Detached Eddy Simulation (IDDES) schemes [30–33]. Kestrel is developed and maintained by the Computational Research and Engineering Acquisition Tools and Environment, Air Vehicle (CREATE-AV) project and executed by the Department of Defense High Performance Computing Modernization Program (DOD HPCMP). This software package was originally developed to support acquisition efforts that required multidisciplinary analysis of vehicles including aerodynamics, dynamic stability and control, structures, propulsion, and store separation. A Common Scalable Infrastructure allows a modular approach for which the different multidisciplinary analysis methods may be either coupled or decoupled from each other.

The Kestrel Computational Fluid Dynamics flow solver (KCFD) is a finite-volume, cell-centered, unstructured flow solver for both two- and three-dimensional configurations. Solutions can be executed on a variety of cell types including tetrahedra, prisms, pyramids, and hexahedra. Parallel processing is executed by splitting the computational domain into the same number of zones as processors, and a Method of Lines approach is utilized such that the temporal and spatial integration schemes are decoupled from each other. A second-order accurate spatial algorithm is used, and up to a second-order accurate temporal scheme is implemented with a subiteration point-implicit algorithm. A wide number of settings can be used to control the behavior of the computational solver. Some of these values can dramatically affect the fidelity and stability of a solution, so great care must be taken when setting each parameter.

In some cases, it may be necessary to accurately resolve a flowfield exhibiting separation or other complex offbody flowfield features. While a large unstructured grid can be generated, it may be desirable to implement an adaptive mesh routine to yield a high-resolution grid where large gradients exist while relaxing the cell size in other portions of the flowfield. If this is selected in Kestrel, a dual-mesh approach, including a static near-body unstructured grid and an adaptive offbody Cartesian grid, is employed. Similar to KCFD, SAMAir, the off-body Cartesian grid solver, is dependent upon a number of parameter values chosen by the user. Unlike the user-generated unstructured grid, both the initial and final Cartesian grid is generated automatically by SAMAir. A trimmed internal unstructured grid is combined with user-specified outer boundary domain limits for the Cartesian grid. The overlap between the two grids and the associated grid density is generated by SAMAir such that the structured and unstructured cell sizes are similar at the edge of the inner grid. Refinement is executed at a user-specified number of iterations for a given maximum cell size, and refinement tracks the magnitude of vorticity (ω). Seen in Fig. 18, a refined cell has sides that are one half the length, in all three dimensions, of a neighboring, larger cell. Large grids may contain tens of thousands of zones with large differences in cell sizes, so the user must carefully consider the refinement of the inner grid and the size of the computational domain.

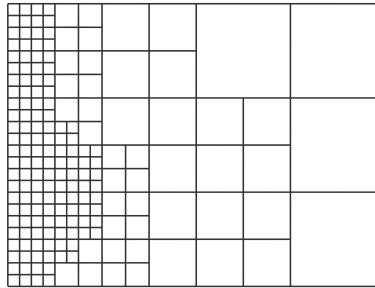


Fig. 18 Schematic of an example Cartesian grid with cell sizes one-half the length of a neighboring, larger cell.

C. Computational Resources

All simulations were performed on Pleiades, a large-scale Linux cluster located at the NASA Advanced Supercomputing (NAS) facility at the the NASA Ames Research Center. The computer consists of 158 racks of nodes, over 11,000 nodes, over 241,000 compute cores, and nearly one petabyte of memory. Cores are connected through InfiniBand with a partial hypercube topology. A number of computational chips can be used for simulations, and most simulations were performed with the Intel Haswell, Skylake, and Cascade Lake nodes. Depending on the complexity of the simulation, most notably the presence of the tower, computations were performed with anywhere from 1,000 to 3,400 processors resulting in jobs that took between 24 and 100 hours. As database-level analysis was performed, great care was taken to

conserve disk storage space. These efforts included saving a subset of the simulation at a given time step, slices through the volume domain, or only saving the surface data. A standard job, in which only limited volume data were saved, used approximately 600 GB of disk space.

D. GridTool

GridTool, a component of the NASA Langley Tetrahedral Unstructured Software System (TetrUSS), was used to prepare the geometry for both grid generation and solution setup [34, 35]. Within GridTool, surface patches defining the entire OML are defined and then grouped to form components. Patches can be defined by a single or multiple underlying surfaces. By leveraging automatic geometry programs augmented with significant user work, more than 7,300 surfaces and nearly 4,500 patches were used to define the surface OMLs. Patches on the OMLs are defined by many different curves that are usually, but not always, coincident with an underlying surface. These surfaces, most of which are non-rational B-splines, were systematically and carefully constructed by a small team of engineers at LaRC across two different branches. Many patches were combined together to generate one component, as seen in Fig. 19(a). In this image, each color represents one component, each of which is represented by many patches. A large number of protuberances was retained over the entire vehicle, a subset of which are shown in the figure. The grid density was defined based upon the size and location of various sources. These must be carefully constructed to ensure an adequate computational grid is generated. Many thousands of sources were hand placed on the geometry to specify the grid sourcing throughout the vehicle, and the tower geometry and associated sourcing is shown in Fig. 19(b).

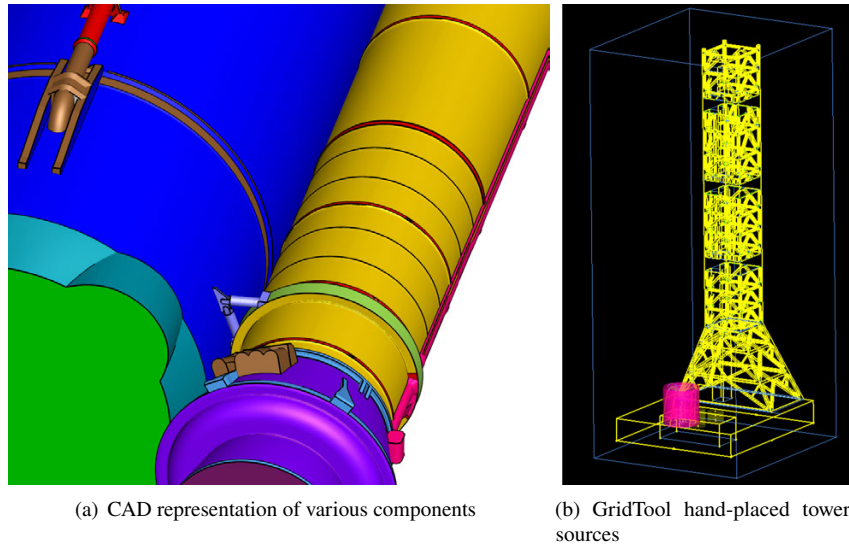


Fig. 19 Computational model including (a) CAD geometry depicting many components and (b) hand-placed sourcing in GridTool.

E. HeldenMesh

With maturation of the SLS program, the existence of new tools allowed for standard practices to be updated for improved workflow. HeldenTool, a geometry tool developed by Helden Aerospace, was used for both surface representation and sourcing. Similar to the functionality of GridTool, HeldenTool can be used to define the surface geometry, boundary conditions, patches, and components. HeldenTool, and the associated HeldenMesh, uses automated sourcing based on the patch names, which requires minimal hand work. This automatic sourcing yielded more than 50,000 sources for the SLS Block 1 Cargo vehicle. HeldenMesh is a three-dimensional unstructured grid generator that triangulates the surface, uses the advancing-layer method to grow the viscous grid, and the advancing-front method to grow the outer mesh. Within the advancing layers technique, the viscous grid spacing is defined by

$$\delta_j = \delta_1 \left[1 + R_1 (1 + R_2)^{j-1} \right]^{j-1} \quad (1)$$

in which δ defines the cell spacing, j represents a grid index, δ_1 is the user-specified cell height for the first cell, and R defines two growth-rate parameters [36]. As seen in the equation, the number of layers for the viscous grid cannot be specified by the user. This viscous grid continues to grow until the cell size is similar to the size generated by the source distribution.

F. Lineloads

Line loads and line moments are a mission-critical product within the SLS design framework [37–39]. Like spanwise load distributions on an airplane wing, these partially integrated surface stresses enable structural, control, and performance assessments not possible with only integrated vehicle force and moment information. Mathematically, line loads and line moments are computed as the integrals over a wetted surface with the exclusion of the dimension of interest. If x is that dimension, then the equations are

$$\vec{l}(x) = \oint \vec{\sigma} \cdot \hat{n} dy dz ; \quad (2)$$

$$\vec{l}_m(x) = \oint \vec{r} \times (\vec{\sigma} \cdot \hat{n}) dy dz , \quad (3)$$

in which $\vec{\sigma}$ is the stress tensor, $\hat{n}$ is the surface unit-normal vector, and $\vec{r}$ is the moment arm to an arbitrarily-defined reference point. In practice, line loads are computed using a surface mesh binning procedure. A surface mesh is segregated into bins along the axis of interest (with width of, e.g., Δx) and then the mesh is fully integrated within each bin [40]. This process yields centerline-integrated loads, which retain the dimensional dependency desired. Representative line loads of all three components (axial, side, and normal) for the SLS are shown in Fig. 20. The nondimensional distributions are indicated by $\Delta C_{A,Y,N}/(\Delta x/L)$ in which A , Y , and N are the subscripts for the specific direction of interest. While the data in the figure are irrelevant in this methods section, it is noted that the case was executed at $\alpha_P = 50$ deg and $\phi_P = 0$ deg. Data for the centerbody is shown in black while the two SRBs are shown in red and blue for each body. At this condition, near-constant values of the axial force coefficient line load result from the 0 deg roll angle. Peaks of the side force coefficient line load near the SRB noses are a result of the asymmetric vortices on these components. Finally, the normal force coefficient line load shows significant variation over the length of the entire launch vehicle.

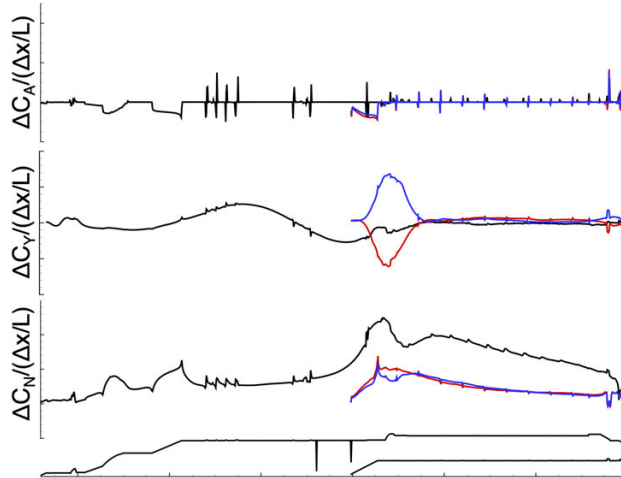


Fig. 20 Example SLS line loads for the axial, side, and normal components of force.

G. Tecplot Chorus

Database-level analysis of computational data is a time-intensive effort that requires significant postprocessing and analysis. This work, largely manual in nature, can be streamlined and enhanced with computational software. Tecplot Chorus, a database-level management software package, was investigated for applicability to the SLS program. This

software, which exists on NAS, does not require files to be downloaded to a local computer to visualize or plot results and leverages the more-typical Tecplot 360 software program. Chorus allows the user to simultaneously visualize results from numerous computational simulations at the same time such that different simulations can be visualized with a few clicks of a mouse instead of tedius, somewhat cumbersome, manually sifting through data. To evaluate the effectiveness of the software, a representative database was interrogated. A catalog of Tecplot visualization templates and analysis scripts was developed to systematically extract flow visualization and performance coefficients, all which were visualized within Chorus.

IV. Computational Methods

With the maturation of the SLS program, the computational methods in the liftoff and transition flight regime have been developed and refined. These efforts include development of high-quality computational grids, including both the nearbody and offbody grids. Additionally, the baseline computational setup has been developed and thoroughly defended through an exhaustive study by Pomeroy et al. [15]. Finally, the effect of Kestrel versions on the solution has been systematically updated as new versions of the software are released. Information in this section includes an explanation of the current best-practice methods.

A. Grids

It is widely known that the computational mesh used in a study can have dramatic effects on the accuracy of the simulation. The effect of the grid is first order, and the importance of a high-quality grid cannot be overstated. As the Kestrel formulation employs a near-body unstructured grid overlapped with an offbody Cartesian grid, the integrity of both computational grids must be verified. As the offbody grid is subject to adaptive mesh refinement, the integrity of the Cartesian grid must be verified at numerous freestream conditions or rocket configurations.

Prior to execution in Kestrel, the Carpenter tool was used to prepare the unstructured geometry prior to Cartesian grid overlap. The Carpenter tool, distributed as part of the Kestrel suite from DOD CREATE-AV HPCMP, truncates the grid at a user-specified distance off the surface of the vehicle surface. This distance, constant through the entire domain, was selected such that sufficiently-fine resolution would capture any flow separation in the wake immediately downstream of the body. Two views of the inner/outer grids are shown in Fig. 21. The static, inner, unstructured grid is shown in gold. The Cartesian grid, shown in gray, corresponds to the Cartesian grid that has been subject to adaptive mesh refinement. A zoomed view depicts details of the overlap region. As visualized in the file, the smallest cell size in the Cartesian grid, which is generated as part of the solution process, is of a similar cell size as the outer-most unstructured cell.

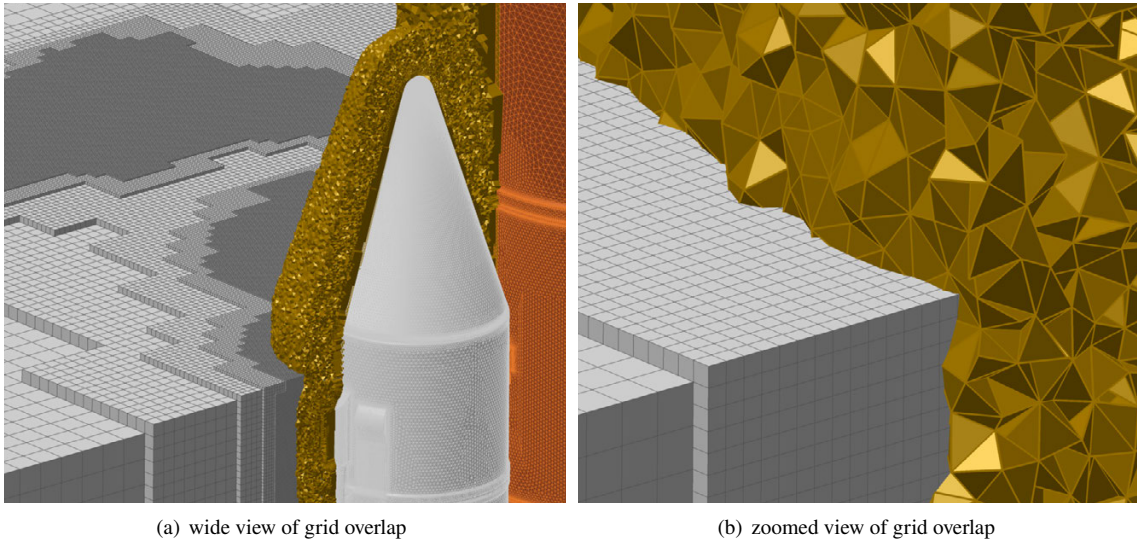


Fig. 21 Volume grid depicting unstructured inner grid and overset offbody Cartesian grid with (a) wide view and (b) zoomed view.

1. Unstructured Inner Grid

Grids in the early portion of the SLS program were generated in the Tetrahedral Unstructured Software System (TetrUSS) grid package (VGRID) and subsequently trimmed using Carpenter at 24 inches. Best practices were later updated to generate HeldenMesh grids that were trimmed at 36 inches as discussed in Ratnayake et al. and Pomeroy et al. [7, 15]. As previously mentioned, the unstructured surface grid was generated in HeldenMesh using methods generated over the course of the SLS program. Using the geometry as defined in GridTool, a large number of source distributions on a variety of patch families were declared and generated by HeldenMesh. For a typical configuration, in excess of 50,000 sources were generated, resulting in approximately 1.1 million triangular surface cells, depending on the specific SLS configuration. The size and stretching ratios for these cells varied significantly across the surface of the rocket.

A significant number of small-scale features were appropriately modeled. These include attachment brackets, connection hardware, camera mounts, and assorted aerodynamic fairings visualized in Fig. 22. The forward attach bracket that connects the SRB to the core is visualized in Fig. 22(a) in which the SRB has been removed from the plot for ease of visualization. Two liquid oxygen supply lines, one on each side of the core, are mounted on the outside of the core, and the forward end of one of the liquid oxygen (LOX) lines is drawn in Fig. 22(b). This LOX line is comprised of a long, symmetric cylinder in addition to a large number of mounting brackets, all of which are appropriately modeled. The downstream, or aft, end of the SRB is depicted in Fig. 22(c,d). A large number of features (e.g., booster separation motors and circumferential rings) are attached to the outside of the SRBs.

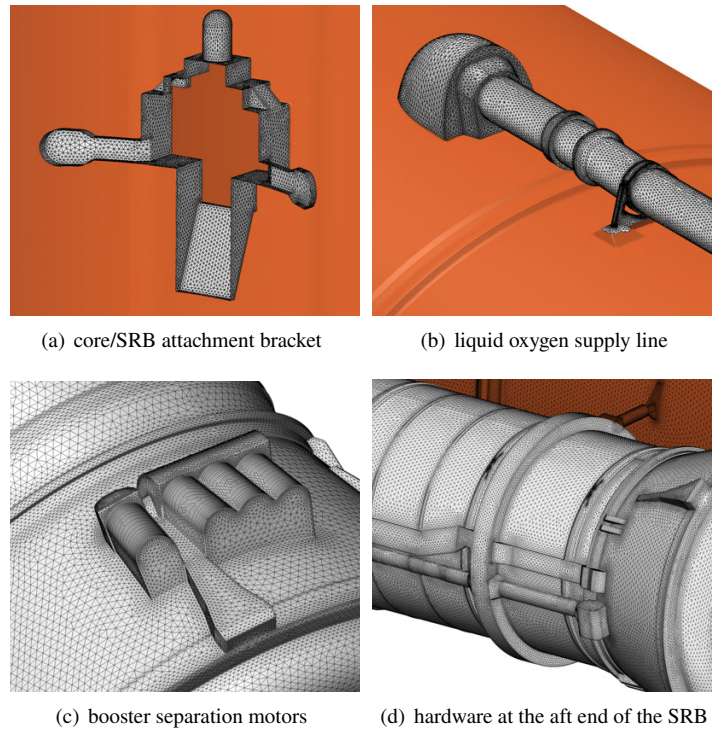


Fig. 22 Surface grid capturing numerous features such as (a) bracket connecting the core to the SRB, (b) liquid oxygen supply line, (c) booster separation motors, and (d) complex hardware at the aft end of the SRB.

The resulting surface grid, quantified by both y^+ (dimensionless wall distance) and volume of the first cell, is visualized in Fig. 23 for the Block 1 Cargo vehicle. The y^+ plot was generated with $\alpha_P=50$ deg. As shown in the plot, extremely small values of y^+ are present over much of the vehicle with some elevated values resulting near the vortices. Ideally, y^+ would be less than 0.7 at all surface locations over the entire flight envelope. However, elevated y^+ values, even in excess of 1.0, are seen over the SRB noses. Figure 23(b) plots the volume of the first cell over the SLS. It is clear that reduced cell sizes define small-scale features, such as the circumferential rings, with wider spacing declared on the core.

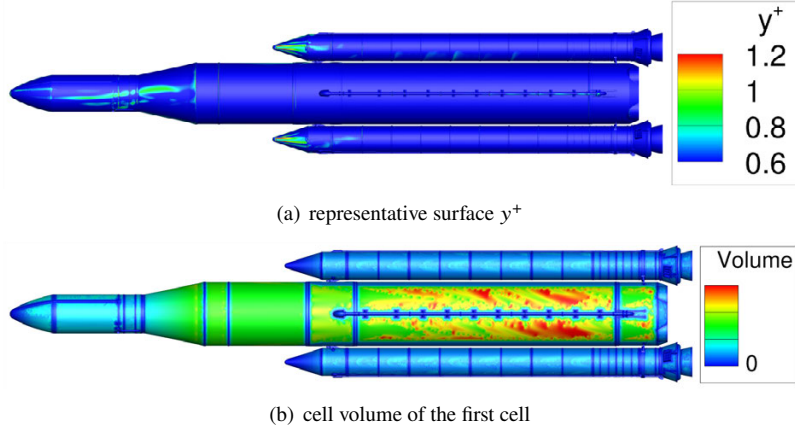


Fig. 23 Unstructured Block 1 Cargo surface grid quantified by (a) y^+ and (b) cell volume of the first cell.

2. Initial Outer Cartesian Grid

Before the first iteration, or time step, is computed, an initial offbody grid is generated. This grid is later subjected to offbody refinement, but an initial grid is independent of the anticipated flowfield characteristics or any adaptive mesh refinement settings. Slices of this initial grid at a constant body station and waterline are plotted in Fig. 24 in which the mesh is colored by the three-dimensional cell volume. The initial Cartesian grid is comprised of about 315 million cells distributed through nearly 30,000 blocks. While the inner grid extends a specified distance from the surface, the Cartesian grid extends far into the outer domain.

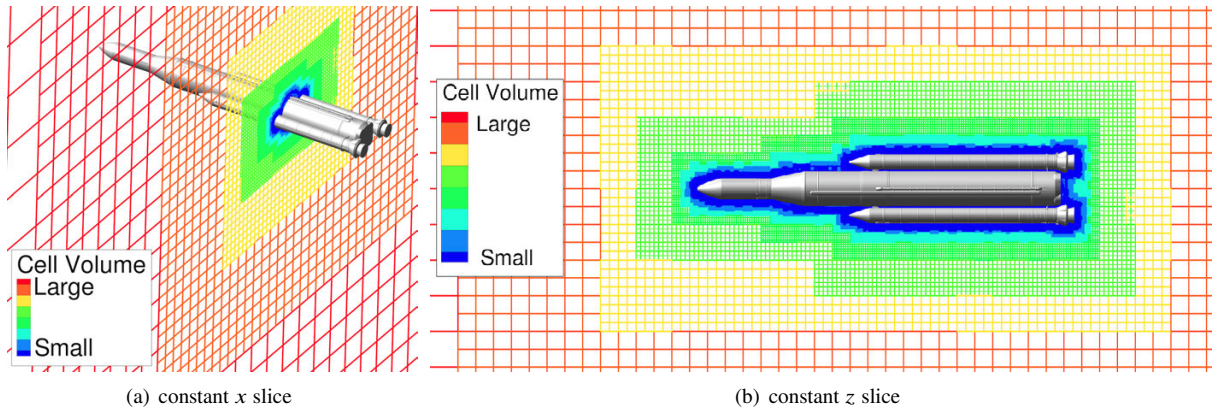


Fig. 24 Two views of the original Cartesian grid showing slices at (a) constant x and (b) constant z .

Within the adaptive mesh refinement process, it is possible to declare the outer bounds in which the offbody grid is refined. In an ideal situation, the refinement region would extend far into the wake to capture the downstream behavior of the wake. However, the cost of these simulations must also be considered when setting the refinement limits. These limits must be carefully considered while the fidelity of the simulation is considered for a given computational cost, and engineering judgment must be applied to select an appropriate domain. Figure 25(a) presents a visual representation of a representative rocket and a specified refinement box region. For ease of viewing, the rocket geometry has been projected onto the x , y , and z planes. If refinement regions are desired in multiple locations in the computational domain, numerous refinement boxes can be specified, as seen in Fig. 25(b). All analyses discussed in this paper were completed with one refinement domain, but active efforts are being implemented with the use of multiple refinement domains. For example, increased grid refinement is specified around the SRBs without overresolving the flowfield bounded by the outer refinement box, seen in the image.

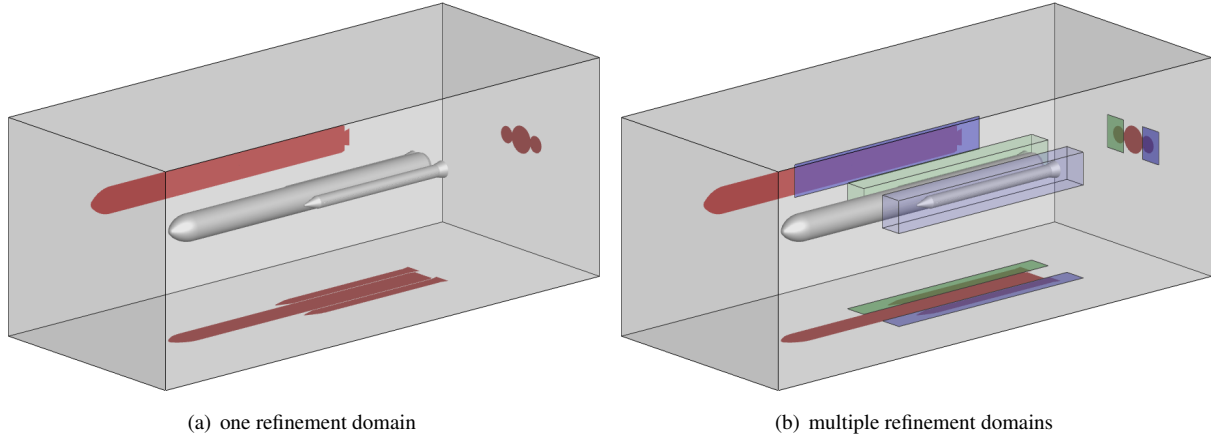


Fig. 25 Outer bounds of refinement domain with a rocket geometry showing rocket and projected geometry for (a) one refinement domain and (b) multiple refinement domains.

3. Cartesian Adaptive Mesh Refinement

Offbody adaptive mesh refinement is applied by adding grid density in regions of high gradients in the flowfield. As the unsteady flowfield and offbody adaptive grid affect each other, both the flowfield solution and Cartesian grid must reach a statistically-steady state before either time-averaging the solution or performing unsteady aerodynamic analysis. Figure 26 shows a body station cut at two different time steps including a time step before the solution is sufficiently set up and also a slice in which both the flowfield and grid are established.

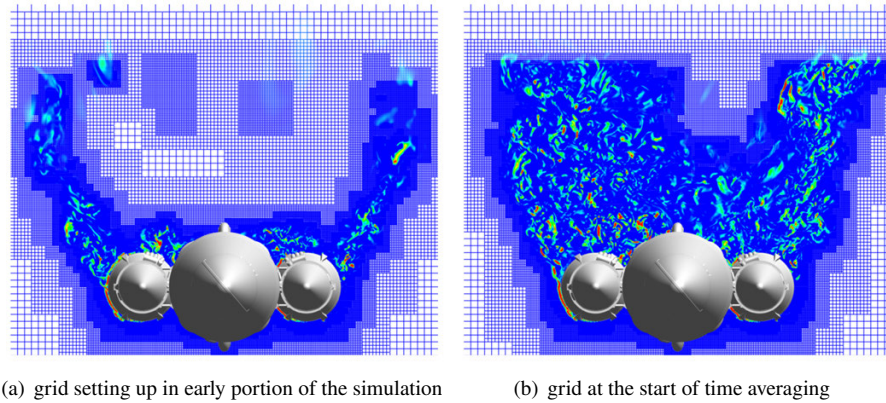


Fig. 26 Adaptive mesh refinement at (a) early portion of simulation and (b) beginning of time averaging.

For adaptive mesh refinement, the physical parameter of refinement is specified by the user as one of many selections. Within Kestrel, the grid can be adapted based on the local values of density, enthalpy, entropy, a shock sensor (based on pressure gradient), Q criterion, or ω . In addition to the parameter upon which the solution is adapted, the sensitivity of the flowfield quantity, known as the threshold, can be declared for a simulation. The metric of interest, and the sensitivity of this value to gradients in the flowfield, must be carefully selected to ensure adequate grid refinement without overresolving the flowfield. As seen in Fig. 27, these choices can lead to no, limited, desirable, or excessive grid refinement. For the cases in which the grid is insufficiently refined, key flowfield features will not be accurately captured, shown in Fig. 27(a,b). Alternatively, a sufficiently refined grid, visualized in Fig. 27(c,d) will capture all features of interest. It is seen in the figure that Fig. 27(c,d) capture a larger wake in both the y and z directions relative to the insufficiently-refined grids. While an adequately-refined grid will capture all key aerodynamic features, excess grid refinement in regions of limited flow gradients results in increased computational cost with a limited increase in

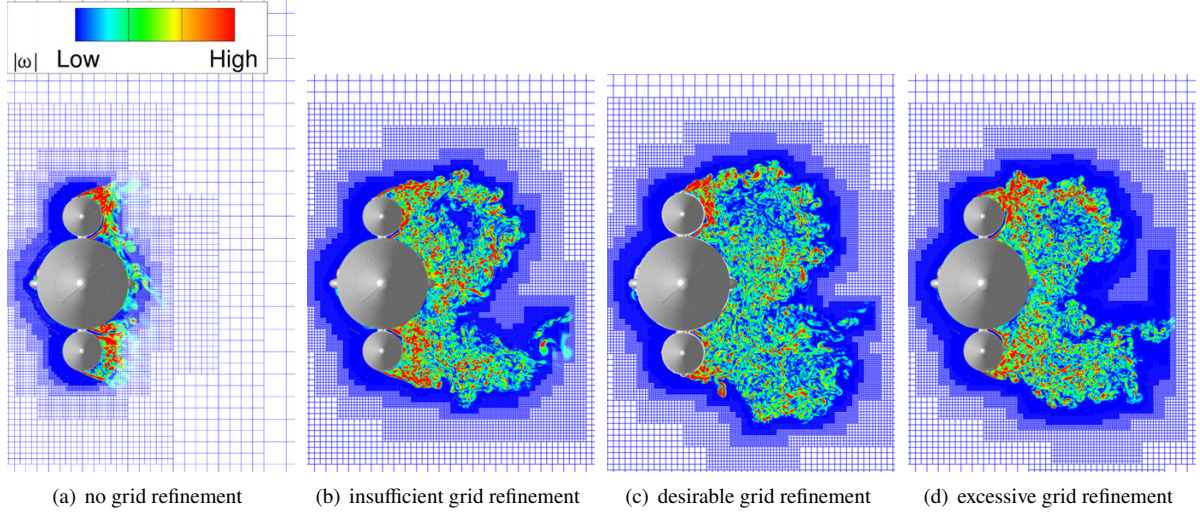


Fig. 27 Adaptive mesh refinement at a slice near the middle of the SRBs at the final time step showing (a) no grid refinement, (b) insufficient grid refinement, (c) desirable grid refinement, and (d) excessive grid refinement.

solution fidelity. This is seen in Fig. 27(d) such that the most-downstream extent of the grid is overrefined as no key flowfield features are observed in that location. As the accuracy of the solution is a function of the refinement selections, one must use the best engineering judgment to carefully balance size of the grid and computational cost.

Even with the selection of appropriate refinement parameters, the integrity of the grid refinement must be ensured as a function of time. As the grid refinement is inherently related with the computations, the grid will differ at various time steps. This is shown in Fig. 28 with a representative SLS solution at 1.000 sec., 5.000 sec., and 7.000 sec. Figure 28(a) depicts the solution and grid at an early part of the solution in which the flowfield and mesh has not yet reached a statistically-steady state. However, Fig. 28(b,c) shows slices for which the flow, and grid, depict minimal variations. Behavior such as this indicates the grid has reached a sufficiently-steady state for the slice shown in the image.

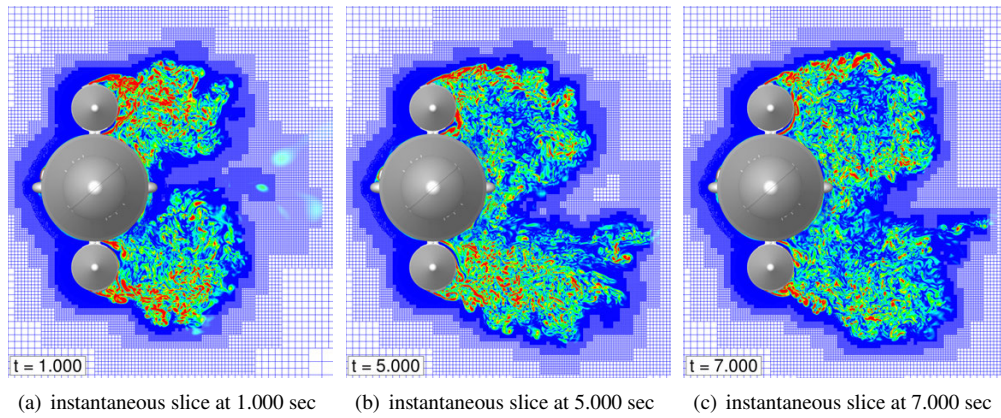


Fig. 28 Flowfield and grid at a slice near the middle of the SRBs at (a) 1.000 sec., (b) 5.000 sec., and (c) 7.000 sec.

B. Computational Setup

The baseline computational setup is similar to those used in previous studies [7, 9, 10, 15, 21, 33]. Since a wide number of settings can be selected, the LaRC SLS CFD team collaborated with Kestrel developers Scott Morton and David McDaniels for guidance regarding the initial selection of these input parameters [30, 41]. Values selected for the

baseline solution are found in this subsection. The exhaustive study examining the independent sensitivity of many of these values can be found in Ref. [15]. The KCFD settings of interest in this analysis, along with the associated baseline values, are presented in Table 1 [33]. In particular, these analyses confirmed that the Spalart-Allmaras (SA) IDDES computational scheme must be employed for adequate solution quality.

Table 1 KCFD Input Values.

Parameter	Value
n_{its}	14,000
Time Step	0.0005 sec.
Time Averaging Start	5.0 sec.
Total Simulation Time	7.0 sec.
Turbulence Model	SA IDDES fully turbulent
Inviscid Fluxes Scheme	HLLE++
Spatial Accuracy	Second Order
Temporal Accuracy	Second Order Gauss-Seidel

For problems of this nature, the database requires the generation of steady state forces and moments acting on the vehicle. Due to the unsteady nature of the flowfield, these time-dependent simulations will never converge toward steady values. Fortunately, these values do fluctuate around a certain mean value after many time steps for which the solution has set up and reached a statistically-steady state. As the time step can have a significant effect upon the fidelity and convergence of the simulation, the dimensional value must be carefully selected. Shown in Table 1, dt was specified as 0.0005 sec. The nondimensional time step (dt^*), as defined in Eq. 4 and reported to only one significant digit, was approximately

$$dt^* = \frac{V_\infty}{D_{core}} dt \approx 0.004. \quad (4)$$

In general, it is desired to have a nondimensional time step less than 0.01 and for the flow to not advance more than a quarter cell per dimensional time step. Based on this analysis, the lower of the two results should be selected for the simulation. For this simulation, the flow advances no more than a reference quarter cell per iteration and dt^* is less than 0.01, yielding a sufficient baseline selection of dt . Similar to other parameters, the effect of this value was investigated by Pomeroy, et al. [15].

Numerous settings are relevant to SAMAir, the outer solver, that must be selected independently of the KCFD input values. In general, the same settings were used with KCFD and SAMAir. The offbody grid refinement is performed within SAMAir, and commenced after the first 500 iterations. Subsequent adaptation was performed every 250 iterations with a refinement based upon ω . Refinement was performed over the entirety of the simulation.

C. Database Postprocessing

Large-scale efforts for database construction necessitates a large team to provide sufficient program support. With approximately ten people supporting computational efforts at various points over the SLS program, a standard approach must be employed by all team members. In addition to the computational approach in Sec. IV.B, postprocessing of these results was also standardized. Building upon technology developed for the Constellation program, a new python-driven system, which leverages both Tecplot 360 and the associated PyTecplot software, generates a standard set of plots and integrated quantities (e.g., line loads). These standard methods ensure that all simulations performed in support of SLS can be easily compared to other cases in the database.

D. Comparison of Kestrel Versions

As aerodynamic support of the SLS program has spanned many years, computational methods have been improved and refined with subsequent analysis. Of particular interest are modifications made to the computational grid as well as

the use of new versions of Kestrel. The Block 1 Cargo vehicle was used to check the effect of grid and Kestrel version. All simulations in this subsection were run at $\alpha_P=50$ deg and $\phi_P=0$ deg. This condition was selected due to the complex flowfield that includes separated flow, asymmetric vortices, and a Coanda effect. The effect of different grids and Kestrel versions are quantified for this particular condition. This is not intended to be a high-level uncertainty quantification effort, which would require data across the entire database to suitably capture the computational uncertainty due to Kestrel versions. The development of methods to quantify database-level uncertainty is in progress.

1. Grid Differences

As the computational methods for SLS matured, the best practices for a desirable surface grid were also updated. Over the course of the program to date, simulations have been run with grid version 6.4 (v6.4), v8.3 (as extensively discussed in Sec. IV.A), and v9.3. These grids represent improvements in both improved OML modeling and grid distribution. All three grids were generated using HeldenMesh and trimmed 36 inches from the vehicle surface. This yielded a total of approximately 140, 96, and 112 million cells for inner grids v6.4, v8.3, and v9.3, respectively. Simulations with the same setup were executed on all three grids to quantify differences in the solutions.

The time histories of the integrated force coefficients, normalized by the total force coefficient at the final time step for grid v8.3, for all three grids are shown in Fig. 29. The thin lines correspond to the instantaneous force coefficient. Time-averaged values, beginning at time step 10,000, are shown as color-coded thick lines for all grids. Due to the

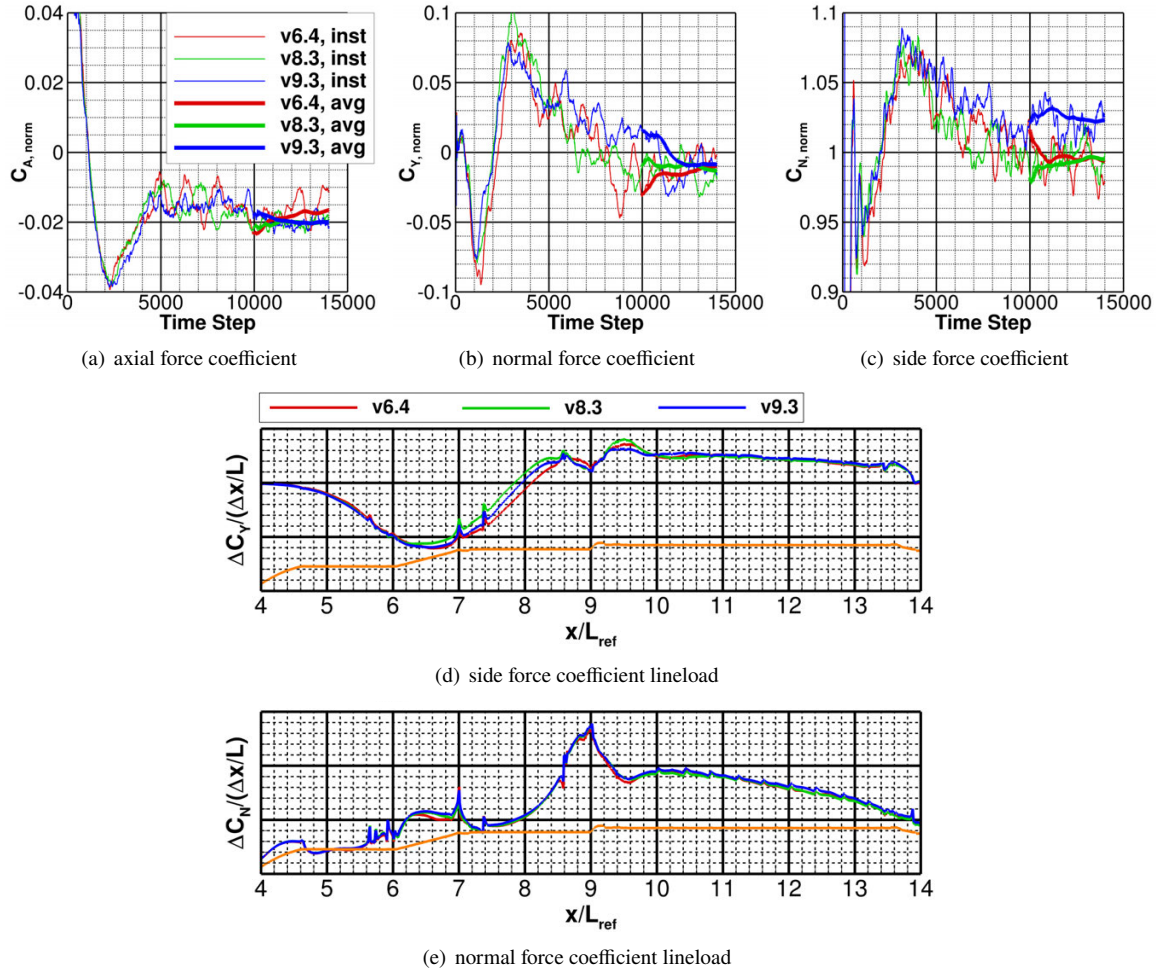


Fig. 29 Effect of grid version on instantaneous and average normalized vehicle forces, including (a) axial, (b) normal, and (c) side force coefficients, as well as (d) side and (e) normal force coefficient line loads on the core plotted with the core outline (orange).

selected condition, the normal force coefficient is significantly larger than both the axial and side force coefficients. Consequently, so that differences can be accentuated, the y-axis scale is different for all three coefficients. In general, the force coefficient histories are similar, with some differences expected as mesh improvements were made. These similarities are evident in both the instantaneous and time-averaged values. As shown in the figure, minimal variations are observed in $C_{A,norm}$ and $C_{Y,norm}$, the two smaller force coefficients for both the instantaneous and time-averaged metrics. Contrary to these two force coefficients, relatively larger differences are observed in the $C_{N,norm}$. Curiously, the two earliest grids, v6.4 and v8.3, yield decreased $C_{N,norm}$ relative to the newest grid, v9.3. Seen in the y-axis labels, $C_{N,norm}$ is significantly larger than both the axial and normal force coefficients at this particular flight condition. As both the grid density and surface patch representation vary between the three grids, it is difficult to isolate the independent effect of these characteristics. The results for all three force coefficients indicate it is important to maintain consistency and uniformity when generating data sets. Efforts are underway such that uncertainty quantification of these differences in force coefficients, and moment coefficients (not shown), can be determined.

In addition to the integrated forces, the distributed line loads on the vehicle are also of interest. Figure 29(d) presents the time-averaged core side force coefficient line load for all three grids. In addition to the line loads, the core geometry profile is shown for visualization purposes. The longitudinal location is normalized by a program-specified reference length (L_{ref}). In general, good agreement is found over the forward portion of the LVSA, upper stage, and aft portion of the SRBs. This observation indicates that the asymmetric vortices, forward of the LVSA, are being resolved in a similar manner. This observation is evidenced by the same sign of the line load, indicating similar topological structure of the asymmetric vortices, and similar magnitudes over much of the core. Despite these similarities, deviations are observed in the both the forward-most portion of the core ($7 < x/L_{ref} < 8.5$) and slightly aft of the top of the LOX line ($9.2 < x/L_{ref} < 9.5$). The normal-force coefficient core line loads are shown in Fig. 29(e). Seen in the image, good agreement is seen over the entire core. Localized spikes through the vehicle, in particular on the LVSA and SRBs, are caused by numerous protuberances, such as cameras and SRB circumferential rings. Driven by the large-scale separation on the leeward side of the vehicle, the close agreement of C_N indicates the unsteady flowfield is being resolved in a similar manner.

2. Major Version Differences of Kestrel

Occasionally, new major versions of Kestrel are released. While early work was executed using Kestrel version 6.4, the latest simulations were computed using Kestrel version 12.4. Through time, significant efforts have been undertaken with major versions 6.4, 8.3, 10.3, and 12.4. For comparison, simulations with Block 1 Cargo grid v8.3 were executed using Kestrel versions 10.3 and 12.4. The resulting vehicle integrated force coefficients are plotted in Fig. 30. As expected, some differences are observed in both the instantaneous values and the time-averaged metrics. Ideally, these values would be extremely similar between the two cases. However, systematic code improvements are found to result in slight differences in the resulting computation. While some deviations are present, overall, the integrated metrics agree well with each other. There is a slight reduction in the magnitude of $C_{N,norm}$ and $C_{Y,norm}$ for Kestrel version 12.4 relative to 10.3, especially between 6,000 and 14,000 time steps.

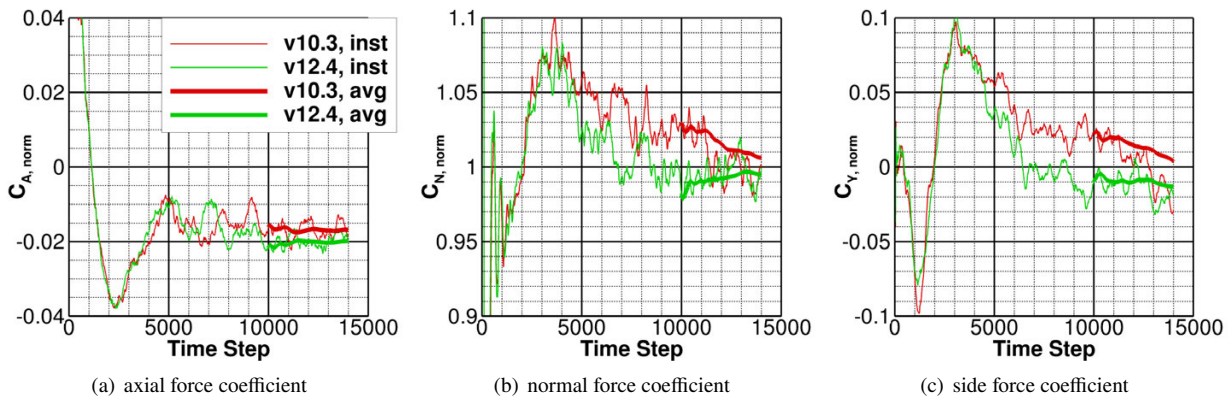


Fig. 30 Effect of major Kestrel version on instantaneous and average normalized vehicle forces including (a) axial, (b) normal, and (c) side force coefficients.

Time-averaged surface pressure distributions on the oblique leeward side of the vehicle for Kestrel versions 10.3 and 12.4 are plotted in Fig. 31. As shown in the legend, blue indicates a low value of C_p (suction), and magenta corresponds to an elevated value of C_p (pressure). Topologically, the two solutions agree well with each other. The key features include a strong asymmetric vortex on the starboard side of the LVSA, decreased C_p through the SRB/core gap, and low C_p on the outboard part of the SRB noses. The presence of these features in both solutions corresponds to similar integrated forces, as previously discussed. Seen in the figure, there is a slightly larger region of orange contours near the top of the core stage for Kestrel version 10.3 relative to 12.4. This results from a slightly larger vortex sweeping across the LVSA. These differences, in part, contribute to the difference in the time-averaged coefficients, in particular the normal and side forces. In addition, increased acceleration of the flow around the forward portion of the LOX line is observed for Kestrel version 10.3 relative to version 12.4.

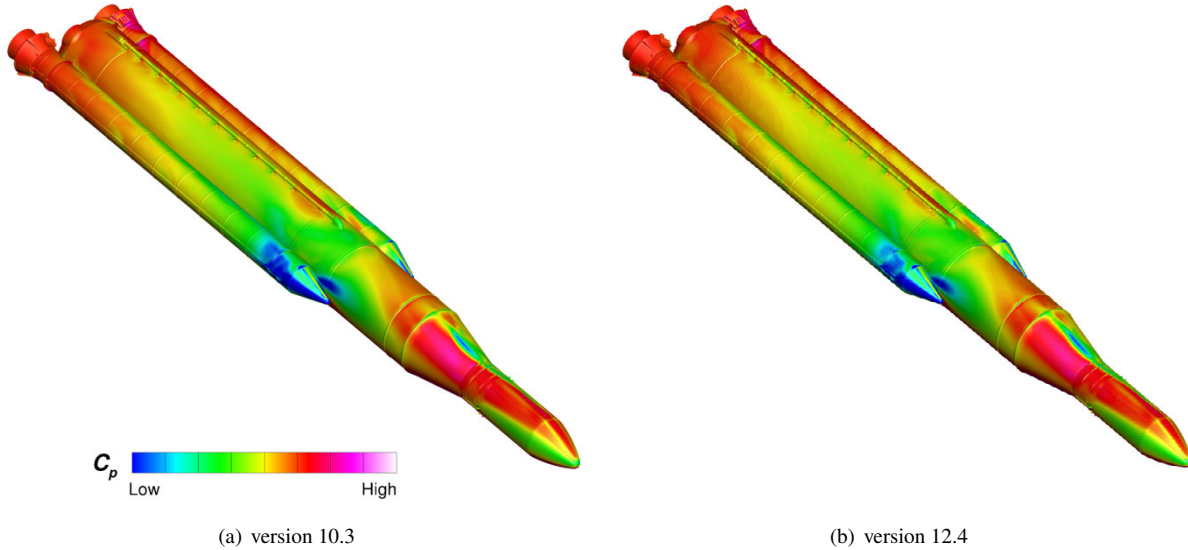


Fig. 31 Effect of major Kestrel version on surface C_p for versions (a) 10.3 and (b) 12.4.

3. Minor Version Differences of Kestrel

Finally, an investigation was undertaken to quantify the differences in minor version updates of Kestrel. In particular, the behavior of Kestrel versions 12.2, 12.3, 12.4, and 12.4.1 were compared using grid v9.3. As previously discussed, time-averaged line loads are of significant importance as these distributions are a key database deliverable. Figure 32 includes the core line load force coefficient line loads for the four Kestrel minor versions with the outline of the core shown for visual reference. Shown in Fig. 32(a), the core axial coefficient force coefficient line load for the Kestrel versions are nearly identical at all body stations. Local spikes in C_A are present near component junctions, such as the upper stage and the LVSA. These sharp increases are also seen near the top of the SRBs, $x/L \approx 0.85$. The SRB rings affect the loads on the core, as sharp increases in C_A are seen at a regular frequency.

Figure 32(b) presents the core normal force coefficient line load for the four Kestrel versions of interest. Overall, excellent agreement is seen for the four cases across the entire core. This indicates that all key flowfield features are being predicted in a similar manner, a key observation. Some very slight isolated differences are seen over and aft of the LVSA ($6 < x/L_{ref} < 8$). In this region, Kestrel versions 12.4 and 12.4.1 yield a slight increase in C_N loading relative to the other cases. Data agree well on core line loads in the region of the SRBs, a notoriously difficult flowfield to computationally capture. This observation indicates that there are no major differences in the Coanda states at any longitudinal locations, an encouraging result. Similar to Fig. 32(a), the SRB rings are predicted in a similar manner.

Finally, the side force coefficient core line loads are plotted in Fig. 32(c). Excellent agreement is observed over the upper stage, LVSA, and upper portion of the core. In addition, the data over the aft portion of the core in the vicinity of the SRBs are predicted in a similar manner. However, minor differences in the loading near the SRB noses are seen for these versions ($9 < x/L_{ref} < 11$). This portion of the flowfield is notoriously difficult to predict, and it is not necessarily

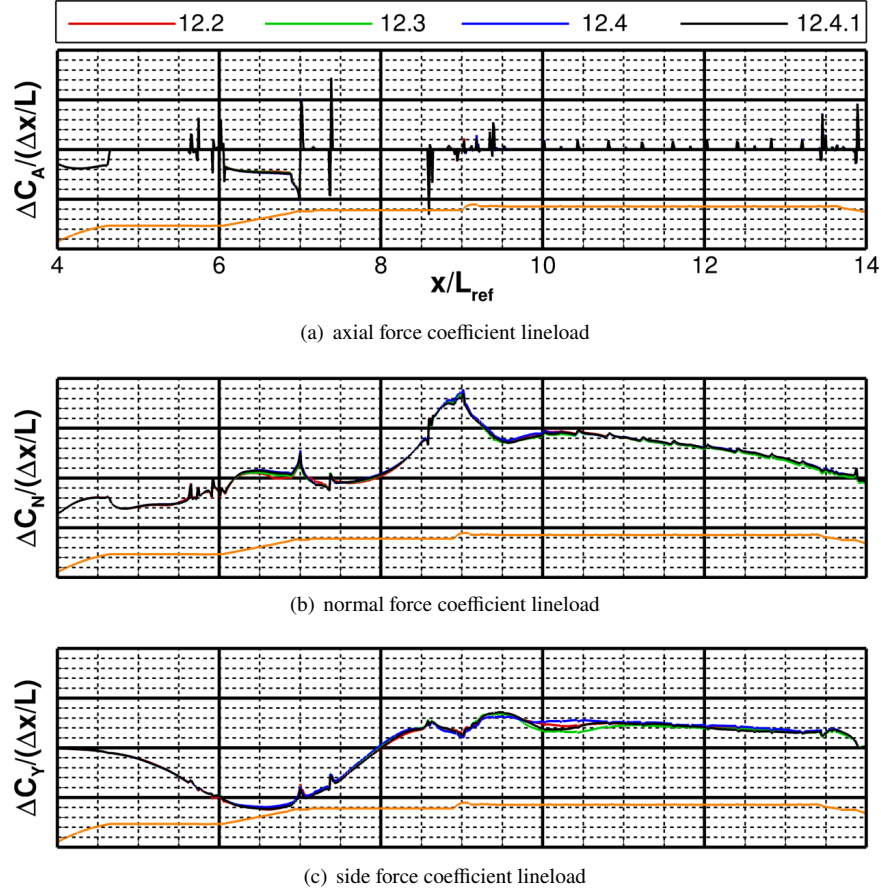


Fig. 32 Effect of minor Kestrel version improvements on the core lineloads including (a) axial, (b) normal, and (c) side force coefficients.

a surprising result that these differences are observed [9, 15]. This behavior is driven by differing prediction of the suction through the booster core/booster gap, similar to that shown in the aforementioned Fig. 31. In general, there are no significant differences in the core lineloads between minor updates of Kestrel.

E. Comparisons to Experimental Data

A comparison of best-practice computational data and experimental data, collected at the NASA LaRC 14- by 22-Foot Subsonic Tunnel (14x22), is shown in Fig. 33 in which $\alpha_P=50$ deg and $\phi_P=0$ deg. The data are presented at three different body stations, as depicted in the figure. Computational data were extracted at the same points as the instrumented test article. Each of these circumferential points is shown with a small symbol in which squares and circles represent the computational and experimental results, respectively. As depicted in Fig. 4, a circumferential ϕ_P of 180 deg corresponds to the downstream-most point on the launch vehicle, which is nominally opposite the systems tunnel. The centerbody of the model was instrumented with pressure taps at seven body stations comprised of 12 taps per ring. No surface taps were present on either of the SRBs as these were instrumented with force balances [6]. Overall, the two data sets show many similarities at all three body stations. Excellent agreement is found in both the attached and separated regions, and this observation is encouraging when considering the degree of separated flow. It is noted that small differences are observed near ϕ_P of 90 and 270 deg, which corresponds to the outward-most portion of the centerbody that forms the gap.

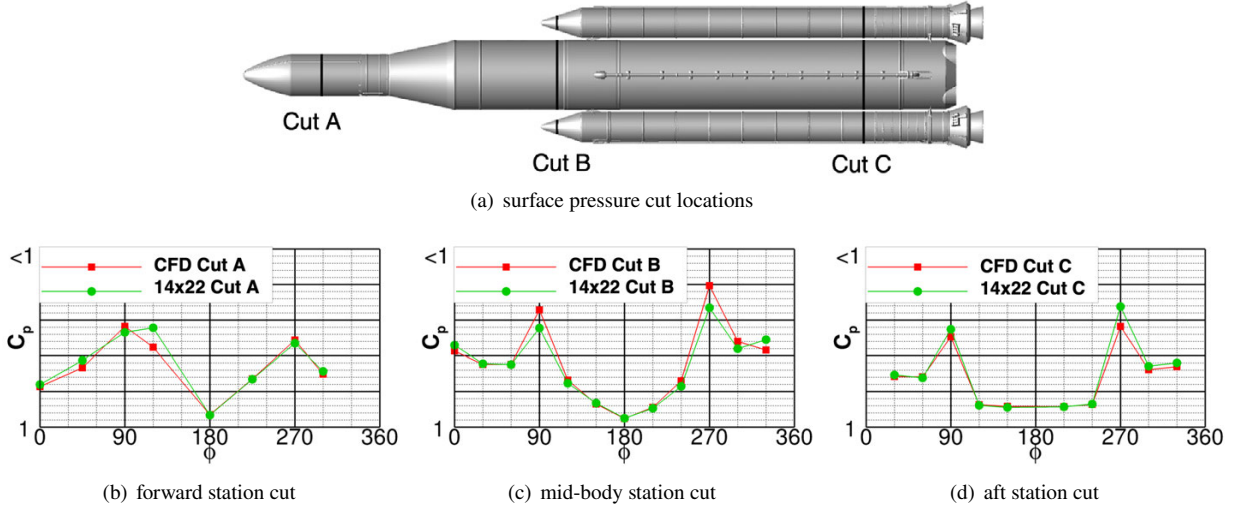


Fig. 33 Experimental 14x22 and computational pressure cuts at (a) forward, (b) mid, and (c) aft body stations.

F. Data-Fused Reduced-Order Modeling

The liftoff and transition line loads databases are generated with a method that synthesizes both experimental and computational results. This approach, called data fusion (DF), is used to ensure that the reported line loads agree with experimentally-measured force and moment coefficients. This procedure takes the following steps to reconcile the computationally-derived line loads with the experimentally-derived integrated loads [8, 42]:

- 1) represent the entire collection of CFD surface data set as a linear sum of weighted principal components, which are identified via the covariance matrix and its eigenvectors;
- 2) interpolate the principal component coefficients within the parameter space to increase the number of surface solutions within the database;
- 3) adjust both source and interpolated principal component coefficients as little as possible to yield an integrated (computationally sourced) surface set equal to the integrated (experimentally sourced) load set;
- 4) compute line loads from adjusted surface stresses (both pressure and skin friction) within the entire database parameter range; and
- 5) organize the adjusted, interpolated line load set into the deliverable database.

Ensuring that the delivered line loads integrate to the loads measured within the wind tunnel tests yields line loads, which were not existent within the original CFD solutions. However, as is often the case in data fusion, the resulting line loads serve as an acceptable compromise between multiple incommensurate data sources, which cannot otherwise be corrected to agree with one another.

A flowchart for database development, depicting the relationship between the experimental data and delivered database, is shown in Fig. 34. Data from an experimental test, including integrated forces and moments (F&M) and surface port pressures, are evaluated. Based upon these analyses, a design of experiments (DOE) method is employed to optimize the CFD run matrix. This step reduces the number of computational simulations needed for a high-fidelity database. These data are utilized in the development of a reduced order model (ROM), which is based upon the computational line loads as well as pressure, and skin friction distributions. Computationally-derived line loads are then augmented with the original experimental data to generate a data-fused reduced order model (DFROM), from which a line loads database is delivered.

V. Support for SLS Program

As discussed in Sec. II, a number of studies were performed in support of program needs. Four of these topics are presented in this section namely the effect of the mobile launcher, analysis with an atmospheric boundary layer, and the coupled effect of the hatch and CAA. It is noted that database methods remain unchanged relative to previously-published

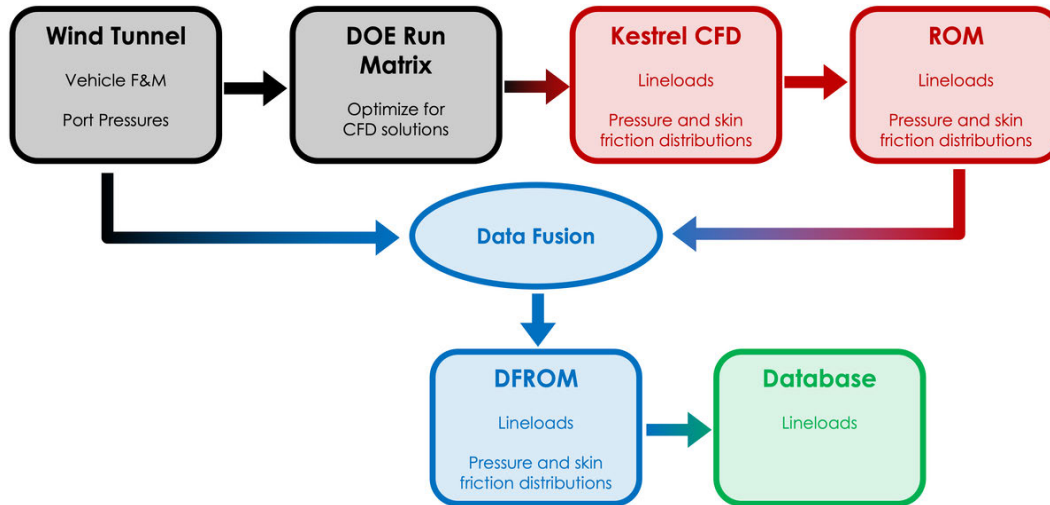


Fig. 34 Flowchart showing database generation process.

data by Ratnayake et al. [7]. All cases in this subsection were executed at Mach 0.183 and Reynolds number based on the core diameter (Re_D) of 615,000.

A. Mobile Launcher

The Mobile Launcher significantly affects the flow around the rocket and the rocket also affects the flow around the tower. It was desired to understand the effects of different Mobile Launcher configurations upon the aerodynamics of the Block 1 Crew vehicle. Consequently, computational analyses on two Mobile Launchers, namely the Mobile Launcher-1 Extended (ML-1E) and Mobile Launcher-2 (ML-2). A CAD representation of ML-1 and ML-2 is shown in Fig. 35. No official CAD model of the ML-1E exists, and thus, the baseline ML-1 is shown in the figure for comparison purposes. The ML-1E, solely used for computational analysis, is an extension of the ML-1 with an additional truss

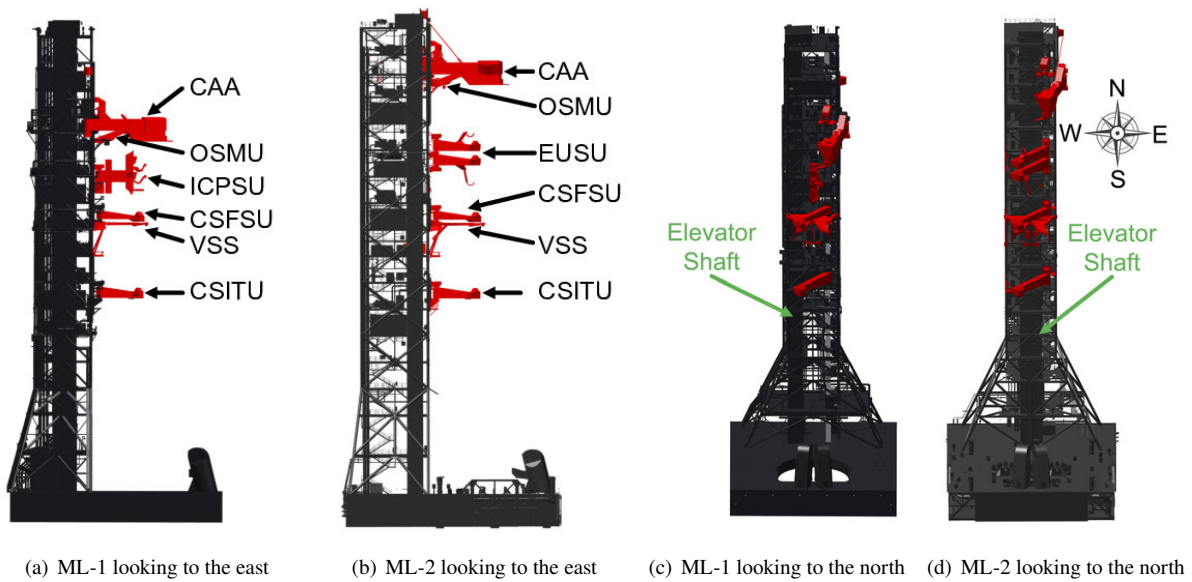


Fig. 35 CAD models, looking to the east, of both the (a) ML-1 and (b) ML-2 as well as (c) ML-1 and (d) ML-2, as viewed looking to the north.

structure added to the top of the tower. The views in Fig. 35(a,b) are shown as if the reader is looking to the east. Similarly, Fig. 35(c,d) are shown as if the reader is looking to the north. A compass rose in the oblique view is shown to orient the reader. Seen in the figure, the two towers are topologically similar to each other. Both structures contain a similar truss structure and associated systems, as labeled. From the top of the tower to the bottom, these key systems include the Crew Access Arm (CAA), Orion Service Module Umbilical (USMU), Interim Cryogenic Propulsion Stage Umbilical (ICPSU), Exploration Upper Stage Umbilical (EUSU), Core Stage Forward Skirt Umbilical (CSFSU), Vehicle Stabilizer System (VSS), and Core Stage Inter-Tank Umbilical (CSITU). It is noted that only the ML-1 contains the ICPSU while only the ML-2 includes the EUSU. Seen in the figure, some key differences are observed with the two towers. In particular, ML-2 is slightly taller than ML-1. This is necessary as the Block 1B vehicle requires a larger tower than that for the smaller Block 1 rocket. Additionally, ML-2 is more porous than ML-1. Finally, the elevator location on ML-1E is on the west side of the tower while the ML-2 elevator shaft is on the south side of the tower.

Computational OMLs of the two towers are shown in Fig. 36. Some key simplifications were made on these OMLs relative to the program CAD shown in Fig. 35. These choices were made such that the computations could be executed with a reasonable degree of fidelity while not overcomplicating the geometry or generating an unreasonable number of grid points. In particular, the tower does not contain systems that protrude from the tower. In addition, the interior structure of the tower was significantly simplified. While these two computational geometries do not capture the blockage through the tower, the similarities between the two towers are sufficiently similar such that the aerodynamic differences between the towers can be determined.

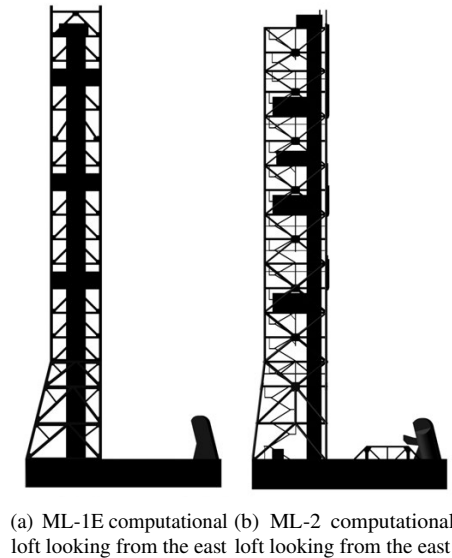


Fig. 36 Computational models looking from the east, for (a) ML-1E and (b) ML-2.

Computational results for the Block 1B Crew vehicle in proximity to either ML-1E or ML-2 were obtained for ground wind azimuth angles (ϕ_{azi} as defined in Fig. 6) from 0 to 360 deg at 30 deg increments. For these simulations, the rocket was located on the launch pad such that $h/L=0.0$ (see Fig. 6(b)), and consequently that α_P was 90 deg. For comparison purposes, the same conditions were run for the Block 1B Crew rocket on both launch towers.

Numerical results from Kestrel were obtained and analyzed to quantify the vehicle aerodynamic effects resulting from the presence of either tower. These data include surface pressure coefficients, integrated surface line loads, and integrated force and moment coefficients. Representative surface C_p data for the vehicle next to either tower are shown in Fig. 37 at $\phi_{azi} = 0$ deg. For this simulation, the rocket is downstream of, and thus in the wake of, the mobile launch tower. Unlike the case for ML-2, data for the ML-1E, shown in Fig. 37(a), indicate a strong low-pressure region on the port side of the vehicle core and port SRB. This region has decreased pressure relative to the ML-2 solution. At this particular freestream condition, such an effect can be attributed to the flow separation from the edges of the ML-1E west-side elevator shaft, which thus impacts the port side of the vehicle. Conversely, the presence of the south-side location of the ML-2 elevator shaft shields the vehicle against the incoming northerly ground wind. This effect eliminates any large C_p gradients on the port side of the vehicle.

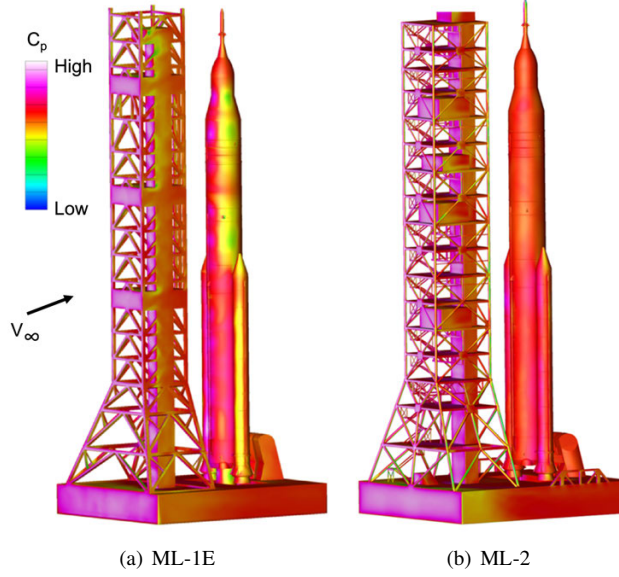


Fig. 37 Surface C_p at $h/L = 0$ and wind from the north ($\phi_{azi} = 0$ deg) in proximity to (a) ML-1E and (b) ML-2.

The normal and side force coefficient line load distributions are plotted in Fig. 38. In the plot, ML-1E data are shown as solid lines with ML-2 depicted as dashed lines. Color-coded lines correspond to the centerbody, starboard SRB, and port SRB. An axis label is provided at a value of 0. In general, the vehicle in proximity to ML-2 is subjected to decreased loads relative to the ML-1E case. This observation is especially evident when considering the forces acting on the centerbody, seen as a shift toward the 0 mark. Similar to the surface C_p data, the decreased loading on the centerbody is, in large part, due to the large wake behind the elevator shaft located at the south side (or furthest downstream for this condition) of the tower. The wake downstream of the south-located elevator shaft on the ML-2 tower shields the centerbody, thus decreasing the loading on this component relative to the core and ML-1E tower.

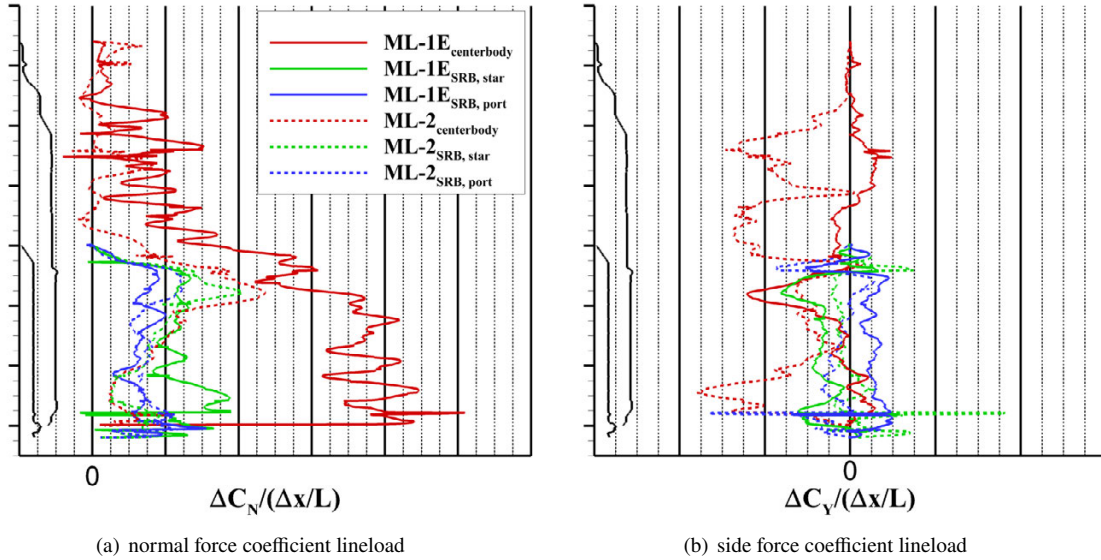


Fig. 38 Integrated line loads on the Block 1B Crew vehicle mounted on two Mobile Launchers at $h/L = 0$ and $\phi_{azi} = 0$ deg including (a) $\Delta C_N/(\Delta x/L)$ and (b) $\Delta C_Y/(\Delta x/L)$.

Figure 39 shows the integrated, time-averaged C_N and C_Y on the Block 1B Crew vehicle for a range of azimuthal angles. This plot presents data at all computed conditions, which was comprised of a range of ϕ_{azi} for given freestream conditions. Similar to the previously-discussed data, the vehicle is unloaded when in proximity to ML-2 relative to ML-1E at primarily low ϕ_{azi} . It is evident that the wake from the elevator shaft affects the flow at not only $\phi_{azi}=0$ deg, but at angles in excess of 45 deg from the zero azimuth angle case.

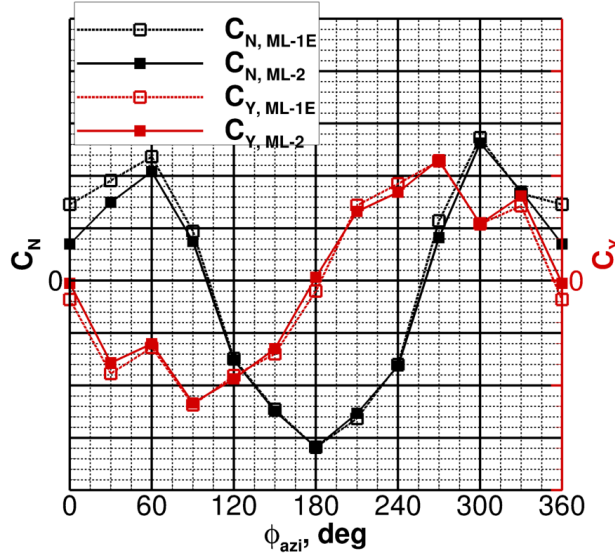


Fig. 39 Time-averaged normal and side force coefficients exerted on the Block 1B Crew vehicle mounted on two different Mobile Launchers at $h/L=0$ and $\alpha_P=90$ deg.

B. Atmospheric Boundary Layer

The overall aerodynamic characteristics of the vehicle in proximity to the ground can be quantified by using uniform flow inputs, as previously presented. In a real-world situation, the rocket and tower are subjected to a large atmospheric boundary layer. Analysis with different nonuniform freestream conditions can rapidly increase the size of these delivered databases, and thus, care must be taken when developing the associated run matrix. It is possible to simulate atmospheric boundary layers in Kestrel, albeit it is nuanced and not simple when executed as of version 10.3. In particular, the nonuniform boundary layer profile must be imposed on the inflow boundary of an unstructured grid rather than on the Cartesian grid aligned with one of the three coordinate axes (x , y , and z). As the boundary layer cannot be prescribed on a Cartesian grid, simulations must be executed with a fully-unstructured formulation. As the unstructured grid is not trimmed nor overlapped with a Cartesian grid, adaptive mesh refinement with such an approach is not possible. With this approach in Kestrel, the velocity flowfield with the atmospheric boundary layer profile can be imposed at the upstream boundary for roll angles of 0, 90, 180, or 270 deg, corresponding to winds from the north, east, south or west. For all other roll angles that are not a multiple of 90 deg, the unstructured grids for the vehicle and tower must be rotated relative to the outer boundary unstructured grid and Cartesian grid to provide an adequately-developed atmospheric boundary layer.

The ground wind profiles were selected as a maximum value to ensure the integrity of the rocket and all subsystems at the specified worst-case scenario. The atmospheric boundary layer for the simulation was developed from standard, previously-defined SLS specifications [43]. In particular, the Design Specification For Natural Environments (DSNE) wind profiles were used. The wind velocity profiles are specified by Eq. 5 in which u is the wind speed, $u_{18.3}$ is the velocity at 18.3 m (60.0 ft), and z is the elevation in meters.

$$u(z) = u_{18.3} \left(\frac{z}{18.3} \right)^{1.42(u_{18.3})^{-3/4}} \quad (5)$$

Based on this equation, four DSNE velocity profiles in metric units are shown in Fig. 40. These profiles correspond to the extreme conditions permissible at four stages of the prelaunch/launch stages. These conditions include the cases in

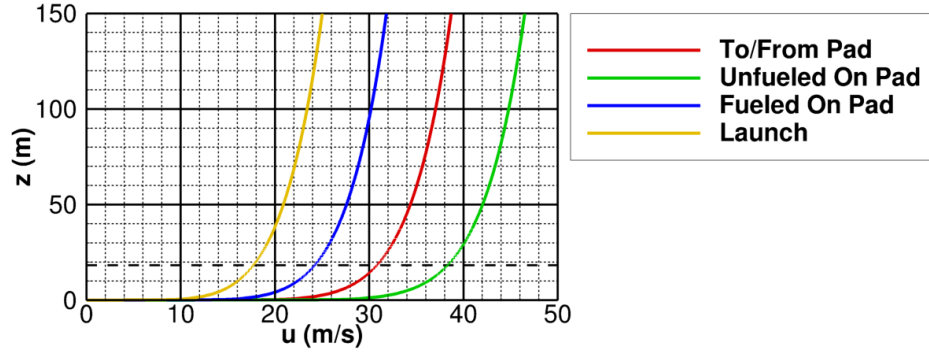


Fig. 40 Limiting DSNE atmospheric boundary layer profiles for prelaunch and launch.

which the vehicle is being transported to the launch complex, prelaunch prior to fueling, prelaunch after fueling, and launch. For reference, a thick, black, dotted, horizontal line is shown at 18.3 m (60.0 ft). Shown in the image, the most stringent constraint is at launch ($u_{18.3}=17.7$ m/s), then a fully-fueled vehicle on the pad ($u_{18.3}=24.2$ m/s), followed by unfueled transport between the VAB and launch complex ($u_{18.3}=30.8$ m/s), and finally the unfueled vehicle on the launch pad ($u_{18.3}=38.3$ m/s). For all profiles, the velocity rapidly increases in magnitude from the no-slip condition on the ground to a short distance above the ground, say 15 m. Above this elevation, the freestream velocity gradually increases to the maximum velocity at the top of the profile used in this analysis. Note that the velocity does not asymptotically approach a constant value at high elevations. That is to say that a gradient in velocity as a function of altitude is finite at the maximum elevation for SLS analysis.

Preliminary reasoning suggested that, when considering aerodynamic coefficients normalized by local dynamic pressure, the effect of an atmospheric boundary layer profile, instead of a uniform velocity profile, was of less importance than other parameters of interest (e.g., angle of attack, roll angle, and the vehicle and tower geometry). Consequently, it was decided to simulate one of the more stressing DSNE wind profiles to determine an estimate of the differences between cases with and without an atmospheric boundary layer. Of particular interest was the aerodynamic loading on the forward attach bracket in which the maximum loads were exerted at ϕ_{azi} of 270 deg. In addition to this loading constraint, winds from ϕ_{azi} at 0 and 180 deg (from the north and south, respectively) would have significant vehicle/tower interactions. Therefore, it may be difficult to isolate the effect of an atmospheric boundary layer at these azimuth angles. On the other hand, winds from ϕ_{azi} of 90 and 270 deg (from the east and west, respectively), would likely result in substantial vehicle/tower interactions. Consequently, these conditions would exhibit larger differences between the atmospheric boundary layer and constant-velocity profile simulations than differences for a case in which ϕ_{azi} was either 0 or 180 deg. Because of the maximum loading on the attach hardware and decreased vehicle/tower interactions, a single simulation was executed at ϕ_{azi} of 270 deg.

Computational results for the two cases in discussion are plotted in Fig. 41. Instantaneous data are shown for the final time step of the solutions. A slice at the vehicle centerline, quantified by Mach, is plotted. In the figure, freestream flow is from the west, or left to right in the image. The south-facing side of the vehicle is shown, and thus the tower, located on the north side of the slice, is not visible. Note the reduction in Mach number upstream of the vehicle for the atmospheric boundary layer solution. A highly-unsteady, separated wake is seen downstream of the vehicle in both solutions. The incoming flow for the uniform freestream velocity contains more momentum than the atmospheric boundary layer case. Consequently, in close proximity to the ground, decreased momentum is observed in the wake for the boundary layer simulation relative to the baseline solution, evidenced by a larger region of low Mach.

Time-averaged surface pressure data, for both the vehicle and tower, are shown in Fig. 42. The standard uniform freestream flowfield is plotted in Fig. 42(a) while the solution subjected to an atmospheric boundary layer is shown in Fig. 42(b). Note that the computational domain extended a large distance in all three dimensions from the rocket. The surface of the Earth, with a no-slip boundary condition, was not simulated. While all key flowfield features are visible in both solutions, some differences in the pressures are noticed, most notably over the LVSA and upper portion of the core. In this region, the atmospheric boundary layer solution exhibits decreased flow acceleration over the rocket relative to the uniform velocity profile case. This difference results in a reduction of both the normal and side loading at this freestream condition. No significant differences are observed over the SRBs or the core in close proximity to the

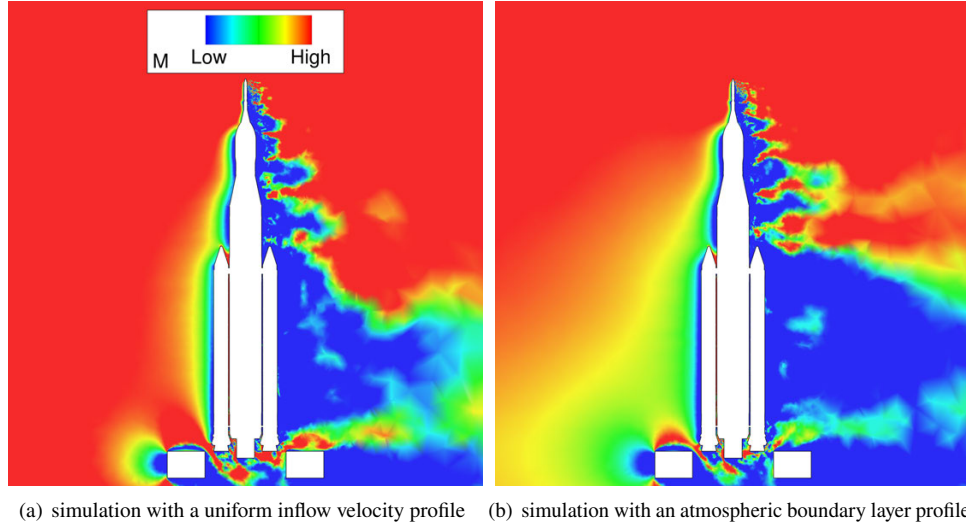


Fig. 41 Slice of Mach number aligned with the vehicle centerline for an instantaneous (final time step) simulation with $\phi_{azi}=270$ deg for (a) a uniform inflow velocity profile and (b) atmospheric boundary layer profile.

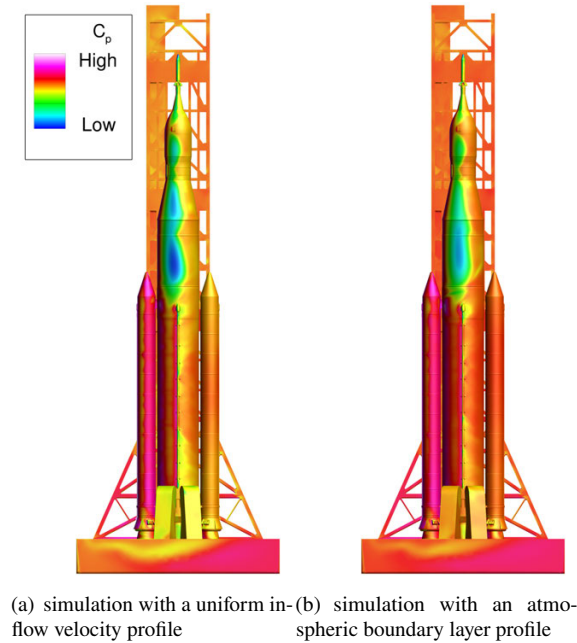


Fig. 42 Surface pressure contours on vehicle at ϕ_{azi} of 270 deg subject to (a) a uniform freestream flow and (b) atmospheric boundary layer profile.

boosters. The effect of the boundary layer is evident on the vehicle platform with increased C_p , thus decreased flow acceleration, over the downstream portion of the platform. Overall, minimal differences are observed on the tower.

The sectional line loads exerted on the core quantified by side force and normal force for the two cases of interest are plotted in Fig. 43(a). In these plots, the uniform velocity profile data are shown in red, and the atmospheric boundary layer case is shown in blue. The standard nondimensional line loads were converted to dimensional values to compare the total loading on the vehicle. The uniform-velocity case (blue) was scaled by local dynamic pressure such that the

dimensional forces could be determined. Conversely, the atmospheric boundary layer simulation (red) was scaled by the freestream dynamic pressure. The line loads between the two cases are quite similar near the top of the rocket including the upper stage and the LVSA, and the top portion of the centerbody. However, differences in both side and normal force (missile axis) are observed over the upper portion of the centerbody, especially in side force. In this region, the atmospheric boundary layer yields more side force relative to the uniform freestream case. In the same figure, the normal force line load shows similar behavior over the upper stage, LVSA, and also the upper portion of the centerbody, slightly further down the rocket than the side force. However, a reduction in normal force for the atmospheric boundary layer case relative to the uniform freestream solution is observed near the SRB noses. Similar agreement is seen over the lower portion of the rocket.

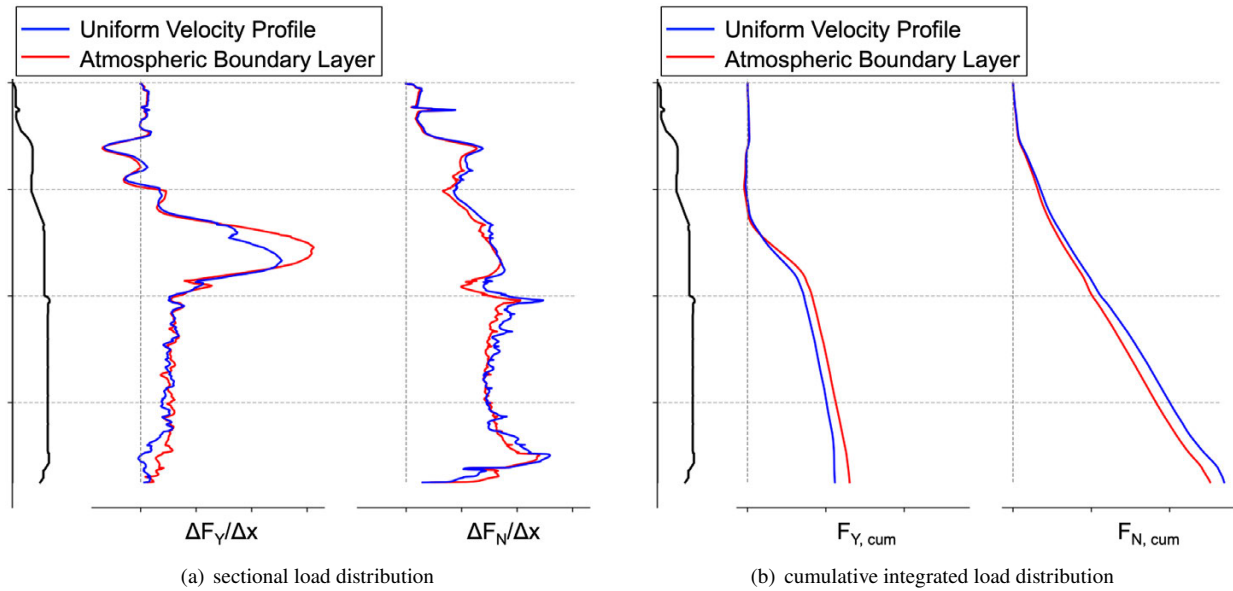


Fig. 43 Dimensional line loads on SLS Block 1B Crew vehicle for side force and normal force quantifying (a) sectional load distribution and (b) cumulative integrated load distribution.

Figure 43(b) presents the integrated line loads over the vehicle. In this figure, the loads are cumulatively integrated down the rocket such that there is no loading at the top of the vehicle and the total integrated centerbody loads are quantified at the bottom of the plot. In this format, it is useful to visualize the points in which the differences in loads vary the most. Similar to the sectional forces, the largest deviations in side force occur at the top of the constant-diameter portion of the centerbody leading to minimal additional variations over much of the rest of the vehicle. The increase in sectional side force nearest to the ground results in a slight increase in integrated side force over the lowest part of the centerbody. Differences in normal force are nuanced relative to the side force. The decrease in sectional normal force at the top of the boosters also results in a decrease in normal force relative to the upper portions of the vehicle.

C. Launch Abort System Hatch Opening

In addition to ensuring the vehicle performance is acceptable in the low-speed regime of flight, the safety of the crew must also be satisfied at all times. In particular, a safe emergency egress from the rocket must be ensured, as discussed in Sec. II.F. While exiting from the vehicle, whether in an emergency situation or not, the astronauts pass through the double-hatch system (Fig. 17) and through the CAA (Fig. 16) before entering the tower. The hatch system is comprised of the Orion hatch and the larger LAS hatch. Both hatches deploy simultaneously. It is the larger, outer LAS hatch, which is exposed to the largest wind loads when the CAA white room weather seal door is retracted, letting freestream flow into the room and allowed to impinge on the LAS hatch, which is of particular concern to the program. Consequently, aerodynamic databases were provided for the forces and moments exerted upon the LAS hatch as a function of wind direction and hatch deployment angle.

To generate high-fidelity loads, simulations were executed with four components including the tower, vehicle, CAA, and hatch. The hatch is never deployed if the CAA is fully retracted, so simulations were performed with the CAA in the fully-deployed position, however, with the weather seal door retracted. The requested data corresponded only to the aerodynamic loads on the hatch, and integrated forces and moments were not needed on either the vehicle or tower for these purposes. As loads were only needed on the hatch, the computational region of interest is a small subset of the entire computational model. As the hatch geometry is both small and very high on the launch vehicle, some geometric simplifications were made such that the computational cost could be reduced. The full model is shown in Fig. 44, which includes the modeled tower (black), vehicle (gray), CAA (red), and hatch (blue). A wide, zoomed, and detailed view are all shown. Seen in the image, the tower geometry was truncated below a body station approximately in the middle of the vehicle. In this region, the truss structure was removed, but the elevator shaft was retained. In addition to tower simplifications, both SRBs were removed from the model.

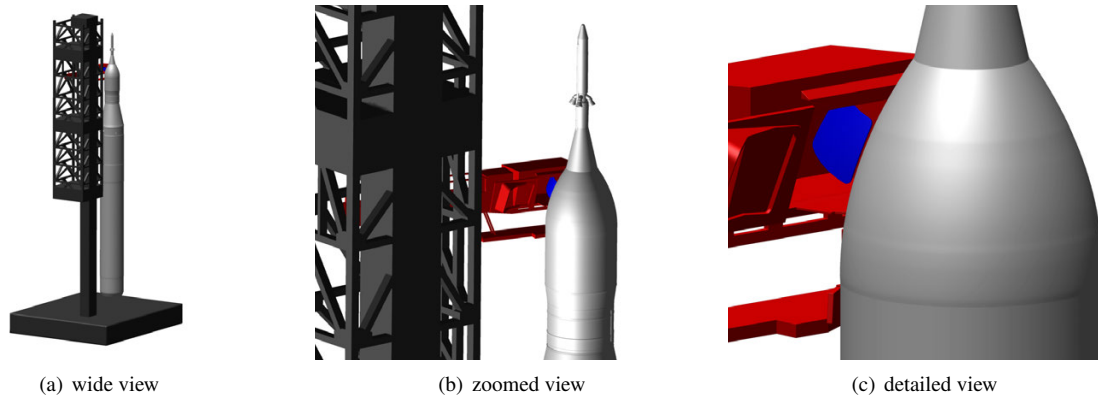


Fig. 44 Computational model used for hatch systems showing the truncated tower (black), Block 1 Crew vehicle (gray), CAA (red), and LAS hatch (blue) at (a) wide, (b) zoomed, and (c) detailed views.

While the lower part of the tower and boosters certainly have an impact on the resulting aerodynamic flowfield, the air near the hatch and CAA will be minimally affected by flow that is more than 100 ft away from the geometry of interest. The LAS hatch was modeled as a surface near a watertight rocket geometry. In reality, an open LAS hatch exposes the interior of the Orion vehicle to the outside environment and will have an effect upon the aerodynamic loading of the hatch, but it is deemed second order. The actual region between the Orion vehicle and the LAS contains positive pressure relative to the outside air. Consequently, this pressure generates an outward force on the LAS hatch, which will then provide an assistive hatch opening moment in the early portion of the system deployment, and thus a watertight vehicle (without positive internal pressurization) will yield a conservative result relative to the true solution. In addition, modeling of an internal cavity on the simulation would greatly increase the geometric and computational complexity of the analysis. Because a closed vehicle will yield a conservative aerodynamic result with decreased complexity, it was decided not to model the interior geometry.

A top view of the Block 1 Crew launch vehicle, shown with the CAA and a portion of the tower, is shown in Fig. 45. The top portion of the CAA and the white room has been blanked such that the hatch deployment can be seen in the schematic. Both a wide and zoomed view are shown with five different hatch deployment angles (θ). Consistent with Fig. 6(a), the wind azimuth angle is shown along with the hatch θ . By definition, a θ of 0 deg is when the hatch is in the fully-retracted position on the side of the rocket, while positive values of θ exist with increasing deployment angles.

A database was generated for a range of hatch deployment angles (θ) and wind directions (ϕ_{azi}). Seven different θ values, ranging from fully closed (0 deg) to fully deployed (58.8 deg) were analyzed at 26 freestream wind angles and one freestream velocity. While all six forces and moments certainly contribute to the loads on the hatch, analyses showed that the total forces and moments are dominated by the normal force and moment (missile axis). The aerodynamic loads ultimately result in a net moment that either promotes deployment, referred to as an opening moment, or hinders deployment, referred to as a closing moment. These data are shown in Fig. 46 in which the hatch deployment angle (θ) is labeled on the x axis. The line and symbol color for the wind angle ranges from dark to light with increasing wind angle. Labels on the left side of the plot indicate the direction of an opening and closing moment relative to a zero-moment line. Analysis was concentrated around cases with hatch deployment angles of 5, 35.7, and 58.8 deg. Most, but not all, cases

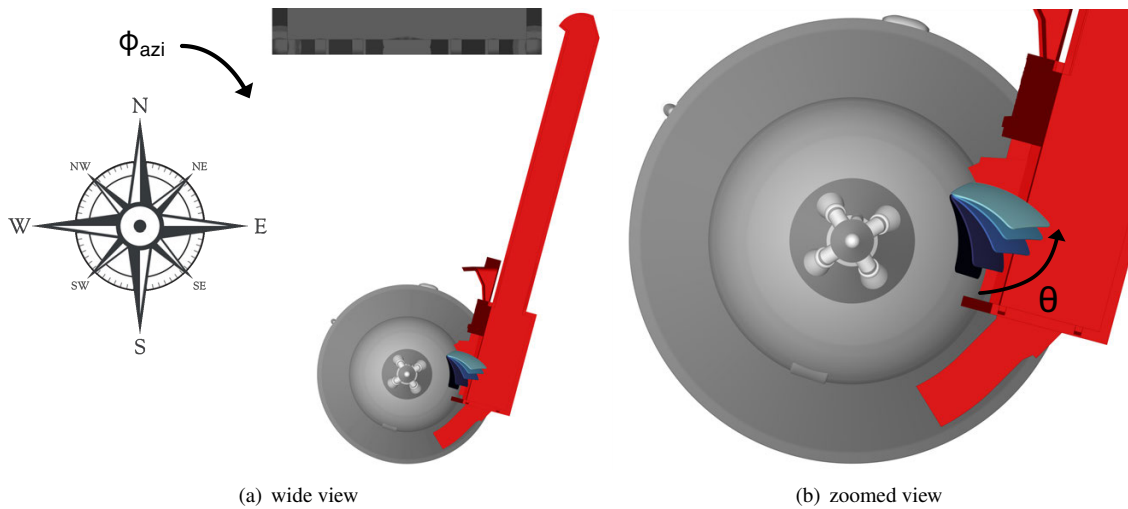


Fig. 45 Coordinate system for hatch analysis including (a) top view with ϕ_{azi} direction and (b) zoomed view showing hatch deployment angle (θ).

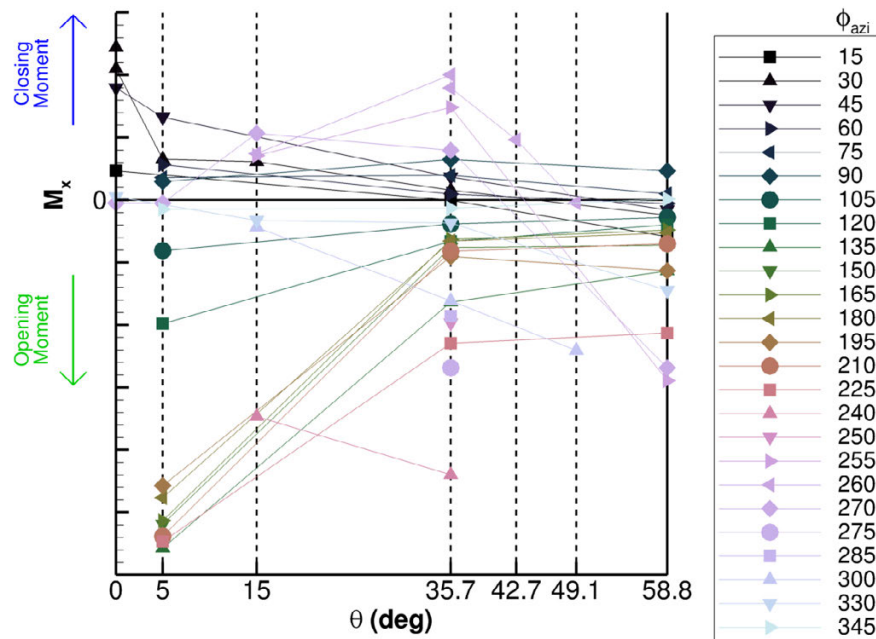


Fig. 46 Effect of hatch deployment angle and wind direction upon the hatch hinge opening moment (M_x).

resulted in an opening moment, which would aid astronauts during an emergency egress situation. In general, a closing moment results from winds from the west, northwest, north, or northeast (centered around 0 deg) with maximum loads at about 260 deg, a wind from the west. These extreme conditions must be considered when evaluating the ability for the system to operate effectively.

VI. Conclusions and Future Work

This review paper includes a summary of computational efforts from the NASA Langley Research Center to predict the low-speed flight characteristics of the SLS vehicle. The particular region of interest ranges from when the vehicle is on the launch pad, until Mach 0.3, when ascent is defined to begin. In this relatively short period of flight, the vehicle

is exposed to a wide range of conditions including angle of attack from 0 to 90 deg and 360 deg of roll angle. The high-alpha conditions on a three-body vehicle result in an extraordinarily complex flowfield that includes a variety of flowfield features, such as asymmetric vortices and the Coanda effect. To accurately resolve these flowfields, complex IDDES (Improved Delayed Detached Eddy Simulations) computations, coupled with an adaptive grid, were executed using the Kestrel CFD program developed by the DOD HPCMP CREATE-AV group.

Computational methods have been developed such that academic-fidelity computations are executed in a production environment. This rare approach is necessary to provide high-quality aerodynamic databases to other SLS subteams. Databases were calculated for both the isolated vehicle and the vehicle in close proximity to the launch tower. Through exhaustive efforts, it was ultimately concluded that the adaptive mesh routines must be employed at least 1.5 core diameters downstream of the leeward edge of the vehicle. This level of offbody refinement is necessary to ensure the proper surface pressure distribution is being predicted on the rocket. As with any large-scale computational effort, the fidelity of the simulation, and thus extent of grid refinement, must be balanced with the available computational resources. It was also confirmed that the time step for these simulations must be sufficiently small such that the nondimensional time step is less than 0.01, a general guideline accepted in the CFD community.

Uncertainty quantification of computational datasets is still limited to external comparisons: usually code-to-code as well as code-to-tunnel frameworks. Quantification of uncertainty on distributed loads datasets like lineloads remains an active area of research, as does the improvement of UQ on integrated quantities of interest, which are primarily sourced from computational data. Data fusion and sensitivity studies remain promising avenues through which computational datasets can be more rigorously bounded in future SLS generations. With a large-scale program extending over many years, improvements to computational solvers, at times significant, result in various versions of the code being executed for different databases. Numerical results from different code versions, while close, are not identical. While consistency of analysis is paramount, these differences contribute a not-insignificant amount of uncertainty to the system.

In the future, it is desired to have an improved understanding of the aerodynamics of multi-body vehicles. While some experimental work has investigated Coanda effects on the SLS, an extensive computational study has not been conducted. Consequently, unsteady simulations will be performed on both a two-dimensional three-body cylinder geometry and an SLS vehicle. Of particular interest is the flow between the gaps and in the wake for Reynolds numbers as low as 200,000 and as high as 10 million. An ongoing effort is focused upon the effect of roughness on a simplified SLS model. Instead of a computational roughness model, surface-mesh scale artificial roughness is being applied to understand the turbulent wake development. Finally, the fluid-structure interactions of an SLS-type geometry will be computed with Kestrel and compared to experimental data. A structural response model is available in Kestrel for a user-provided geometry.

Computational support will continue to be critically important to the success of the SLS program. Following the launch of Artemis I, careful comparisons will be made between the flight data and computational results. These lessons learned will carry forward into the SLS program. Development of SLS vehicles will continue into the future. Similar low-speed computational support will be provided for the Block 1B and Block 2 vehicles. This will include database development for the full vehicle and any other trade study support and program requirements. In addition, development of unsteady lineloads is planned to inform the Ground Wind Loads database. As the SLS program matures, the computational tools for the low-speed regime have been systematically refined. Nearly ten years of efforts, extending back to the time period immediately after the end of the Constellation program, have resulted in exhaustive support of the SLS program. Best-practice standards will continue to be refined in the future, ensuring delivery of high-quality databases to the program.

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