

Improved Techniques for Measuring Static Ground Wind Loads on the NASA Space Launch System Mobile Launcher 2

Jesse G. Collins*, Lee J. Mears†, Patrick R. Shea‡, Sarah L. Langston§, Morgan A. Walker¶, and Jeremy T. Pinier||
NASA Langley Research Center, Hampton, VA, 23681

Vertical distribution of static ground wind loads was directly measured on Mobile Launcher ground support hardware to the NASA Space Launch System (SLS) at 1.75% scale in the Langley Research Center 14- by 22-Foot Subsonic Tunnel. Low-speed wind tunnel testing in the liftoff phase of flight was conducted for the SLS Block 1B family of rockets with their associated ground support systems. Improved methods for measuring and estimating static ground wind loads on the launch tower assembly are introduced in detail. A novel, distributed loads measurement technique is introduced and compared against lower-fidelity, previously utilized methods.

Notice to the Reader

The Space Launch System, including its predicted performance and certain other features and characteristics, have been defined by the U.S. Government to be Controlled Unclassified Information (CUI). Information deemed to be CUI requires special protection and may not be disclosed to an international audience. To comply with CUI restrictions, details such as absolute values have been removed from some plots and figures in this paper. It is the opinion of the authors that despite these alterations, there is no loss of meaningful technical content. Analytical methodologies and capabilities are discussed; significant and interesting technical results are still present; and meaningful conclusions are presented.

Nomenclature

Symbols

C_D	=	Wind-axis Drag Coefficient
C_N	=	Body-axis Normal Force Coefficient
C_Y	=	Body-axis Side Force Coefficient
Drag	=	Wind-axis Drag Force
NF	=	Body-axis Normal Force
PM	=	Body-axis Pitching Moment
PMW	=	Wind-axis Pitching Moment
SF	=	Body-axis Side Force
SFW	=	Wind-axis Side Force
YM	=	Body-axis Yawing Moment
YMW	=	Wind-axis Yawing Moment
U	=	Local Freestream-Aligned Velocity
U_∞	=	Freestream Velocity
Ψ_{azm}	=	Wind Approach Azimuth Direction

*Research Engineer, Configuration Aerodynamics Branch, Member AIAA ✉ jesse.g.collins@nasa.gov

†Research Engineer, Configuration Aerodynamics Branch, Member AIAA ✉ lee.j.mears@nasa.gov

‡Research Engineer, Configuration Aerodynamics Branch, Senior Member AIAA ✉ patrick.r.shea@nasa.gov

§Research Engineer, Configuration Aerodynamics Branch, Member AIAA, ✉ sarah.langston@nasa.gov

¶Research Engineer, Configuration Aerodynamics Branch, Member AIAA

||Research Engineer, Configuration Aerodynamics Branch, Associate Fellow AIAA ✉ jeremy.t.pinier@nasa.gov

Acronyms

AGL	=	Above Ground Level
BMC	=	Balance Moment Center
CAA	=	Crew Access Arm
CSFSU	=	Core Stage Forward Skirt Umbilical
CSITU	=	Core Stage Inter Tank Umbilical
DSNE	=	Design Specification of Natural Environments
EUSU	=	Exploration Upper Stage Umbilical
F/T	=	Force and Torque
ICPSU	=	Interim Cryogenic Propulsion Stage Umbilical
KSC	=	Kennedy Space Center
LaRC	=	Langley Research Center
LC-39B	=	Launch Complex 39B
ML	=	Mobile Launcher
MLP	=	Mobile Launch Platform
ML-2	=	Mobile Launcher 2
NASA	=	National Aeronautics and Space Administration
OSMU	=	Orion Service Module Umbilical
SLS	=	Space Launch System
SLSP	=	Space Launch System Program
SRB	=	Solid Rocket Booster
TSM	=	Tail Service Mast
VAB	=	Vehicle Assembly Building
VSS	=	Vehicle Stabilizer System

I. Introduction

The NASA Space Launch System is a multipurpose family of heavy-lift rockets with a modular design to facilitate a wide array of mission profiles to enable deep-space crewed exploration. Supporting those rockets during assembly, transport to and from the Vehicle Assembly Building (VAB), and liftoff are the NASA mobile launchers (ML). The Mobile Launcher 1 is existing support hardware and serves the SLS Block 1 rockets (currently missions Artemis I-III). The Artemis IV+ missions will work toward establishing the Lunar Gateway and a sustained lunar surface presence. These missions will also prepare humanity for the durations and operations necessary for crewed missions to Mars [1–4]. The Mobile Launcher 2 is in the final design phase and will serve the SLS Block 1B rockets, which are larger, starting with Artemis IV. A schematic of the SLS rockets follows (Figure 1), detailing their capabilities and designated mobile launcher. It should be noted that the “SLS Block 1 Cargo” configuration is not currently on the flight manifest for the Artemis missions.

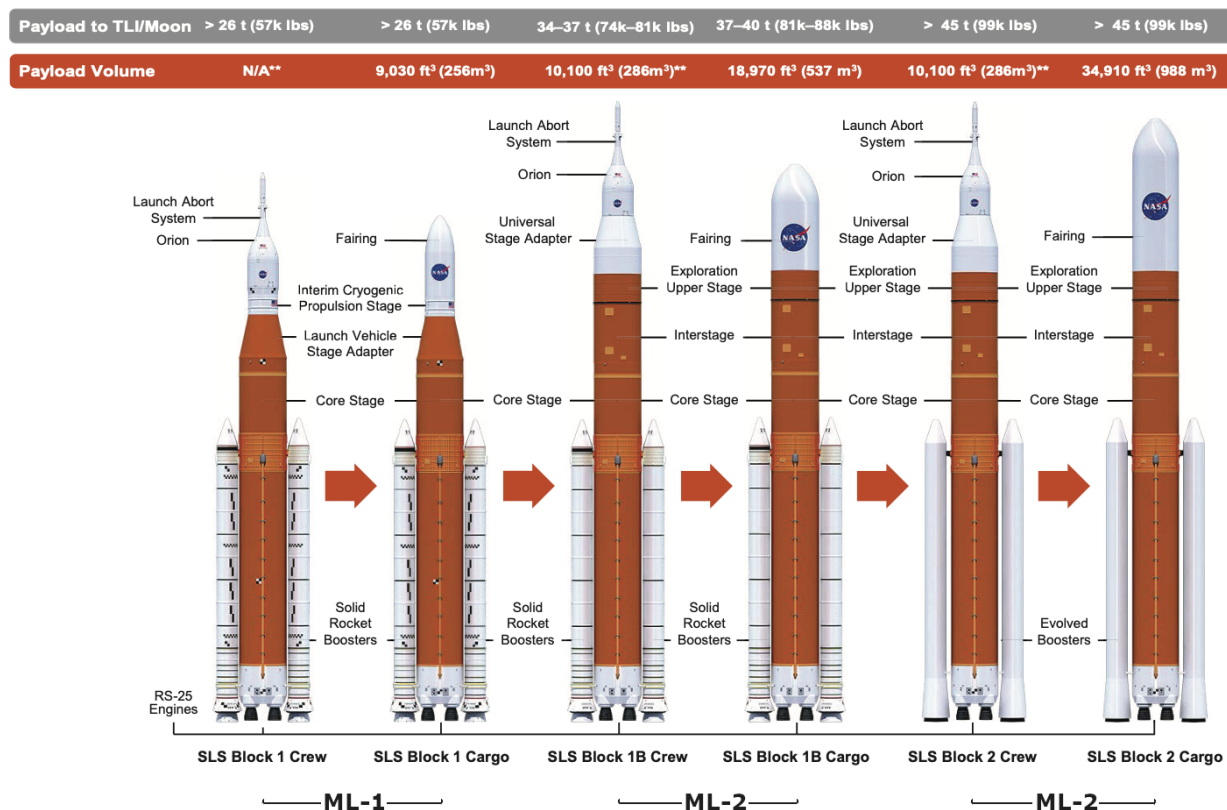


Fig. 1 SLS vehicle designations and capabilities.

The mobile launcher is the “base” that supports the SLS launch vehicle, and it is atop the ML that the vehicle is assembled (stacked), transported, and launched. The ML supports and restrains the upright SLS rocket at two interfaces: the vehicle support posts at the base of each SRB skirt (4 locations per booster), and approximately halfway up the rocket at the vehicle stabilizer system (VSS) that attaches to the vehicle centerbody. The Mobile Launcher is critical infrastructure for the assembly, transport, and launch of NASA Artemis missions. Figure 2 depicts the two mobile launchers side-by-side with their umbilical/support systems highlighted in red. Figure 3 shows the vehicle-to-ML attachment points. In Figures 2 and 3, the ML umbilical systems depicted in red are “space claim” shapes and don’t show intricate detail of these systems. They are simplified geometries only meant to show the general volume of space taken up by these systems. Table 1 identifies these systems and to which Mobile Launcher they are attributed.

Table 1 ML vehicle support systems.

Label	Full Name	Present on:
CAA	Crew Access Arm	Both
OSMU	Orion Service Module Umbilical	Both
EUSU	Exploration Upper Stage Umbilical	ML-2
ICPSU	Interim Cryogenic Propulsion Stage Umbilical	ML-1
CSFSU	Core Stage Forward Skirt Umbilical	Both
VSS	Vehicle Stabilizer System	Both
CSITU	Core Stage Inter-Tank Umbilical	Both
TSM	Tail Service Masts	Both

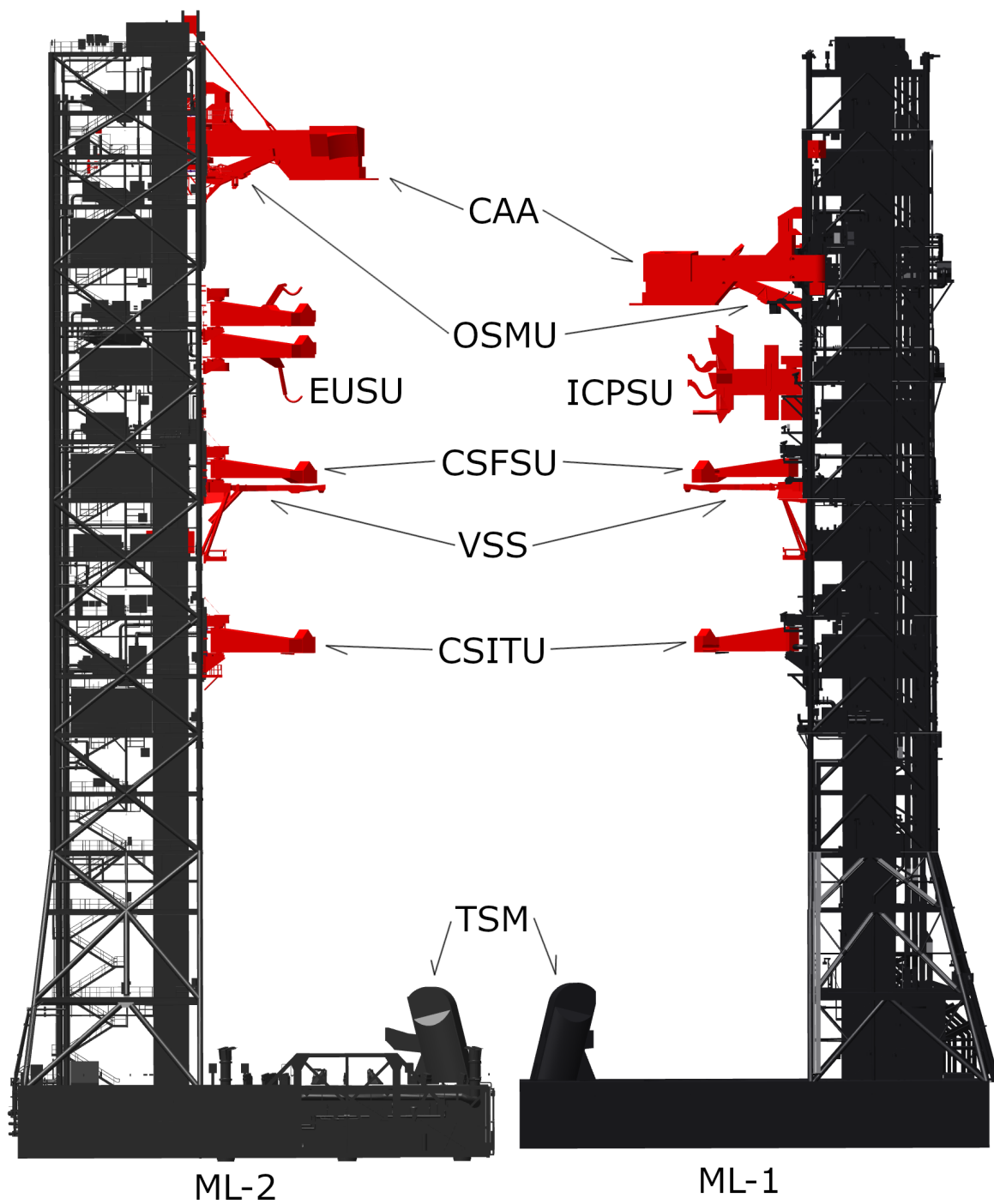
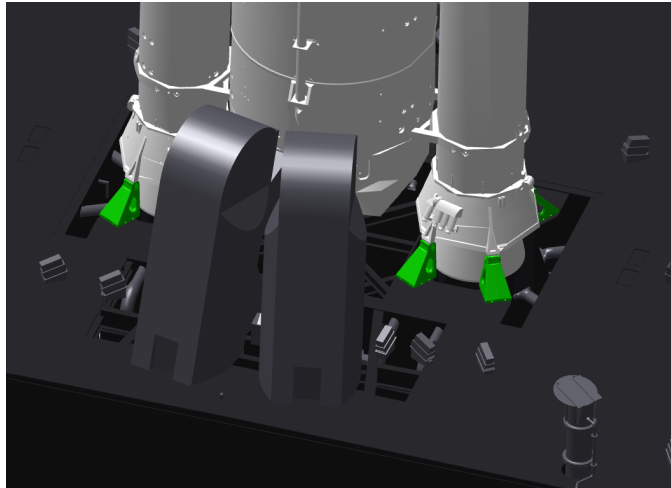
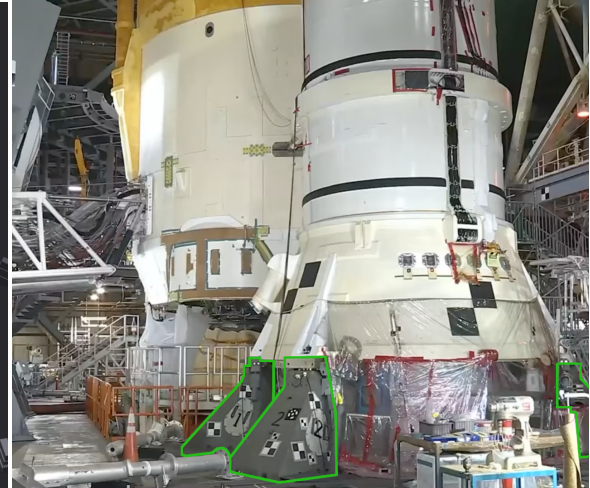


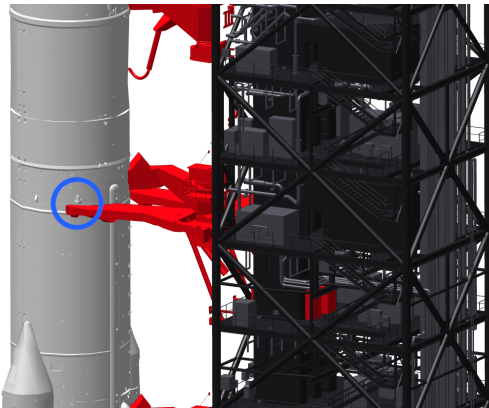
Fig. 2 Mobile Launchers 1 and 2 with service system labels.



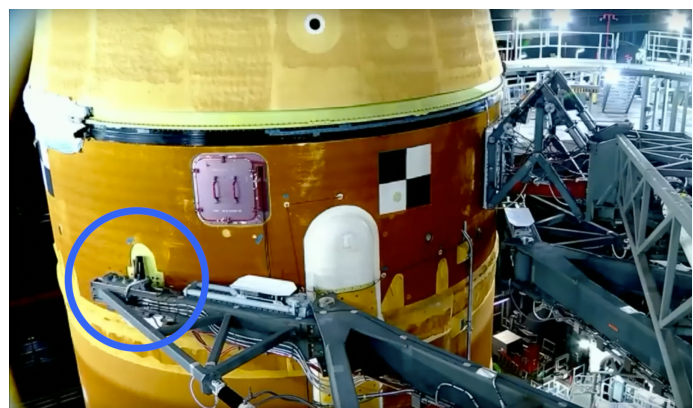
(a) Four support posts at the base of each SRB skirt (shown in green)



(b) Support posts during umbilical release/retract test



(c) Two attachment points to the VSS



(d) VSS attachment points during umbilical release/retract test

Fig. 3 Vehicle to ML attachment points.

At Kennedy Space Center (KSC) during transport between the Vehicle Assembly Building (VAB) to launch complex 39B (LC-39B) and while staged at the launch complex awaiting launch, the SLS vehicle and ML are subject to aerodynamic loads due to ground winds prevalent in the central-Florida eastern coast. Understanding the magnitude and direction of the loads on the SLS and ML (and their effect on vehicle-to-ML interfaces) caused by these ground wind loads is very important to structural design as well as operational wind placard development.

In support of the SLS launch vehicles, the mobile launchers are utilized in a total of four operational phases, each with their own prescribed design limit peak wind velocity profiles, including:

- 1) Vehicle (unfueled) and ML Transport between VAB and LC-39B (Scenario #1)
- 2) Vehicle (unfueled) and ML on-pad stay at LC-39B (Scenario #2)
- 3) Vehicle (fueled) and ML on-pad stay at LC-39B (Scenario #3)
- 4) Vehicle launch at LC-39B (Scenario #4)

These scenarios are described in the public-domain NASA document “SLS-SPEC-159: Cross-Program Design Specification for Natural Environments (DSNE)” [5]. During each of these phases, design peak wind profiles in height are specified by Equation 1 below [6]. The wind profiles specified in “SLS-SPEC-044-07” [6] are reduced from those present in “SLS-SPEC-159” [5]. This is because the original peak profile [5] utilized a 3-sigma enclosure from the surface to 500-ft elevation (AGL), whereas NASA ground support equipment has been historically designed to 2.5-sigma load enclosure.

$$u(z) = u_{18.3} \left(\frac{z}{18.3} \right)^{1.42(u_{18.3})^{\frac{-3}{4}}} \quad (1)$$

Where:

- $u(z)$ = Peak wind velocity as a function of height above ground level (AGL), [m/s]
 $u_{18.3}$ = Tabulated measured velocity at LC-39B at height 18.3 meters AGL, [m/s]
 z = Height AGL, [m]

Tabulated measured velocities at height of 18.3 meters are shown in Table 2.

Table 2 Design peak wind-speed profile values.

		Peak Wind-Speed Profile Velocity			
Height		Scenario 1 Transport To/From Pad	Scenario 2 On-Pad (unfueled)	Scenario 3 On-Pad (fueled)	Scenario 4 Vehicle Launch
m	ft	m/s	m/s	m/s	m/s
18.3	60	30.8	38.3	24.2	17.7

Wind directions as they approach the LC-39B at KSC are defined as shown in Figure 4 [7]. The peak velocities as a function of height are shown in Figure 5.

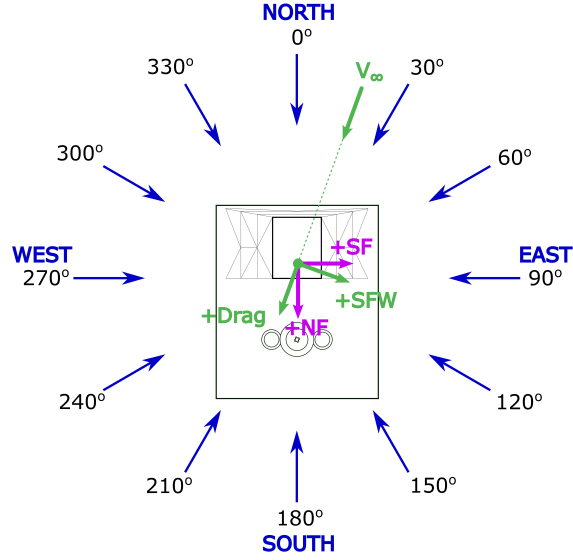
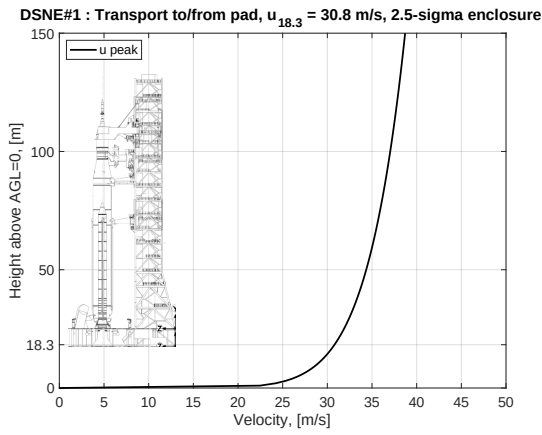
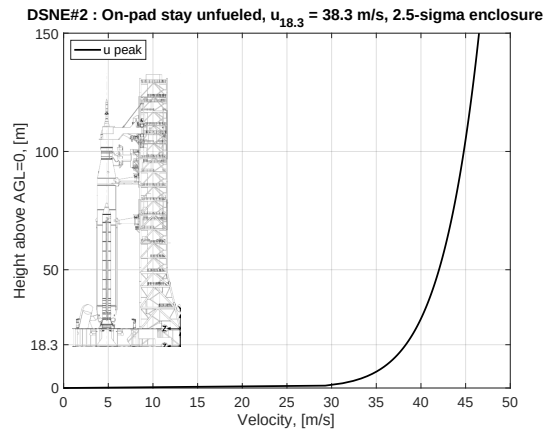


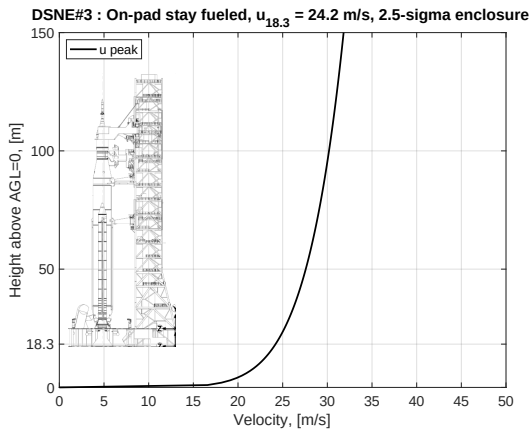
Fig. 4 Incoming wind azimuth (Ψ_{azm}) definition shown in blue. Body axis coordinate system shown in purple. Wind axis coordinate system shown in green.



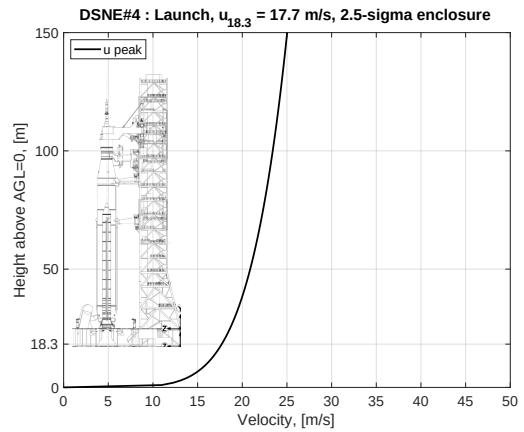
(a) DSNE Wind Profile Scenario 1



(b) DSNE Wind Profile Scenario 2



(c) DSNE Wind Profile Scenario 3



(d) DSNE Wind Profile Scenario 4

Fig. 5 DSNE wind profiles plotted vs. height AGL.

II. Mobile Launcher 2 Test Article Description

A. Background

An instrumented 1.75% scale ML-2 test article was utilized in a liftoff and transition flight phases wind tunnel test of the NASA SLS Block 1B Cargo and Crew rockets in the Summer of 2021. This paper's discussion will focus on the liftoff phase segment of data collection for the ML during that test. This wind tunnel test was conducted at the NASA Langley Research Center (LaRC) 14- by 22-foot Subsonic Tunnel, from dates April 26, 2021 to June 30, 2021. The entire ML was modeled, including the bottom base portion of the tower, referred to as the Mobile Launch Platform (MLP).

B. ML-2 Construction

The ML-2 was assembled from traditional machined parts of aluminum, Carbon-infused Nylon 3D printed parts, and eight six-component force and moment transducers manufactured by ATI Industrial Automation. The construction of the ML-2 test article for static ground wind loads measurements has the following main features:

- Aluminum construction of the MLP with a set of four force/moment transducers underneath the entire ML
 - These transducers provide a measurement of the global loads exerted on the entire ML
- Stainless steel vertically-oriented bar cantilevered to the top surface of the MLP (acts as a support beam for the rest of the tower)
- Eight force and moment transducers mounted on the bar, distributed along its length
- Nine 3D-printed sections of the tower (internally referred to as “tiers”), eight of which mount to the metric end of the transducers along the length of the bar
 - These tier sections mounted to individual transducers allow for the direct measurement of the distribution of load along the ML tower
- Representative, deployable umbilical systems

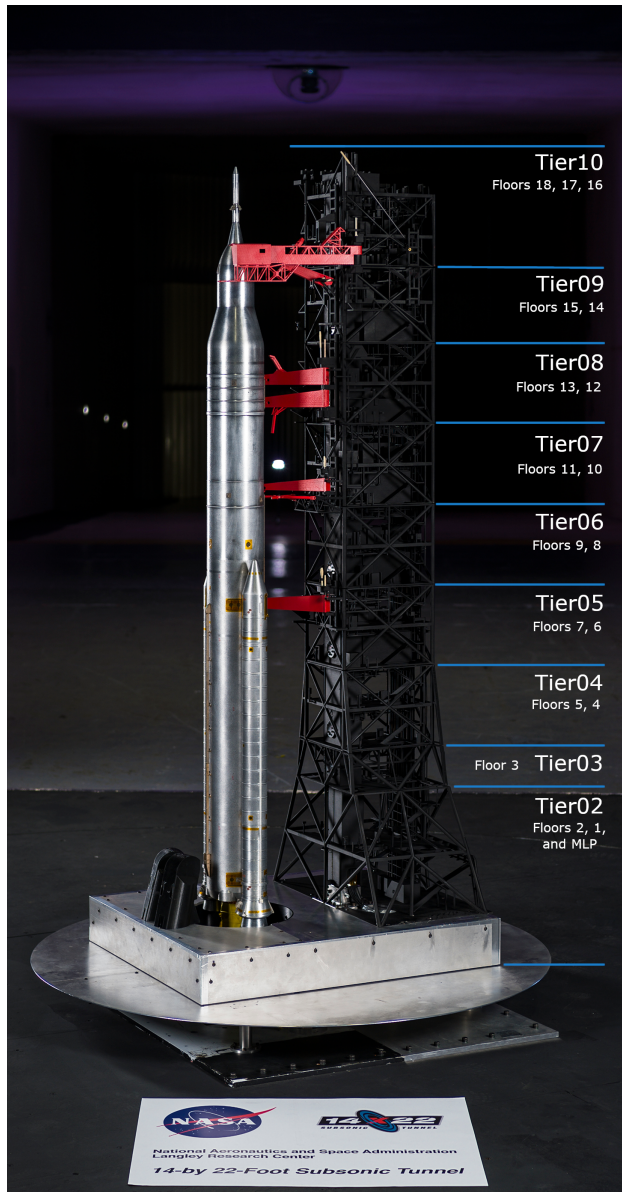
Figure 6 shows two views of the ML-2 test article. In the first, everything above the circular flow-splitter disk is measured by the tower global balance (excepting the vehicle, which has its own balance). In the second view, the individual tiers can be seen along with the internal support beam with the force and moment measurement transducers embedded inside.

Figure 7 shows two views of the metric gaps in this system. In all aspects and dimensions of the design for this assembly, metric gaps were included to ensure there was no fouling and thus corruption of aerodynamic measurements. The 3D printed model shown in Figures 6 and 7 contain an exceptional amount of detail that cannot be reasonably achieved with traditional machining methods. Construction resolution limitations necessitated that many features less than four inches (full-scale) were removed from the model. This limitation translates to model-scale features less than 7 build-layers thick per the 3D printer's build resolution. Of the individually metric tiers (those that mount to the support beam through a transducer connection), six of them are sized such that they represent two floors of the tower structure. One of them represents three floors, and another represents one floor. Part of the decision making process for this arrangement was driven by restrictions based on the 3D printer internal build chamber size limits. The entire ML tower is 18 floors tall when counted from the top surface of the MLP (this surface is called ML-Deck 0). Treating the MLP as the “zeroth” floor (of 19 total floor sections) is useful for data analysis later on. The various umbilical and support systems (shown in red) in Figure 6 were manually adjustable to deployed or retracted positions.

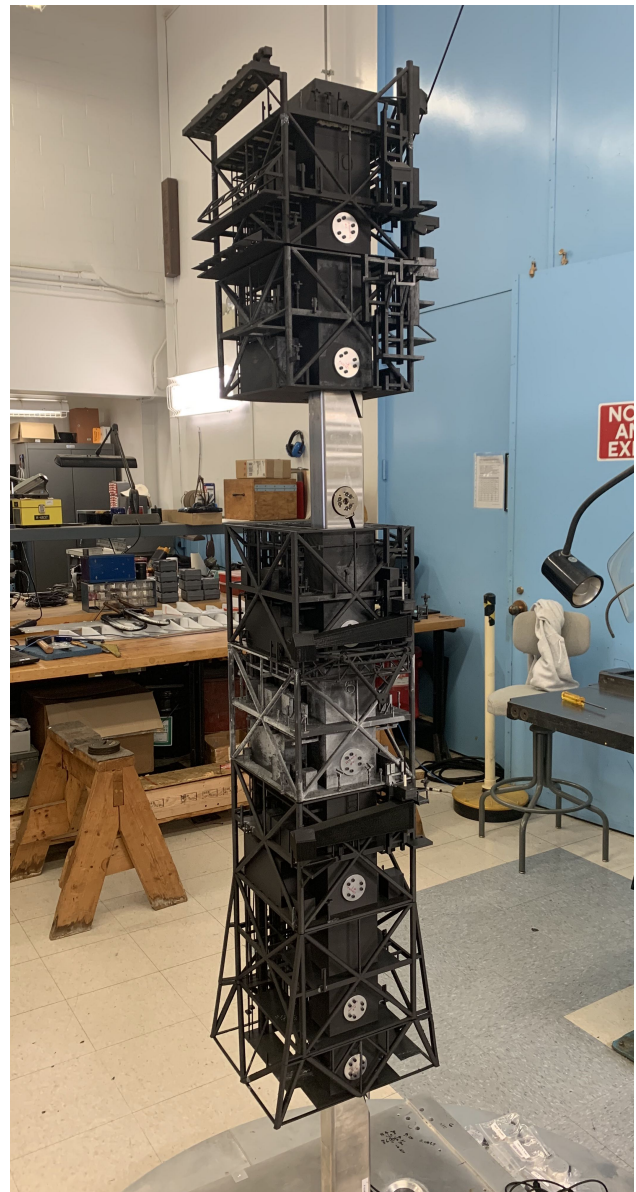
C. Instrumentation

A total of twelve force and moment transducers were utilized, sourced from two product lines at ATI Industrial Automation, Inc. Four devices were F/T Sensor: Delta units with the US-150-600 standard calibration. The other eight devices were F/T Sensor: Mini45 units with the US-60-80 standard calibration. The four Delta units were arranged at the corners of an internal sandwich assembly with bottom and top plates, shown in Figures 8 and 9.

These four ATI Delta measurement devices were utilized to make a single six-component balance measurement with a virtual balance moment center (BMC) located near the midpoint of the support beam. This location assignment is dependent on how the system was calibrated in situ (techniques developed by Toro & Parker [8], and Commo et al. [9]). This single six-component measurement is referred to as the global balance and measures loads on the entire ML. The tower as built up and shown in Figures 6 and 7 with 3D-printed sections, utilizes eight ATI Mini45 measurement devices. This is shown in Figure 10. Each Mini45 device was utilized to only measure the aerodynamic loads on one tier. The factory-provided calibrations were sufficient for use and no in situ calibration was necessary.

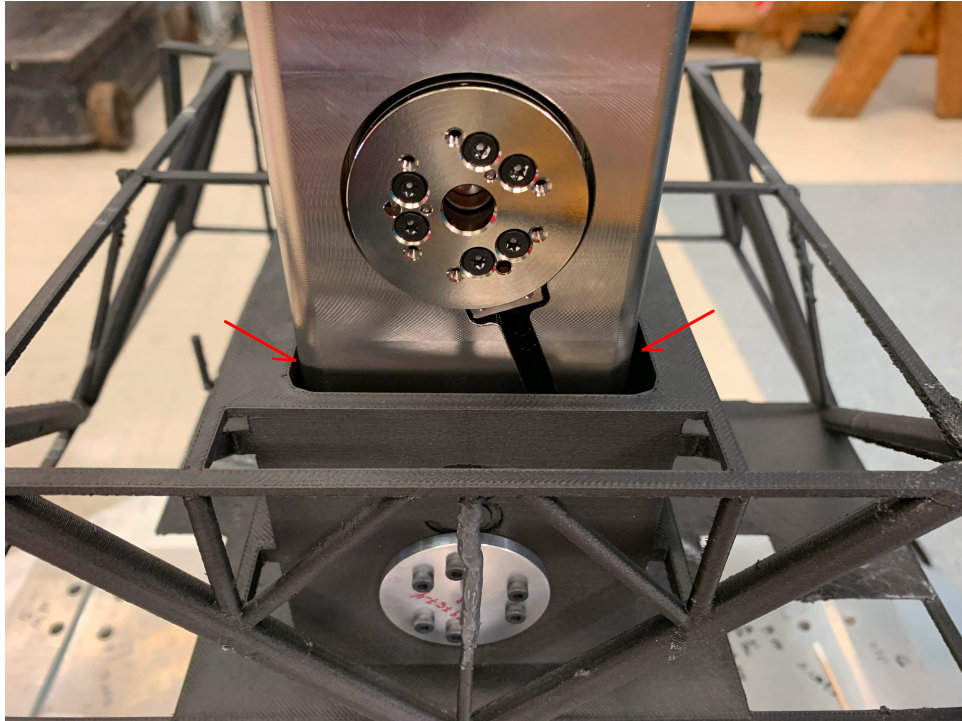


(a) Liftoff testing configuration in the test section



(b) Preparation area build-up

Fig. 6 The ML-2 test article.



(a) Metric mounting surface of transducer as well as shaft-to-tier metric gaps



(b) Tier-to-tier metric gaps

Fig. 7 Metric gaps in the individual tier measurement system.

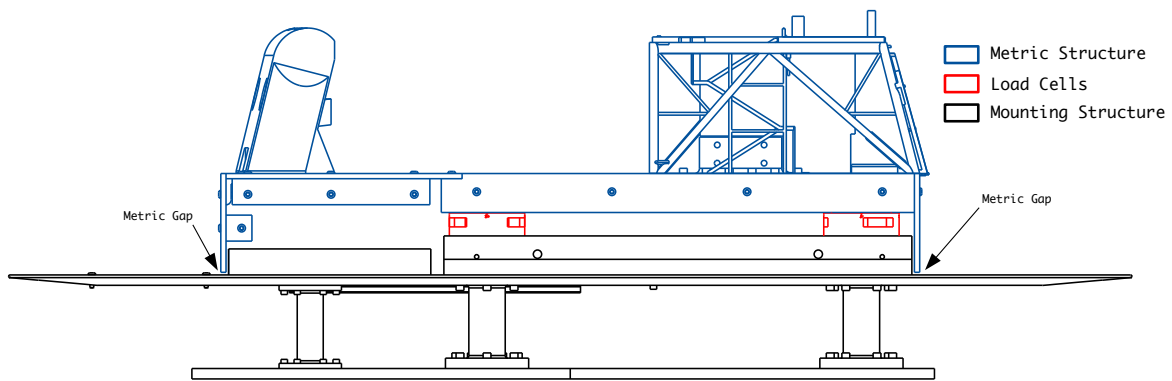


Fig. 8 ATI Delta load cells forming base global measurement, side view.

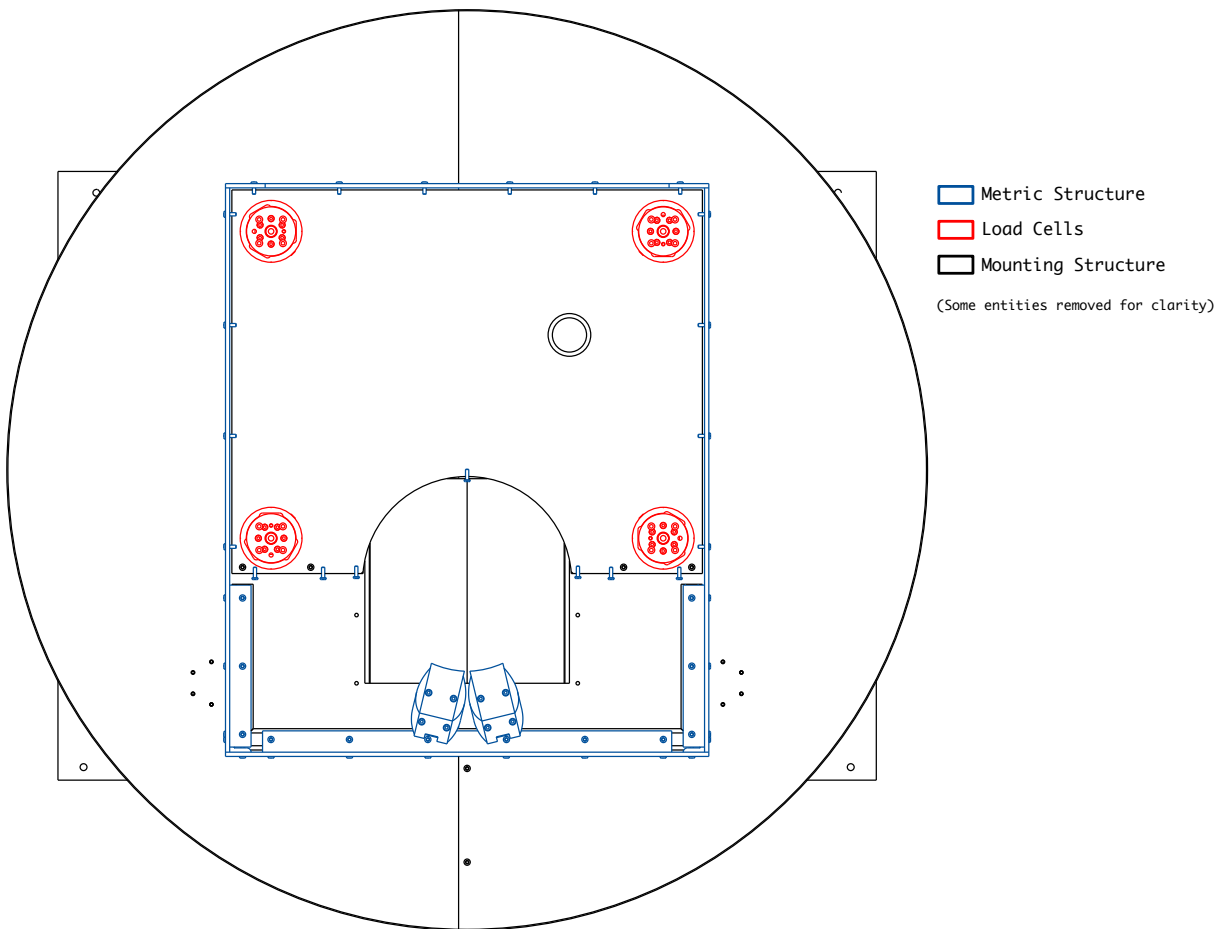


Fig. 9 ATI Delta load cells forming base global measurement, top view.

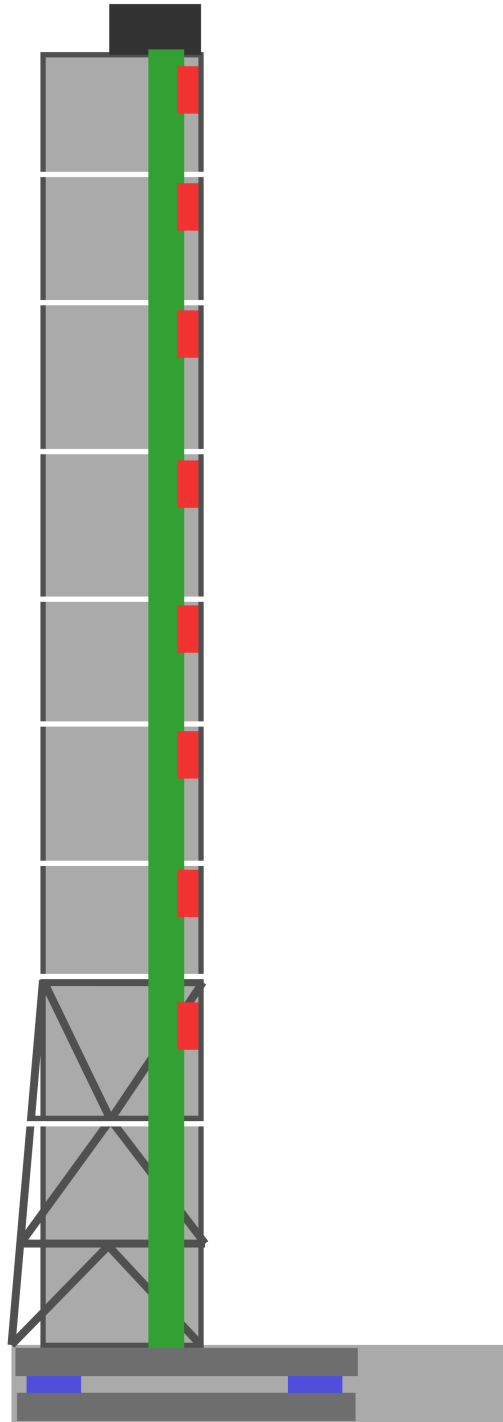


Fig. 10 ATI Mini45 load cells (red) forming distributed support beam measurements, side view. ATI Delta units depicted in blue. Support beam depicted in green.

Because of this arrangement of measurement devices it can be seen in Figure 10 that the first two floors of the tower itself (above ML Deck 0) are not individually metric like the other tiers. Because of this, the resultant loads on this lowest Tier02 (which is inclusive of the platform and the first two floors above ML Deck 0, per Figure 6) can be calculated as such:

$$NF_2 = NF_{gb} - \sum_{n=3}^{10} NF_n \quad (2)$$

$$SF_2 = SF_{gb} - \sum_{n=3}^{10} SF_n \quad (3)$$

$$PM_2 = PM_{gb} - \sum_{n=3}^{10} PM_n \quad (4)$$

$$YM_2 = YM_{gb} - \sum_{n=3}^{10} YM_n \quad (5)$$

Where:

- NF = Body-axis Normal Force
- SF = Body-axis Side Force
- PM = Body-axis Pitching Moment
- YM = Body-axis Yawing Moment
- X_2 = Calculated Force or Moment component of Tier 02
- X_{gb} = Measured Force or Moment component of the global balance
- X_n = Measured Force or Moment component of individually metric Tier **n**

All tier measurements are translated to the global measurement balance moment center.

III. Results and Discussion

An unexpected result becomes apparent when comparing the individually metric tier data between cases with the vehicle present and not-present. Figure 11 shows drag coefficient data for each individually metric tier on the ordinate with the zero-crossing levels indicated by the tier data series label. These results, as a function of incoming wind azimuth, show that several of the tiers measure negative wind-axis drag for certain wind angles when the vehicle is present. This correlates strongly with the lower tiers of the tower, particularly the tiers below which the SRBs are also present on the vehicle. It is expected that the additional width of the vehicle plus the SRBs is creating a large wake region with recirculating flow that is impinging on the leeward side of the mobile launcher for winds from the south. Figure 6 shows that tiers 05, 04, and 03 are in the wake of the wider region of the vehicle, where this activity is seen in Figure 11. Tier 06 also has a single datum in the wind azimuth space that becomes very slightly negative, though effectively is zero. This activity is only present on southerly winds (azimuth = $\sim 180^\circ$) when the flow direction is such that the ML is in the direct wake of the vehicle (Figure 4).

This poses an important improvement upon the previous model used to estimate full-scale loads on the ML. The previous model was informed by wind tunnel data that only had the global balance. This meant that the method of how to distribute the load along the height of the ML had to be informed by an area analysis. Formerly, the global measurement would result in global wind-axis coefficients, which could be multiplied by the area of the individual tiers to result in an estimate of the full-scale acting loads on that section of the ML. This method required the assumption that globally acting force/moment coefficients can be applied locally. A comparison of this old method of full-scale load calculation to the newer method informed by more distributed measurements is shown in Figure 12.

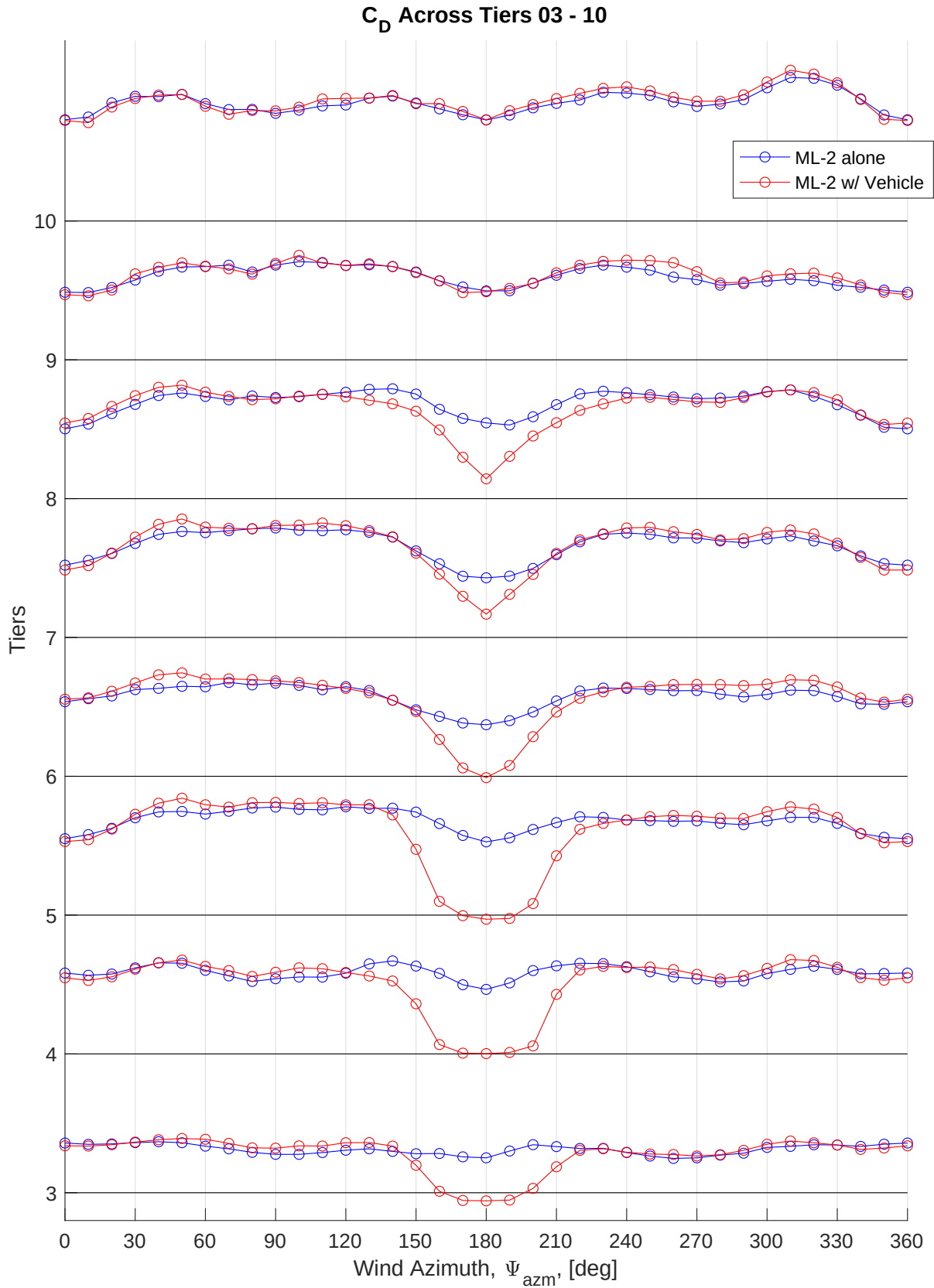


Fig. 11 Tier Drag coefficients. $C_D = 0$ lines are indicated by the label for each tier.

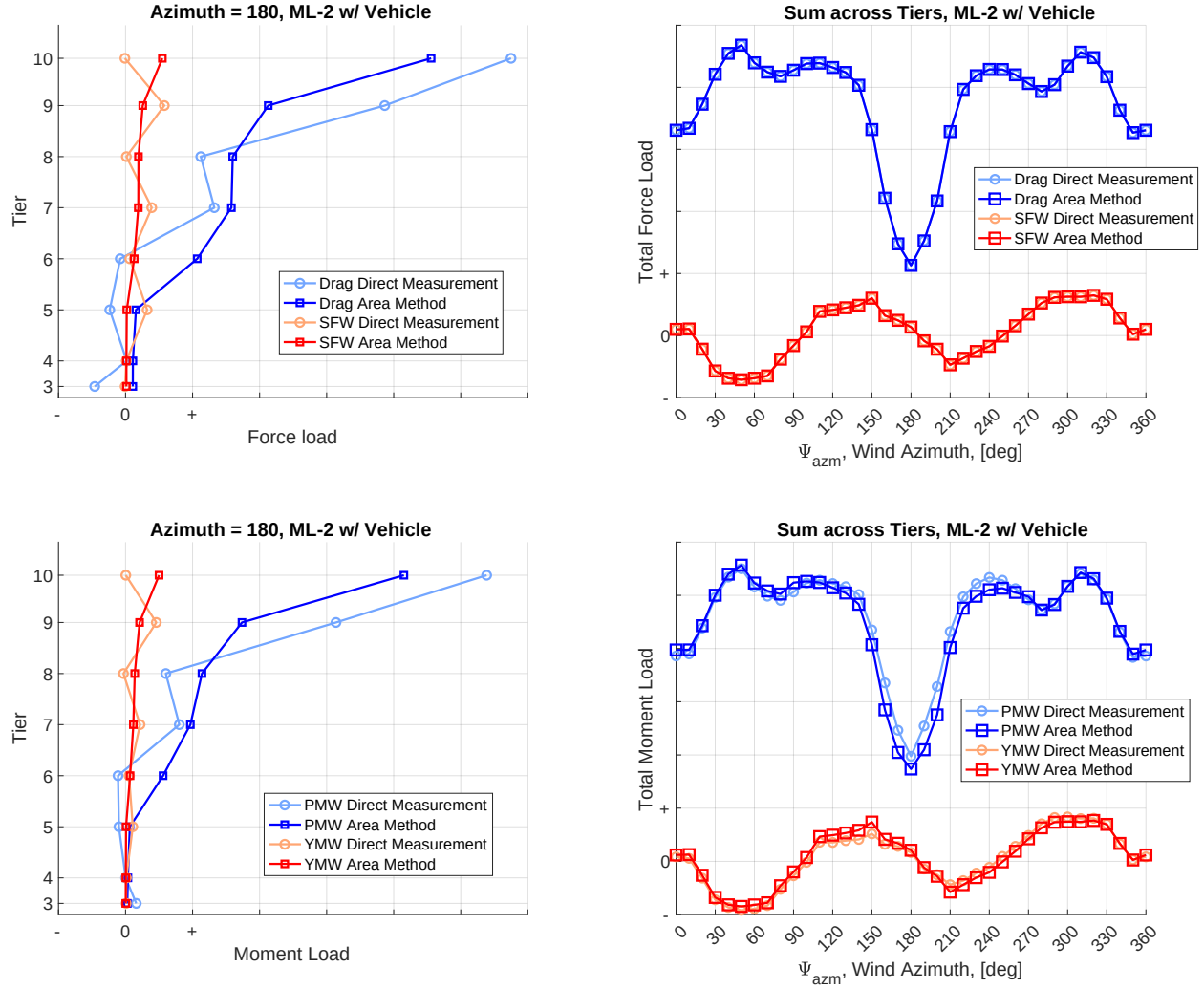


Fig. 12 Load distribution method comparison.

For the full scale force comparisons (Drag and Side-Force-Wind(SFW)), it is by definition that the sum across tiers is equal between the methods. However, Figure 12 shows that the distribution of forces is different and the direct measurement method (circle markers) yields the results seen earlier in Figure 11: some of the tiers measure negative drag, which is not possible using the area-based distribution of load method.

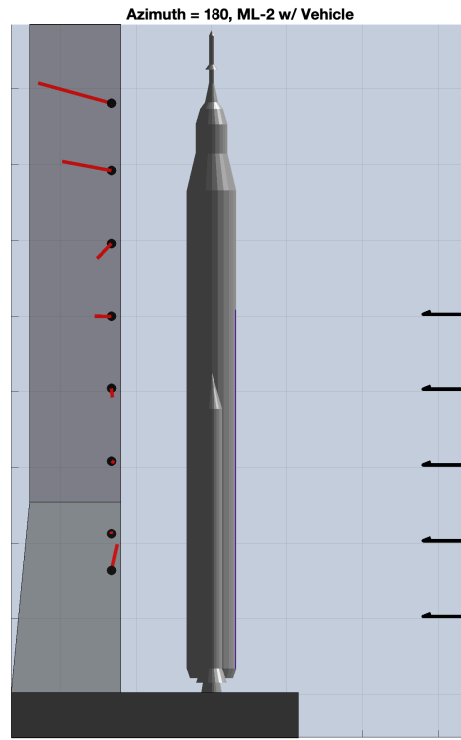
Similarly, the area-based distribution method causes the moments, particularly wind-axis pitching moment (PMW), distributions to be improperly represented. Also notable is the total sum of moments: because of the computation to sum up moment contributions across the height of the ML, the total sum won't necessarily be the same. It can be seen that the area-based distribution method causes reduced estimates of total acting PMW across a wide azimuth range, but especially where vehicle-to-ML flow blockage occurs.

Another interesting result from the distributed loads data collection was the identification of appreciable amounts of axial load (upward directed force) acting on some of the individual ML tiers.

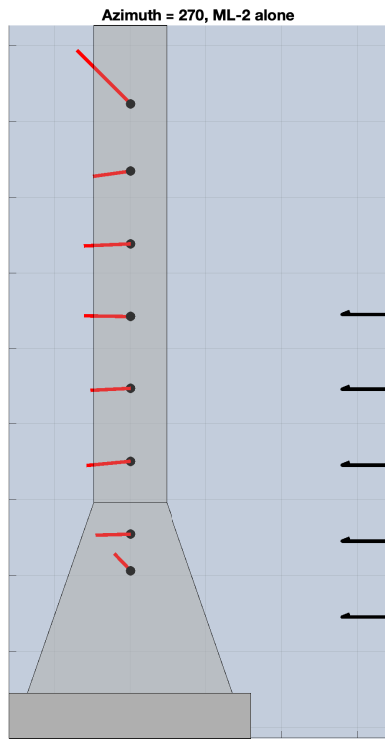
In Figures 13(a)-13(d), the black dots represent the individual tier measurement BMCs, with the red vector anchored to them representing the relative magnitude and direction of the full force vector. The higher tiers consistently exhibit axial force. This is likely explained by the curvature of flow streamlines around and over the top of the ML itself. Flow curvature causes acceleration directly above the ML, which could be causing the observed suction force. Less expected is the consistent axial force on the lowest individually metric Tier03. This might be explained by the fact that Tier03 is in the region of the ML where the cross-section begins tapering outward with decreasing elevation. Tier04 is also near this geometry change, but by Tier03 the cross-section growth is in full effect.



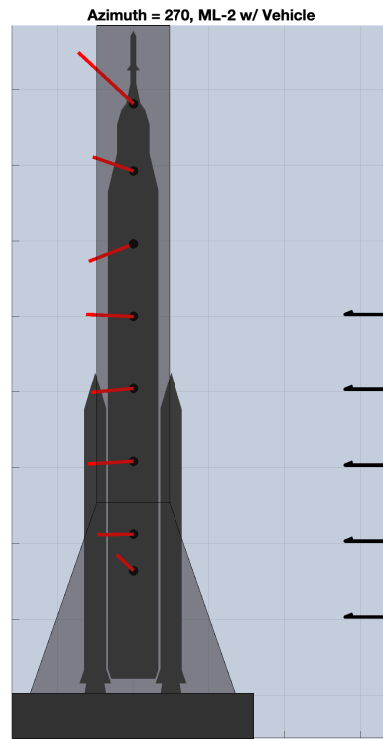
(a) No vehicle present, $\Psi_{azm} = 180^\circ$, viewed from west



(b) Vehicle present, $\Psi_{azm} = 180^\circ$, viewed from west



(c) No vehicle present, $\Psi_{azm} = 270^\circ$, viewed from north



(d) Vehicle present, $\Psi_{azm} = 270^\circ$, viewed from north

Fig. 13 ML-2 tier axial Load comparison.

In previous testing that only utilized ML global balance measurements, measured axial loads were largely ignored. The ML base test article requires a large cylindrical cut-out in order for the rocket vertical sting support to be able to pass-through such that the SLS can elevate relative to the ML (simulating liftoff). Also shown in Figure 6 is the circular splitter plate disk, which was designed with stand-off posts to lift the bottom of the ML test article out of the wind tunnel boundary layer (~5 inches in height as measured by the flow survey rake [10]). Thus, the ML base environment is known to be different than the full-scale ML.

During testing, significant flow occurred through the MLP vehicle sting pass-through. This was inferred by observing the deflection of bristles on an underside mounted brush seal. Thus, axial force measurements were not considered accurate representations of full-scale wind loads. As a result, in the estimation of full-scale loads for the ML, axial loads are not normally considered. There is no technical concern with any of the distributed axial loads observed with respect to the ML-2 or the vehicle; the axial loads are dwarfed by the entire structure's dead weight.

IV. Concluding Remarks

Static distributed ground wind loads for the SLS Mobile Launcher 2 were measured and presented from recent wind tunnel experimentation at the NASA LaRC 14- by 22-foot Subsonic Tunnel. Due to greater fidelity of test measurements, the vertical distribution of loads on the ML-2 could be directly measured instead of estimated using the distribution of frontal projected area. This test technique improvement resulted in a higher quality, more accurate database product than what was previously issued. The former area-based calculation methods were less accurate in estimating the distribution of loads as well as in calculating the total sum of moment loads. Both of these metrics are very important with respect to vehicle-to-ML interface loads as well as operational wind placards. This distribution information allows the database users to more accurately estimate loads in specific regions of the launch assembly, such as interface loads between the ML and vehicle through the VSS. This information can avoid costly redesigns of critical structural systems while still ensuring safety margins are met. The more spatially-resolved measurement technique illuminated the counterintuitive result that some elevations of the ML-2 experience negative drag due to large wake regions shed by the vehicle and its flanking SRBs. It was also discovered that an upward-force acts on several sections of the ML-2, although these are very small fractions of the ML and vehicle dead-weight and thus not utilized in database construction. The spatially resolved measurement technique will continue to be a unique and valuable tool for SLS Program static ground wind loads measurements and database construction for future tests in the Block 2 vehicle configurations.

References

- [1] NASA, “Artemis Plan: NASA’s Lunar Exploration Program Overview,” September 2020.
- [2] Blevins, J. A., Campbell Jr., J. R., Bennett, D. W., Rausch, R. D., Gomez, R. J., and Kirs, C. C., “An Overview of the Characterization of the Space Launch System Aerodynamic Environments,” AIAA Paper 2014-1253, AIAA Aerospace Sciences Meeting, National Harbor, MD, 2014.
- [3] Pinier, J. T., Herron, A. J., and Gomez, R. J., “Advances in the Characterization of NASA’s Space Launch System Aerodynamic Environments,” AIAA Paper 2019-3397, AIAA AVIATION Forum, Dallas, TX, 2019.
- [4] Donahue, B., “Space Launch System: Development Status,” AIAA Paper 2016-5415, AIAA SPACE Forum, Long Beach, CA, 2016.
- [5] NASA, “SLS-SPEC-159 : Cross-Program Design Specification for Natural Environments (DSNE),” Revision I, October 2021.
- [6] NASA, “SLS-SPEC-044-07 : Cross-Program Vehicle Design Environments, Volume 7: Natural Environments,” Revision F, September 2020.
- [7] NASA, “SLS-SPEC-048 : Cross-Program Integrated Coordinate Systems,” Revision F.1, February 2018.
- [8] Toro, K. G., and Parker, P. A., “Unique Booster Force Measurement on NASA’s Space Launch System (SLS),” Oral Presentation, Presented at AIAA SciTech Forum 2018 in Kissimmee, FL, 2018.
- [9] Commo, S. A., Toro, K. G., Parker, P. A., and Chan, D. T., “Development of an Improved Force Measurement Capability for the Liftoff and Transition Wind-Tunnel Test of NASA’s Space Launch System,” Oral Presentation, Presented at the 11th International Symposium on Strain-Gage Balances in Cologne, Germany, May 2018.
- [10] Gentry Jr., G. L., Quinto, P. F., Gatlin, G. M., and Applin, Z. T., “The Langley 14- by 22-Foot Subsonic Tunnel: Description, Flow Characteristics, and Guide for Users,” Tech. Rep. 3008, NASA, Langley Research Center, Hampton, Virginia, 1990.