Analysis of Transonic Unsteady Aerodynamic Environments using Unsteady Pressure Sensitive Paint for the Space Launch System Block 1 Cargo Launch Vehicle

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Predicting launch vehicle unsteady aerodynamic loads due to buffet remains a significant challenge. Current practices for modeling buffet environments involve the development of buffet forcing functions using discrete unsteady pressure measurements acquired during wind-tunnel tests. These practices often result in significant uncertainty in buffet environments for coupled loads analyses due to the complex spatio-temporal nature of the unsteady pressure field and the challenge of its estimation using discrete sensors. Unsteady pressure sensitive paint, on the other hand, can provide unsteady pressure data at a comparatively high spatial density and may overcome the challenge of unsteady pressure field estimation with discrete sensors and lead to improvements in the development of buffet forcing functions. In this paper, comparisons of the fluctuating pressure field are made for the Space Launch System Block 1 cargo launch vehicle measured using unsteady pressure sensitive paint and pressure transducers.

Note 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 Sensitive But Unclassified (SBU). Information deemed to be SBU requires special protection and may not be disclosed to an international audience. To comply with SBU 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.

Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ARC</td>
<td>Ames Research Center</td>
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<tr>
<td>ATAT</td>
<td>Ascent Transient Aerodynamics Test</td>
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<tr>
<td>BFF</td>
<td>buffet forcing function</td>
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<tr>
<td>ICPS</td>
<td>interim cryogenic propulsion stage</td>
</tr>
<tr>
<td>LSRB</td>
<td>left solid rocket booster</td>
</tr>
<tr>
<td>LVSA</td>
<td>launch vehicle stage adapter</td>
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<tr>
<td>OML</td>
<td>outer mold line</td>
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<tr>
<td>PSD</td>
<td>power spectral density</td>
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<tr>
<td>PT</td>
<td>pressure transducer</td>
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<tr>
<td>RBM</td>
<td>rigid buffet model</td>
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<tr>
<td>RSRB</td>
<td>right solid rocket booster</td>
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<td>SLS</td>
<td>Space Launch System</td>
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<tr>
<td>SRB</td>
<td>solid rocket booster</td>
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<tr>
<td>uPSP</td>
<td>unsteady pressure sensitive paint</td>
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<tr>
<td>UPWT</td>
<td>Unitary Plan Wind Tunnel</td>
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Nomenclature

\[ \Delta C_p = \text{fluctuating (mean-removed) pressure coefficient} \]
\[ \Delta C_{p,\text{rms}} = \text{root-mean-square of the fluctuating (mean-removed) pressure coefficient} \]
\[ D_{\text{ref}} = \text{payload fairing reference diameter} \]
\[ M_{\infty} = \text{freestream Mach number} \]
\[ Rn = \text{Reynolds number} \]
\[ \text{rms} = \text{root-mean-square} \]
\[ U_{\infty} = \text{freestream velocity} \]
\[ x, y, z = \text{longitudinal, lateral, and vertical body axes} \]
\[ \alpha = \text{angle of attack} \]
\[ \beta = \text{sideslip angle} \]
\[ \theta = \text{body coordinate system clocking angle} \]
\[ \xi_s = \text{nondimensional longitudinal position aft of the payload fairing shoulder} \]
\[ \sigma = \text{standard deviation} \]

I. Introduction

Despite decades of flight experience, predicting and estimating launch vehicle unsteady aerodynamic loads during ascent remains a significant challenge. Predicting buffet environments, for example, where a complex spatio-temporal pressure field may excite low-frequency launch vehicle structural modes, is important for coupled loads analyses but remains a source of large uncertainty. Typically, the largest ascent buffet loads are experienced during acceleration through transonic flight conditions, when various complexities increase the challenge of developing general models for the prediction of buffet:

1) the nature of unsteady transonic flow, to include separated flow, shock-boundary layer interactions, and flow past protuberances;
2) the expense of unsteady aerodynamic testing;
3) the challenge of simulating unsteady flight environments (experimentally or computationally);
4) the repeatability of experimental data (realization-to-realization differences associated with a stochastic process).

Further complications may arise from aeroelastic coupling, the impact of accelerating flight on unsteady fluctuating pressures, and uncertainty in the estimation of buffet-specific environments from flight data for tunnel-to-flight comparisons.

One method to estimate buffet environments for launch vehicles is through extensive wind-tunnel tests of rigid buffet models (RBMs) instrumented with a large number of unsteady pressure transducers (PTs). Time histories from these PTs are then used to estimate buffet forcing functions (BFFs) – orthogonal load time histories at a series of longitudinal vehicle stations that are used to approximate buffet forces for simulation of the vehicle structural responses during coupled loads analyses. Using a discrete number of PTs in this BFF development process often leads to significant uncertainty in approximating the buffet forces that are associated with the unsteady pressure field. This uncertainty often leads to increased structural margins in the vehicle design and increased development cycle time in cases where initial discrete PT tests did not fully capture or significantly overpredicted peak buffet environments due to the placement of a limited number of sensors. In spite of these shortcomings, BFFs developed using this methodology have been used extensively in several launch vehicle programs [1-3].

Important questions related to the development of BFFs from wind-tunnel tests using PTs still remain:

1) **Peak environments**: Given the relatively sparse spatial distribution, were maximum unsteady environments measured at specific test conditions?
2) **Local environments**: Related to the question above, were relatively-local environments adequately measured and characterized?
3) **Field estimation from discrete points**: At least for the dominant flow features, were the relative scales of structures accounted for properly?
4) **Uncertainty**: What is the uncertainty in modeling buffet environments using BFFs?
5) **Simulation accuracy**: How well do wind-tunnel tests approximate the unsteady environments experienced during ascent and are the developed BFFs adequately approximating the buffet environments for structural response simulations?
In addition to continued wind-tunnel tests of launch vehicle RBMs to estimate configuration-dependent buffet loads, several research programs have been conducted or are underway to improve current practices and address some of these questions. Using data from the Ares I-X wind-tunnel and flight tests, efforts have been made to improve understanding of the relationship between wind-tunnel and flight environments [2]. Another line of inquiry seeks improved methods to estimate frequency-dependent coherence lengths rather than an average coherence length for integrating pressures in the BFF development process [4][5]. Recent experimental advances in the use of unsteady pressure sensitive paint (uPSP) may also provide an improved data source for developing BFFs as the spatial resolution of the surface pressure field is vastly improved over PTs. Early work comparing uPSP- and PT-derived BFFs has shown this may be promising [4][6][8].

In the remainder of this paper, the measured unsteady pressure field using uPSP will be compared to that measured using discrete PTs. After a brief background on the wind-tunnel test during which the uPSP, PT, and shadowgraph data were acquired and a description of the methodology used for comparing the data, results are presented and discussed for several studies. These studies compare data for several $M_{\infty}$, angles of attack, and uPSP surface grid resolutions to which the uPSP data are projected. Following the description of results, several concluding observations are made to summarize the comparison between uPSP- and PT-measured unsteady environments during this wind-tunnel test.

II. Background

A. Ascent Transient Aerodynamics Test

The most recent Space Launch System (SLS) unsteady aerodynamics test is the Ascent Transient Aerodynamics Test (ATAT), conducted at the NASA Ames Research Center (ARC) Unitary Plan Wind Tunnel (UPWT) in 2019 [9]. During this test, 2.5-percent scale models of two cargo vehicle configurations were tested: (1) Block 1 cargo and (2) Block 1B cargo launch vehicles. Figure 1 illustrates the Block 1 cargo launch vehicle analyzed in this paper with the three bodies (core, left solid rocket booster (LSRB), and right solid rocket booster (RSRB)), interim cryogenic propulsion stage (ICPS), and launch vehicle stage adapter (LVSA) annotated. Test instrumentation included high-speed shadowgraph, unsteady PTs, and uPSP. A summary of test parameters for the ATAT is shown in Table I.

![Wind-tunnel model with annotated vehicle bodies.](image)

![Model surface painted with uPSP.](image)

Fig. 1   SLS Block 1 cargo 2.5-percent scale RBM tested during the ARC UPWT ATAT.
Table 1  Summary of wind-tunnel test parameters for the ATAT.

<table>
<thead>
<tr>
<th>Test section</th>
<th>$M_{\infty}$</th>
<th>$\alpha$ (degrees)</th>
<th>$\beta$ (degrees)</th>
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</thead>
<tbody>
<tr>
<td>9- by 7-ft (Test 376)</td>
<td>1.55 to 2.50</td>
<td>-6 to +6</td>
<td>-6 to +6</td>
</tr>
<tr>
<td>11- by 11-ft (Test 377)</td>
<td>0.70 to 1.40</td>
<td>-6 to +6</td>
<td>-6 to +6</td>
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</table>

In this paper, data analyzed were acquired in the 11- by 11-ft transonic test section of the UPWT. Unsteady PT data for 330 transducers were acquired for each point at 10,000 Hz for 155,000 samples (approximately 15.5 sec). Additionally, uPSP data using 4 cameras were simultaneously acquired at 10,000 frames per second for one of two durations: (1) 55,042 frames (approximately 5.5 sec) or (2) 96,331 frames (approximately 9.6 sec). Although the record lengths differ for the PT and uPSP data, both acquisition systems were triggered by the same start signal. The approximate $x$-plane where the four cameras were located on the vehicle outer mold line (OML) is shown in Fig. 2a and a representation of the camera mounting configuration in the $y$-$z$ plane (at a constant $x$ station), including the approximate model azimuthal range visible in each camera, is presented in Fig. 2b. In this study, uPSP data mapped to two surface grids are analyzed: (1) fine grid composed of 954,894 nodes (where the pixel-to-node mapping is approximately 1-to-1) and (2) coarse grid composed of 233,651 nodes. The coarse grid was constructed to have approximately $1/4$ the grid density as the fine grid.

Fig. 2  Schematic of the ATAT camera layout.

Unsteady PSP testing of the Block 1 cargo model was conducted over four days during the ATAT in the 11- by 11-ft transonic test section. Test points were acquired at various model attitudes and for $0.70 \leq M_{\infty} \leq 1.40$. Additional information about the ATAT uPSP data processing is available in Ref. [9].

III. Methodology

Data acquired during the ATAT will be used to assess the current capabilities and limitations of uPSP in understanding the spatio-temporal pressure field on a launch vehicle during ascent. The data are organized into three studies focusing on variations in: (1) $M_{\infty}$, (2) angle of attack, and (3) grid density. For each of these studies, uPSP data are analyzed and compared to the distribution of fluctuating pressures measured using PTs. Specifically, root-mean-square (rms) distributions of the uPSP fluctuating pressure coefficient, $\Delta C_{p,\text{rms}}$, will be shown for each of the three vehicle bodies (core, LSRB, and RSRB shown in Fig. 1a). The rms values have been computed over the full bandwidth (10,000 Hz). These distributions are plotted in $x$-$\theta$ space (unwrapped), where the clocking angle $\theta$ is defined according to the convention shown in Fig. 3 (where $\theta = 0$ degrees in the $+z$-direction). Table 2 provides a summary of the uPSP test points
analyzed in this paper.

Fig. 3  Clocking angle, \( \theta \), convention for body coordinate systems. View in the aft-facing, \(+x\), direction.

<table>
<thead>
<tr>
<th>Study</th>
<th>Run</th>
<th>Sequence</th>
<th>Record length (samples)</th>
<th>( M_\infty ) (degrees)</th>
<th>( \alpha ) (degrees)</th>
<th>( \beta ) (degrees)</th>
<th>( R_n/10^6 ) (/ft)</th>
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<tbody>
<tr>
<td>( M_\infty )</td>
<td>3091</td>
<td>12</td>
<td>96,331</td>
<td>0.80</td>
<td>-0.00</td>
<td>0.01</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td>3091</td>
<td>18</td>
<td>96,331</td>
<td>0.85</td>
<td>-0.00</td>
<td>0.01</td>
<td>3.02</td>
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<tr>
<td></td>
<td>3091</td>
<td>29</td>
<td>96,331</td>
<td>0.90</td>
<td>-0.00</td>
<td>0.01</td>
<td>3.01</td>
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<tr>
<td></td>
<td>3091</td>
<td>35</td>
<td>96,331</td>
<td>0.95</td>
<td>0.00</td>
<td>0.01</td>
<td>3.01</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>3066</td>
<td>05</td>
<td>55,042</td>
<td>0.90</td>
<td>-3.99</td>
<td>0.02</td>
<td>3.01</td>
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<tr>
<td></td>
<td>3071</td>
<td>02</td>
<td>55,042</td>
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</tr>
<tr>
<td></td>
<td>3077</td>
<td>04</td>
<td>55,042</td>
<td>0.90</td>
<td>3.99</td>
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<td>3.01</td>
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<td>grid density</td>
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<td>11</td>
<td>96,331</td>
<td>0.79</td>
<td>-0.00</td>
<td>0.01</td>
<td>3.01</td>
</tr>
</tbody>
</table>

For comparison, the same nodes used to generate the uPSP plots are mapped to the nearest PT and the corresponding unwrapped distribution of \( \Delta C_{p,\text{rms}} \) measured using PTs is presented using that defined node-to-PT mapping. The ratio of these plots (ratio of \( \Delta C_{p,\text{rms}} \) values computed using uPSP and the nearest PT) is also presented for an assessment of the “comparability” of these measurement techniques. While this ratio would not fully account for the spatial differences in the density of these measurement techniques, it does provide a similarity metric for assessing differences between the two techniques. Finally, to provide context for these comparisons, shadowgraph data are presented to better understand the flow field generating particular regions of high fluctuating pressures. These shadowgraph data were acquired at matched model attitude and tunnel conditions as the uPSP and PT data, but not during the same test runs due to different illumination requirements.

To support the results discussed in the main sections of the paper, brief notes related to measurement noise and the effect of paint surface roughness on the fluctuating environments are provided in the Appendix.

IV. Results

A. \( M_\infty \) sweep study

For this study, data acquired at \( M_\infty \in \{0.80, 0.85, 0.90, 0.95\} \) and at constant \( \alpha = \beta = 0 \) degrees are analyzed. In Fig. the unwrapped rms distributions of the uPSP fluctuating pressure coefficient, \( \Delta C_{p,\text{rms}} \), are shown for each of the three bodies (core, LSRB, and RSRB). For these figures, the uPSP data are mapped to the fine surface grid (where the pixel-to-node mapping is approximately 1-to-1). This surface grid is used to map the data for all figures in this paper except where noted for the grid density study (Section IV.C).

There are several notable common features for the unwrapped \( \Delta C_{p,\text{rms}} \) distributions in Fig. 4:

1) 1- and 2-camera azimuthal regions: distinct azimuthal bands are present in the data for all bodies and are particularly notable for the launch vehicle core. These are due to the combination of data from two cameras
where the fields of view for multiple cameras overlap, as shown in the schematic in Fig. 2. Where data have been combined from multiple cameras, the underlying measurement noise in the data is reduced leading to lower $\Delta C_{p,\text{rms}}$. Two representative horizontal bands corresponding to the 1- and 2-camera regions are identified in Fig. 4a. Additional comparison of the 1- and 2-camera azimuthal regions is included in the Appendix. Similar noise-related features are present on the outboard sides of the boosters ($\theta = 90$ degrees for the LSRB and $\theta = 270$ degrees for the RSRB).

2) **fiducial patching**: dots of reduced $\Delta C_{p,\text{rms}}$ correspond to fiducials (PTs and registration points) that have been patched using data from surrounding nodes (see Ref. [9]).

3) **elevated levels at the nose and tail**: increased $\Delta C_{p,\text{rms}}$ on the forward and aft sections of the model due to increased camera view angles and reduced lighting. These levels are not flow-induced features, but rather due to increased measurement noise.

4) **reduced coverage in the multibody region**: data for surfaces between the core and boosters are not available due to lack of optical access in-between these bodies.

![Fig. 4 Unwrapped $\Delta C_{p,\text{rms}}$ distributions based on uPSP for increasing $M_\infty$ at $\alpha = \beta = 0$ degrees.](image)

The character and development of several flow features can also be identified in the unwrapped $\Delta C_{p,\text{rms}}$ distributions.
Perhaps most prominently, vertical blue stripes in each figure correspond to expansion regions located between the shoulders (payload fairing, LVSA-to-core, and booster nose cones) and the normal shocks downstream of each. As $M_\infty$ increases, these regions of relatively low $\Delta C_{p,\text{rms}}$ increase in width as the normal shocks move aft. Another region of particular interest is in the vicinity of the SRB forward attachment hardware, where relatively large coherent shed vortices lead to increased downstream fluctuating environments on all three bodies. This characteristic is visible for all conditions shown in Fig. 4 and is most prominent at $M_\infty = 0.95$, with increased $\Delta C_{p,\text{rms}}$ in the wake of the attachment hardware for each body (centered on $\theta = 270$ degrees for the LSRB, $\theta = 90$ degrees for the RSRB, and $\theta \in \{90, 270\}$ degrees for the core). The recirculating flow region located at the concave compression corner between the ICPS and the LVSA, with increased fluctuating pressures, is also visible for each condition.

To highlight the changes in fluctuating environments as $M_\infty$ increases, the ratio of these $\Delta C_{p,\text{rms}}$ distributions to those for the previous $M_\infty$ is shown in Fig. 5. These figures, perhaps more clearly than the $\Delta C_{p,\text{rms}}$ distributions alone, illustrate the features discussed above such as: (1) the aft movement of the normal shocks and associated broadening of the reduced environments between the shoulder and the shock and (2) the increasing magnitude and spatial extent of the SRB forward attachment-induced environments (particularly in Fig. 5c).

Fig. 5  Ratio of unwrapped $\Delta C_{p,\text{rms}}$ distributions based on uPSP at increasing $M_\infty$ and $\alpha = \beta = 0$ degrees.
For comparison, the corresponding unwrapped distribution of $\Delta C_{p,\text{rms}}$ measured using PTs, based on the defined node-to-nearest PT mapping, is shown in Fig. 6. Note that the RSRB was not instrumented. Although the PT data have been mapped to the same grid as the uPSP data this is not an indicator of the sensor density associated with the PTs – data from only 330 PTs were mapped to the unwrapped uPSP grid nodes.

![Diagram showing unwrapped $\Delta C_{p,\text{rms}}$ distributions based on PT data mapped to nearest uPSP nodes for increasing $M_\infty$ at $\alpha = \beta = 0$ degrees.](image)

(a) $M_\infty = 0.80$.
(b) $M_\infty = 0.85$.
(c) $M_\infty = 0.90$.
(d) $M_\infty = 0.95$.

**Fig. 6** Unwrapped $\Delta C_{p,\text{rms}}$ distributions based on PT data mapped to nearest uPSP nodes for increasing $M_\infty$ at $\alpha = \beta = 0$ degrees.

Similar to the unwrapped $\Delta C_{p,\text{rms}}$ distributions based on uPSP shown previously, in Fig. 6 regions of increased fluctuating pressures are identifiable: (1) the normal shocks downstream of the shoulders (payload fairing, LVSA-to-core, and booster nose cones), (2) the region downstream of the SRB forward attachment hardware, and (3) the recirculating flow region at the ICPS. However, comparing Fig. 6 to Fig. 4 illustrates the significant advantage of increased spatial density for localizing and estimating the extent of specific unsteady features. While the aft movement of the payload fairing normal shock as $M_\infty$ increases is measurable with the PTs (Fig. 6), the presence and impact of the LVSA-to-core normal shock is more challenging to characterize due to the more sparse sensor distribution in this region. For the same reason, while the location and extent of increased environments associated with the booster forward attachment hardware can be estimated with the PTs, it is better localized in the uPSP distributions (Fig. 4). However, while the lack
of optical access limits coverage in the multibody region for uPSP, PTs are located in these regions to measure peak fluctuating pressures in-between the bodies.

The ratio of $\Delta C_{p,\text{rms}}$ computed using uPSP and the nearest PT is shown in Fig. 7 for an assessment of the “comparability” of these measurement techniques. As noted previously, the RSRB was not instrumented with PTs during ATAT so the values are blanked for that body. It is notable that the uPSP-to-PT ratio of $\Delta C_{p,\text{rms}}$ is lowest in the regions previously identified as high fluctuating environments: (1) the normal shocks downstream of the shoulders (payload fairing, LVSA-to-core, and booster nose cones), (2) the region downstream of the SRB forward attachment hardware, and (3) the recirculating flow region at the ICPS. This trend in the ratio indicates that the uPSP measurements in these regions of high fluctuating pressures are lower than the measurements using PTs. Outside of these high fluctuating regions, the signal-to-noise ratio for the uPSP node data is less favorable and a significant component of the uPSP-measured $\Delta C_{p,\text{rms}}$ is attributable to measurement noise. The uPSP measurements away from the high fluctuating pressure environments, therefore, are generally higher than the comparison PTs and the uPSP-to-PT ratios are greater than unity. In the 2-camera regions (centered on $\theta \in \{45, 135, 225, 315\}$), the measurement noise is reduced and the uPSP-to-PT ratios are improved and closer to unity. Further discussion of these features is included in the Appendix.

**(a)** $M_\infty = 0.80$.

**(b)** $M_\infty = 0.85$.

**(c)** $M_\infty = 0.90$.

**(d)** $M_\infty = 0.95$.

**Fig. 7** uPSP-to-PT ratio of unwrapped $\Delta C_{p,\text{rms}}$ distributions for increasing $M_\infty$ at $\alpha = \beta = 0$ degrees.
Thenormalshocksonthepayloadfairingandcorearethemostnotableflowfeaturesoutsideofthemultibodyregion that lead to increased fluctuating environments. In Fig. 8 shadowgraph images are overlaid to highlight the changes in the shock position for increasing $M_\infty$. Note that the shadowgraph images were not acquired during the same instance as the uPSP due to illumination considerations, but were acquired at matched model attitude and tunnel conditions. While the model surface roughness pre- and post-paint is not exactly the same, some brief notes are included in the Appendix that suggest that the change in the location of the peak fluctuating pressure due to paint is relatively small at these conditions, and the high-speed shadowgraph images are qualitatively representative of the shock positions.

As $M_\infty$ increases, the shock footprint sweeps aft on the payload fairing and at $M_\infty = 0.90$, the normal shock is located approximately at the center of a densely spaced PT array. For this reason, the $M_\infty = 0.90$ condition is analyzed more closely in the angle of attack study in Section IV.B. For the shock aft of the LVSA-to-core shoulder, as $M_\infty$ increases the longitudinal extent of the shock structure increases, but the sharp shoulder leads to a rapid expansion and recompression shock beginning at approximately the same shoulder station. As discussed above (and shown in Fig. 7), the uPSP generally underpredicts the peak environments associated with the normal shocks relative to the PTs. Since there is a dense PT array on the payload fairing at $\theta = 0$ degrees (corresponding to the clocking angle convention shown in Fig. 3), a more detailed comparison of $\Delta C_{p,rms}$ from uPSP and PTs in the payload fairing normal shock region can be considered.

In Fig. 9 $\Delta C_{p,rms}$ for uPSP slices oriented along a constant clocking angle ($\theta = 60$ degrees) are plotted in comparison to corresponding data for the $\theta = 0$ degrees arrangement of PTs. The uPSP slices are chosen from a 2-camera region (where the comparison above indicated uPSP data are closer to the PTs) and from a clocking angle chosen to avoid crossing PT fiducials. While the vehicle forebody is not completely axisymmetric, the azimuthal variation in $\Delta C_{p,rms}$ as measured by PTs for these conditions is relatively small. In comparison to the PTs, uPSP-measured $\Delta C_{p,rms}$ magnitudes are: (1) higher on the nose (due to increased camera view angles and reduced PSP lighting), (2) lower in the expansion region forward of the shock, and (3) do not match the peak fluctuating levels associated with the shock. Corresponding shadowgraph pixel variance images are shown behind the slices to provide insight to the external flow field.

**B. Angle of attack study**

For this study, data acquired at $M_\infty = 0.90$, $\beta = 0$ degrees, and $\alpha \in \{-4, 0, 4\}$ degrees are analyzed. These cases are highlighted since at this $M_\infty$ and $\alpha = \beta = 0$ degrees the payload fairing normal shock is located approximately at the center of a region instrumented with a densely-spaced PT array (see Ref. [11]), which supports comparisons with the uPSP data. Views in the $x$-$z$ plane of the vehicle pitched to the nonzero angles of attack are shown in Fig. 10 where only an outline of the LSRB nose is shown to highlight the booster forward attachment hardware in red.

Figure 11 presents the unwrapped $\Delta C_{p,rms}$ distributions based on uPSP and comparison distributions based on the measured data at $M_\infty = 0.90$, $\beta = 0$ degrees, and $\alpha \in \{-4, 0, 4\}$ degrees.
Fig. 9  $\Delta C_{p,\text{rms}}$ for constant clocking angle slices of PT ($\theta = 0$ degrees) and uPSP ($\theta = 60$ degrees) data for increasing $M_\infty$ at $\alpha = \beta = 0$ degrees. Background shadowgraph pixel variance images indicate shock unsteadiness.

Fig. 10 Nonzero vehicle angles of attack (in degrees) for which comparisons are made. Only the outline of the LSRB nose is shown so that the booster forward attachment hardware can be seen in red.

PT data by mapping the uPSP nodes to the nearest PT. For the PT plots, $\Delta C_{p,\text{rms}}$ on the RSRB is zero as this body was not instrumented during the ATAT. For the $\alpha = 0$ degrees case (Figs. 11c and 11d), both distributions reflect the increased fluctuating environments associated with the booster forward attachment hardware that are symmetrical on the upper and lower sides of this feature for each body. Qualitatively, the uPSP distribution illustrates the value of the increased measurement density by providing useful data about the spatial extent of this feature.
(a) uPSP, $\alpha = +4$ degrees.

(b) PT mapped to nearest uPSP nodes, $\alpha = +4$ degrees.

(c) uPSP, $\alpha = 0$ degrees.

(d) PT mapped to nearest uPSP nodes, $\alpha = 0$ degrees.

(e) uPSP, $\alpha = -4$ degrees.

(f) PT mapped to nearest uPSP nodes, $\alpha = -4$ degrees.

Fig. 11  Unwrapped $\Delta C_{p,rms}$ distributions based on uPSP and PT at $M_{\infty} = 0.90$ for $\beta = 0$ degrees and several $\alpha$. 
For the $\alpha = +4$ degrees case (Figs. 11a and 11b), the crossflow of the forward attachment wake toward the leeward side ($\theta = 0$ degrees) on each body can also be seen in both the uPSP- and PT-based distributions, with a much clearer qualitative picture of the attitude effect illustrated by the uPSP data. Similarly, for the $\alpha = -4$ degrees case (Figs. 11c and 11d), the shed vortices are directed toward the leeward side of the bodies, leading to increased unsteady leeward pressures and decreased unsteady windward pressures downstream of this feature. The distinct red and blue horizontal bands in these ratio plots are due to changes in the 1- and 2-camera regions as the model attitude varies.

In addition to highlighting the angle of attack effects in the vicinity of the booster forward attachment, the movement of the normal shocks downstream of the payload fairing and LVSA-to-core shoulders can be seen in Fig. 12 (boxed regions in the unwrapped plots). For nonzero angles of attack, the shoulder shocks shift forward on the leeward side ($\theta = 0$ degrees for $\alpha = +4$ degrees and $\theta = 180$ degrees for $\alpha = -4$ degrees) corresponding to the vertical red bands located at each shoulder and extending $\approx \pm 90$ degrees from the leeward centerline. On the windward side, the boundary layer is strengthened and the windward shock moves slightly aft corresponding to the vertical blue bands (reduced unsteadiness) most visible at the LVSA-to-core shoulder and extending $\approx \pm 90$ degrees from the windward centerline. See Ref. 12 for additional discussion related to angle of attack variation associated with shock boundary-layer interactions for cone-cylinder bodies.

Fig. 12 Ratio of unwrapped $\Delta C_{p, \text{rms}}$ distributions based on uPSP for nonzero $\alpha$ and $\beta = 0$ degrees. Payload fairing and LVSA-to-core shoulder regions boxed for emphasis.

Due to the model position and shadowgraph camera placement during testing, changes in the shoulder shock structures are not easily visualized with shadowgraph data for nonzero angles of attack since the vehicle is pitching toward and away from the camera, compounding the additional challenges of analyzing shadowgraph images for axisymmetric flow fields (relative to two-dimensional fields) 13. To provide additional context for the changing shoulder shock structures at different angles of attack, a high-speed shadowgraph pixel variance image for $\alpha = 0$ degrees and $\beta = 4$ degrees is presented in Fig. 13 since the changes in the shock structures are approximately analogous to the pattern that would be expected for this forebody region of the vehicle for the corresponding $\alpha = \pm 4$ degrees and $\beta = 0$ degrees conditions. While the upper edge of the vehicle is slightly obscured by the window frame at the nose of the vehicle, the tilting of the normal shocks relative to the vehicle longitudinal axis (forward on the leeward side and aft on the windward side) can be seen.
Fig. 13 High-speed shadowgraph pixel variance image indicating regions of high flow unsteadiness at $M_\infty = 0.90$, $\alpha = 0$ degrees and $\beta = 4$ degrees. Flow is from left to right.

In Fig. 14 uPSP slices oriented along a constant clocking angle ($\theta = 30$ degrees) are plotted in comparison to corresponding data for the $\theta = 0$ degrees arrangement of PTs. While similar observations can be made comparing the uPSP and PT slices as were made for Fig. 9, here it is notable that although the uPSP peaks do not match the PT peak magnitudes nor locations associated with the shock, the expected forward and aft shifts in the local peaks are present.

![Graph showing $\Delta C_{p, rms}$ for constant clocking angle slices of PT ($\theta = 0$ degrees) and uPSP ($\theta = 30$ degrees) data for $M_\infty = 0.90$, $\alpha \in \{-4, 0, +4\}$ degrees and $\beta = 0$ degrees.]

Fig. 14  $\Delta C_{p, rms}$ for constant clocking angle slices of PT ($\theta = 0$ degrees) and uPSP ($\theta = 30$ degrees) data for $M_\infty = 0.90$, $\alpha \in \{-4, 0, +4\}$ degrees and $\beta = 0$ degrees.

C. Grid density study

For this study, data acquired at $M_\infty = 0.79$, $\alpha = \beta = 0$ degrees and mapped to two different grid densities (fine and coarse) are analyzed. The fine grid approximately corresponds to a 1-to-1 mapping from pixel-to-node and the coarse grid contains approximately $1/4$ the grid density as the fine grid. For the coarse grid, before projecting the image frames to the grid nodes, a 5 by 5 spatial box filter is applied to the images, which serves to increase the signal-to-noise ratio for individual nodes (see Ref. 14 for additional discussion). In addition, for the coarse grid, an improved estimate of the global model surface temperature has been applied for the steady and unsteady PSP solutions.
Figures 15a and 15c present the unwrapped $\Delta C_{p,\text{rms}}$ distributions based on uPSP mapped to the fine and coarse surface grids, respectively. Perhaps most notably, the coarse distribution has significantly less spatial variation than the fine grid data. In addition, the coarse distribution shows: (1) relatively narrow bands of slightly increased fluctuating pressures in the vicinity of the normal shocks aft of the shoulders (payload fairing, LVSA-to-core, and booster nose cones), (2) reduced noise on the forward and aft ends of the vehicle, (3) reduced differences in the azimuthal bands between 1- and 2-camera regions, and (4) reduced prominence of the patched fiducials. The booster forward attachment environments also appear somewhat more distinct.

For comparison, the ratio of $\Delta C_{p,\text{rms}}$ computed using uPSP and the nearest PT is shown in Figs. 15b and 15d for each grid. Since the RSRB was not instrumented during the ATAT, the values are blanked for that body. The coarse grid comparison is more similar to the PT data while generally underpredicting environments for all regions. The expansion regions aft of the vehicle shoulders and forward of the corresponding normal shocks are underpredicted relative to the PT mapped data for both uPSP grid densities.

In Fig. 16, $\Delta C_{p,\text{rms}}$ for uPSP slices are plotted in comparison to corresponding PT data near the payload fairing shoulder. The uPSP azimuthal slices are chosen from a 2-camera region and from a clocking angle to avoid crossing PT
fiducials. While the uPSP slice for the fine grid contains the same features previously discussed in Section IV.A, the coarse grid slice compares a bit more favorably to the PTs. In general, (1) the nose magnitudes are closer to the PTs (uPSP measurement noise is reduced) and (2) the local peak environment at the shock is more distinct, although its magnitude is still lower relative to the PTs. Although additional analysis is required to develop improved pixel-to-grid metrics, the heuristic suggested here is that coarsening the grid to improve the signal-to-noise for each node is potentially quite useful depending on the required spatial resolution for the data (a result discussed in Ref. [14]). Although not presented here, similar improvements in signal-to-noise can be achieved by averaging multiple nodes from the fine grid.

![Graph showing ΔC_p, rms for constant clocking angles slices of PT (θ = 0 degrees) and uPSP (θ = 60 degrees) data for M∞ = 0.79, α = β = 0 degrees, and two grid densities.]

**Fig. 16** ΔC_p, rms for constant clocking angles slices of PT (θ = 0 degrees) and uPSP (θ = 60 degrees) data for M∞ = 0.79, α = β = 0 degrees, and two grid densities.

### V. Conclusion

In this paper, measurements of the fluctuating pressure field for the SLS Block 1 cargo launch vehicle based on unsteady pressure sensitive paint (uPSP) and pressure transducers (PTs) are compared. The uPSP data acquired during the Ascent Transient Aerodynamics Test are unique given the complexity and large size of the model tested, and the large number of unsteady PTs instrumenting the model also provide valuable independent measurements for comparison. In general, it appears that the uPSP-to-PT comparisons are most significantly different in regions of high fluctuating pressure gradients, such as in the vicinity of normal shocks, although it is also shown that measurement noise is a significant contributor to the uPSP-based fluctuating pressures away from these regions of high unsteadiness. In the M∞ and angle of attack studies, it is shown that the uPSP data can provide valuable insight into the fluctuating environments and support high-spatial resolution characterization of the location and extent of critical unsteady flow features. Continued work is required to determine appropriate spatial filtering (either via a coarsened grid or post-mapping averaging of nodes) based on the desired spatial resolution for analysis as well as potentially the flow-driven signal-to-noise ratio. Further evaluation of improved model temperature estimates for the uPSP calibration (image intensity-to-pressure) is also ongoing.

### VI. Appendix

#### A. Node time histories and spectra

While the focus of this paper is on comparing unwrapped ΔC_p, rms distributions and constant clocking angle slices between uPSP and PT data, supplementary data related to time histories and power spectral densities (PSDs) are provided in this section to help explain features noted in the text. In Figs. [17a] and [17c], time histories and PSDs are plotted for a PT (at θ = 0 degrees) and comparison uPSP nodes located at the station corresponding to the payload fairing peak unsteady location. The station is shown with a vertical line on the vehicle in the high-speed shadowgraph pixel variance image. For the 1-camera region data, the uPSP node is located at θ = 15 degrees, and for the 2-camera region data, the uPSP
node is located at $\theta = 30$ degrees. At this station with high flow-driven unsteadiness, the fluctuating pressures based on uPSP are significantly smaller relative to the comparison PT, but the general features of the PSDs are quite similar (prominence and locations of peaks), potentially suggesting that refining the gain factor in the pixel intensity-to-pressure calibration may improve the comparison. As shown in Fig. 17a, differences between the 1- and 2-camera regions are relatively small at this station, indicating that measurement noise is less dominant. In Fig. 17c the coarse grid (with updated surface temperature estimate) compares slightly more favorably with the PT PSD magnitudes than the fine grid.

![Image](image1.png)

![Image](image2.png)

(a) 1- and 2-camera regions for the fine grid at the peak unsteady location aft of the payload fairing shoulder.

(b) 1- and 2-camera regions for the fine grid on the payload fairing downstream of the normal shock.

![Image](image3.png)

![Image](image4.png)

(c) Fine and coarse grids in 1-camera regions at the peak unsteady location aft of the payload fairing shoulder.

(d) Fine and coarse grids in 1-camera regions on the payload fairing downstream of the normal shock.

Fig. 17 Comparison of $\Delta C_p$ time histories and PSDs for PTs and single uPSP nodes at $M_\infty = 0.79$ and $\alpha = \beta = 0$ degrees for two locations on the vehicle: at the peak unsteady location and at a location downstream of the normal shock. Background shadowgraph pixel variance images indicate regions of shock unsteadiness.

In contrast, Figs. 17b and 17d present time histories and PSDs for a PT (at $\theta = 0$ degrees) and comparison uPSP nodes located downstream of the payload fairing normal shock. For the 1-camera region data, the uPSP node is located at $\theta = 15$ degrees, and for the 2-camera region data, the uPSP node is located at $\theta = 30$ degrees. This station has lower flow-driven unsteadiness compared to the payload fairing peak unsteady location, and so the fluctuating pressures based on uPSP are more dominated by measurement noise. As shown in Fig. 17b at this station, differences between the
1- and 2-camera regions are comparatively large, with significant reductions in the noise floor for the 2-camera data (although in comparison to the PT, measurement noise is still present). Similar observations can be made for Fig. 17d where the spatial filtering associated with the coarse grid represents an alternative way to improve the signal-to-noise ratio similar to combining data from multiple cameras.

These supplementary results help explain the nature of the differences between the uPSP and PT data presented in the text and indicate how the comparison changes based on the dominance of flow-driven versus measurement noise-driven unsteadiness. Additional work is ongoing to characterize these differences and develop methods to improve the comparisons between independent data sources.

B. Multiple camera effect

As described in Sec. IV.A, distinct azimuthal bands are present in the uPSP data corresponding to regions covered by 1- or 2-cameras. For the regions in which data from 2-cameras are combined for individual nodes, the measurement noise is reduced. Figure 18 illustrates this feature with several $\Delta C_p,\text{rms}$ station slices on the forebody of the vehicle. The step tops correspond to regions covered by 1-camera and the step bottoms correspond to those with reduced noise in 2-camera regions. Although the vehicle is not completely axisymmetric, the large differences in the stair step pattern are not attributable to physical flow features.

![Figure 18](image)

Fig. 18 $\Delta C_p,\text{rms}$ based on uPSP for station slices at $M_\infty = 0.90$ and $\alpha = \beta = 0$ degrees. Stations corresponding to each azimuthal slice are indicated on the vehicle, with background shadowgraph pixel variance image indicating regions of shock unsteadiness.

To better understand the relative noise reduction between the 1- and 2-camera regions, the ratios between $\Delta C_p,\text{rms}$ clocking angle slices in 2- and 1-camera regions are shown in Fig. 19 for the $M_\infty$ conditions analyzed in Sec. IV.A. The clocking angles chosen are $\theta = 35$ degrees (2-camera region) and $\theta = 10$ degrees (1-camera region). Ideally, based on the weighting of camera data for these overlapping regions, the $\theta = \{0, 45\}$ degrees slices would have been used, but to avoid the impact of PT fiducials the slices analyzed are rotated $\Delta \theta = 10$ degrees away from azimuthal arrangements of PTs.

While there is local variation in the 2-to-1 camera $\Delta C_p,\text{rms}$ ratio, particularly at the nose of the vehicle and near flow-driven features aft of the payload fairing shoulder and LVSA-to-core shoulder, the ratio appears generally uniform
between the two shoulders. If the uPSP pixel data in this region were dominated by uncorrelated measurement noise with standard deviation $\sigma_{1\text{cam}}$, the standard deviation $\sigma_{2\text{cam}}$ of the mean of two of these random variables, $X_1$ and $X_2$, is:

$$\sigma_{2\text{cam}} = \sqrt{\text{Var}\left(\frac{1}{2} (X_1 + X_2)\right)} = \sqrt{\frac{1}{4} \cdot 2\sigma_{1\text{cam}}^2} = \frac{1}{\sqrt{2}} \sigma_{1\text{cam}}.$$  

(1)

So the ratio $\sigma_{2\text{cam}}/\sigma_{1\text{cam}}$ under this noise model would be $1/\sqrt{2}$, which is the value of the black horizontal line plotted in Fig. 19. Although these assumptions oversimplify the problem by ignoring potentially important features of the data processing and do not account for the contribution of flow-driven unsteadiness, this simple model of uncorrelated measurement noise with constant standard deviation does help explain the azimuthal banding as well as the general overprediction relative to PTs shown in, for example, Fig. 7. In regions away from high flow-driven unsteadiness, the uPSP data appear to be dominated by measurement noise, which can be improved upon with camera view overlapping or appropriate spatial filtering (either via a coarsened grid or averaging of nodes).

![Fig. 19 Ratio of $\Delta C_{p, \text{rms}}$ based on uPSP between azimuthal slices located in 2- and 1-camera regions for increasing $M_\infty$ at $\alpha = \beta = 0$ degrees.](image)

C. Shoulder shock movement

Due to different illumination requirements, the shadowgraph images throughout the text were not acquired during the same test runs as the uPSP data, although they were acquired at matched model attitude and tunnel conditions as the uPSP and PT data before the model was painted for uPSP data acquisition. Since the model surface roughness pre- and post-paint is not exactly the same, this section includes supplementary data to show that for the conditions presented in this paper the location of the peak fluctuating pressure does not shift significantly after applying the paint.

Using PT data from points acquired during a prepaint $M_\infty$ sweep, the location of the peak fluctuating pressure downstream of the payload fairing shoulder can be determined. This position is nondimensionalized as $\xi_s = x_s/D_{\text{ref}}$, where $x_s$ is the distance from the payload fairing shoulder and $D_{\text{ref}}$ is the diameter of the payload fairing as shown in Fig. 20a. This nondimensional shock position is plotted as a function of $M_\infty$ in Fig. 20b, where the nondimensional locations of PTs are also shown to provide an indication of the sensor density. For the prepaint $M_\infty$ sweep, depicted with blue markers, as $M_\infty$ increases the aft movement of the peak fluctuating pressure proceeds, particularly for $M_\infty < 0.90$, in discrete steps corresponding to the spacing of sensors in this region. The discrete nature of the estimated shock position demonstrates that even for a high density array of discrete transducers, measuring the location (and corresponding magnitude) of peak environments is a challenge.

Also included in Fig. 20b are red markers corresponding to the peak fluctuating pressure locations estimated using PTs for each of the uPSP conditions analyzed in Sec. IV.A. Figure 21 presents the prepaint high-speed shadowgraph
(a) Geometry definition for nondimensionalization.

(b) Shock position as a function of $M_\infty$.

Fig. 20  Pre- and post-paint payload fairing shock position.

Pixel variance images for each of these conditions as well as the approximate location of the peak fluctuating pressure downstream of the payload fairing shoulder. As shown in Fig. 20, for all cases, the peak location is within one adjacent sensor of the peak locations identified during the prepaint $M_\infty$ sweep. For the qualitative use of the shadowgraph images in this paper, this is deemed adequate, although additional work is required to better understand and characterize the paint surface roughness effects on the measured unsteady environments.

Fig. 21  High-speed shadowgraph pixel variance images indicating regions of high flow unsteadiness for increasing $M_\infty$ at $\alpha = \beta = 0$ degrees. The approximate distance between the payload fairing shoulder and the peak fluctuating pressure downstream of the shoulder is also shown. Flow is from left to right.
Acknowledgments

The authors would like to thank the uPSP test team at NASA Ames Research Center, to include Nettie Roozeboom, Jennifer Baerny, Jie Li, David Murakami, Marc Shaw-Lecerf, Paul Stremel, and Lucy Tang for their invaluable assistance in acquiring, processing, and discussing the uPSP data analyzed in this paper.

References


