

Spatiotemporal Analysis of High-Resolution Pressure-Sensitive Paint Measurements on a Launch Vehicle Wind Tunnel Model

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An accurate understanding of unsteady aerodynamic loads is critical for launch vehicle structural design and for development of the vibro-acoustic environment for payload components. Analysts commonly use point-wise surface pressure measurements from wind tunnel testing to build statistical models of the in-flight turbulent boundary layer flow structures, often extrapolating over large swaths of the surface due to measurement sparsity. We present novel results from a transonic wind tunnel test using fast-response pressure-sensitive paint (PSP) and show how it can be used to visualize and quantify localized turbulent boundary layer wall pressure statistics with unprecedented spatial resolution. The wind tunnel model is a scaled model of the Space Launch System (SLS) rocket Block 1B Crew configuration and analysis focused on the compression corner between the Service Module fairing and the Universal Stage Adapter.

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I. Nomenclature

M	=	Wind tunnel Mach number
α	=	Wind tunnel model angle of attack (deg)
β	=	Wind tunnel model sideslip (deg)
C_p	=	Coefficient of pressure
ΔC_p	=	Fluctuating component of coefficient of pressure
c_1	=	Corcos model cross-spectrum decay coefficient, longitudinal direction
c_3	=	Corcos model cross-spectrum decay coefficient, lateral direction
f	=	Frequency (Hz)
G	=	uPSP gain, relating intensity ratio fluctuation to surface pressure fluctuation (psid)
N_P	=	Number of camera pixels
N_T	=	Number of video frames (i.e., number of time samples)
N	=	Side length of PSP “super pixel” consisting of $N \times N$ source pixels
Δt	=	Time duration between frame exposures (sec)
$dp_i[k]$	=	Fluctuating surface pressure measured by super pixel i at sample time k

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$r_i[k]$	=	Intensity ratio of super pixel i at sample time k
$dr_i[k]$	=	Intensity ratio fluctuation of super pixel i at sample time k
$\tilde{s}_i[k]$	=	Reference intensity (steady-state) of super pixel i at sample time k (counts)
$s_i[k]$	=	Intensity of super pixel i at sample time k (counts)
$\bar{p}_i$	=	Mean surface pressure at location sampled by super pixel i (psia)
$\bar{T}_i$	=	Mean surface temperature at location sampled by super pixel i (degrees F)
$\Phi_{p,i}$	=	Surface pressure power spectral density at location sampled by super pixel i
$\Gamma_{p,ii'}$	=	Surface pressure cross-spectral density between locations sampled by super pixels i and i'
$\gamma_{p,ii'}$	=	Surface pressure coherence function between locations sampled by super pixels i and i'
$\varphi_{p,ii'}$	=	Surface pressure cross-spectral phase between locations sampled by super pixels i and i'
X_{SLS}	=	Space Launch System coordinate system, X-axis (in)
Y_{SLS}	=	Space Launch System coordinate system, Y-axis (in)
Z_{SLS}	=	Space Launch System coordinate system, Z-axis (in)
X_o	=	Reference position on the Orion Service Module fairing (in)
D	=	Orion Service Module fairing outer diameter (in)
X_1	=	Wind tunnel model surface projected coordinate, axial direction (in)
X_3	=	Wind tunnel model surface projected coordinate, circumferential direction (in)
ξ_1	=	Longitudinal (stream-wise) displacement (in)
ξ_3	=	Lateral (span-wise) displacement (in)
u_c	=	Convection velocity (in/s)
u_∞	=	Wind tunnel free-stream velocity (in/s)

II. Introduction

Unsteady Pressure-Sensitive Paint (uPSP) technology provides simultaneously high-frequency and high-spatial resolution surface pressure fluctuation measurements. It has been successfully demonstrated in production wind tunnel test sections and enables state-of-the-art aerospace vehicle design evaluation in ground test facilities [1–8]. Soranna et al. [9] recently developed buffet forcing functions for coupled loads analysis of the Space Launch System (SLS) rocket using uPSP data collected at the NASA Ames 11-by 11-ft Transonic Wind Tunnel (TWT) and compared results to those obtained from fitting to the widely accepted Corcos model [10] for turbulent boundary layer wall pressure statistics. While uPSP data were of sufficient resolution to capture frequencies relevant for full-vehicle buffet analysis, it remains to be seen whether uPSP can advance the state-of-the-art in capturing pressure fluctuations relevant for vibro-acoustic analysis.

uPSP data collected in April 2024 from the Ames TWT with a sub-scale model of SLS Block 1B crew configuration included multiple uPSP camera lens sizes and demonstrated how using a 180 mm lens can provide unprecedented resolution in a localized area of the test model. This enabled visualization of localized flow features such as shockwave-boundary layer interactions and shows promise in validating assumptions commonly made based on physics-based simulation using computational fluid dynamics.

We will summarize the wind tunnel test setup, data acquisition, and data reduction procedures. We validate uPSP-derived spatial coherence measurements against collocated pressure transducer data. The uPSP data present a unique opportunity to observe the flow coherence across a large swath of the wind tunnel model surface, focusing especially on a surface region at the interface between the Orion Service Module (SM) and the Universal Stage Adapter (USA), shown in Figure 1.

We show how the uPSP data validate certain assumptions made by the turbulent fluctuating surface pressure model developed originally by Corcos [10]—a common method for characterizing turbulent wall pressure statistics— and where the model breaks down, demonstrating the value of high-fidelity experimental data for developing launch vehicle aerodynamic environments.

III. Data Acquisition

The uPSP and pressure transducer data analyzed in this study were collected as part of a week-long test event at the NASA Ames TWT. For more detail on the overall test event, equipment setup, and test conditions, we refer the reader to a companion paper by Lash [12]. This paper will focus on data from one of the two wind tunnel model configurations tested as part of the event, a scaled model of the forebody of the SLS Block 1B Crew configuration—Figure 2 shows the

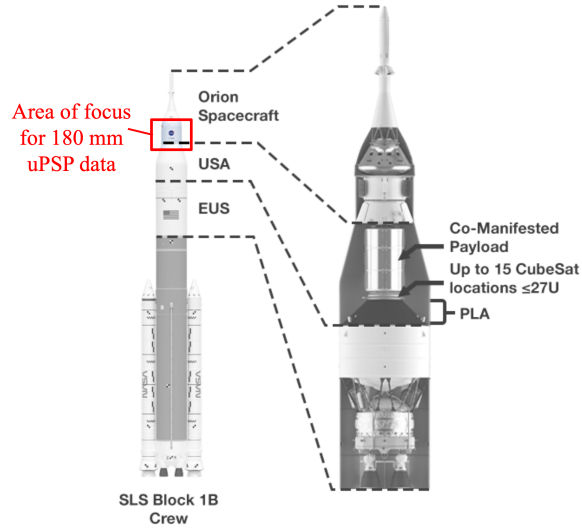


Fig. 1 Area of SLS Block 1B Crew configuration focused on by 180 mm lens uPSP data (adapted from [11]).

model installed in the test section. The model was a 4% scale model of the SLS-28000 series configuration and was the same outer mold line as used in previous testing in 2017 (for thorough test report, see Steva [13]).

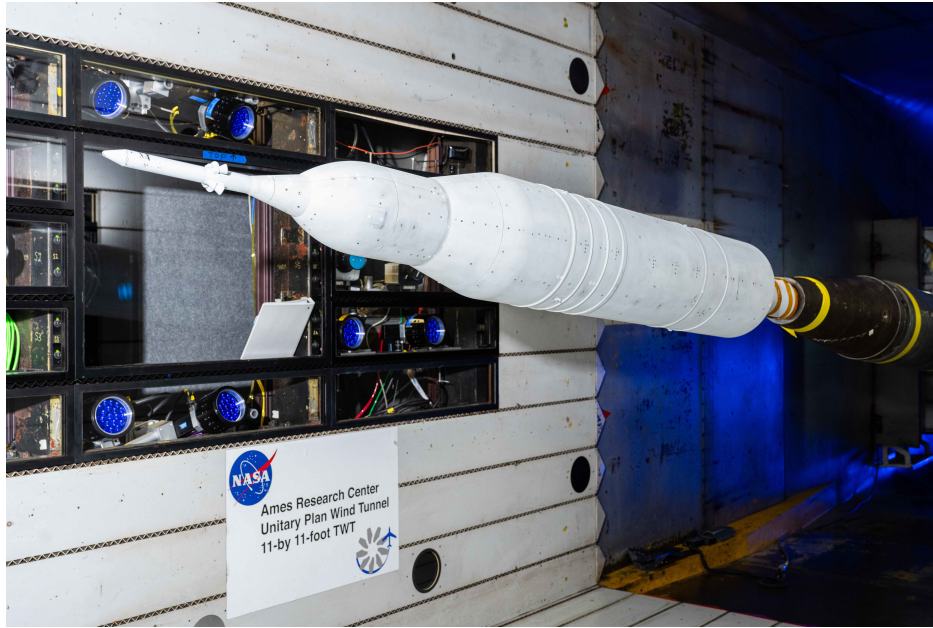


Fig. 2 Wind tunnel model of the SLS Block 1B Crew configuration forebody installed in the NASA Ames TWT in April 2024.

For the majority of the event, all (8) Vision Research Phantom® v2512 cameras were equipped with 35 mm lenses and had comparable spatial resolution on the surface of the test subject. Then, for one day of testing, the lens on one of the upstream sidewall cameras was swapped to 180 mm, resulting in a magnified view of the model surface. Due to a need to simplify changes to hardware install mid-test, no other cameras were repointed after the optics switch, so there were no simultaneous recordings of the same portion of the model surface with 35 mm and 180 mm lenses (besides limited overlap of camera views along their edges). To compare the performance of the two lenses, we use repeat runs with matching wind tunnel conditions.

Although the event included many test conditions at varying Mach number M , angle-of-attack α , and sideslip angle β , this report focuses on test conditions at $\alpha = \beta = 0$ that were measured by the camera equipped with the 180 mm lens.

IV. Data Processing

The following subsections describe the steps taken to reduce the uPSP high-speed video files into a format suitable for analysis. The process is summarized as

- 1) projecting the data into a 3-D coordinate system on the model surface, and
- 2) time-domain signal processing to convert the data from pixel “counts” into quantities related to the fluctuating surface pressure.

A. 3D Projection

A key element of uPSP data processing is to project the data from its source coordinates—camera pixel indices in the image frame—into physically meaningful spatial coordinates on the surface of the wind tunnel model. A process was developed specifically for this study that allowed precise, 3-D comparison between the 35 mm and 180 mm lens uPSP datasets. An illustration of the process is shown in Figure 3. It consists of the following steps:

- 1) A camera calibration was developed based on the first frame in the camera video file, enabling precise determination of the camera pose (translation and rotation matrix) relative to the wind tunnel test subject
- 2) “Super pixels” were formed in the camera plane consisting of 7×7 blocks of source pixels. The super pixel size was determined based on previous analysis of the camera noise, see [14]
- 3) The center of each super pixel was ray-traced to an intersection point with a triangle primitive on the surface of a high-fidelity, 3-dimensional triangulation of the wind tunnel model outer mold line. The ray-tracing was performed using the open source Open3D library [15]
- 4) A new surface triangulation was inferred using the pixel-to-pixel connectivity defined in the camera plane

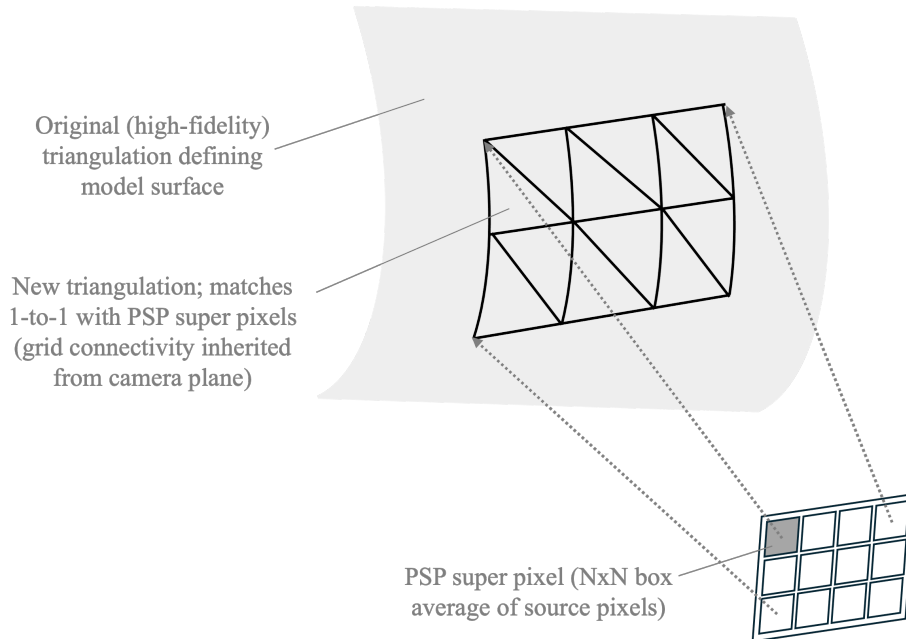


Fig. 3 Procedure to map uPSP camera data onto 3D model surface for 35 mm and 180 mm lens datasets.

The result of this process is shown in Figure 4 for both 35 mm (left) and 180 mm (right) lens configurations. While the 35 mm lens allows for significantly larger surface area coverage, the 180 mm lens has significantly higher spatial resolution. The exact value can vary depending on the surface location; the insets in Figure 4 show the 35 mm lens had approximately 4 super-pixels per linear inch compared to the 180 mm lens which had 16 super-pixels per linear inch. In practice, this means that using the 180 mm lens, a 7×7 super pixel had comparable spatial size to the cylindrical housing for the miniature pressure transducers that were installed flush with the model surface. This is significant because it

allowed for large numbers of uPSP pixels to be averaged—mitigating shot noise—while maintaining a comparable level of measurement attenuation to that of the pressure transducers due to inherent spatial decorrelation of the flow field (for a more thorough review of the subject, see Ref. [16]).

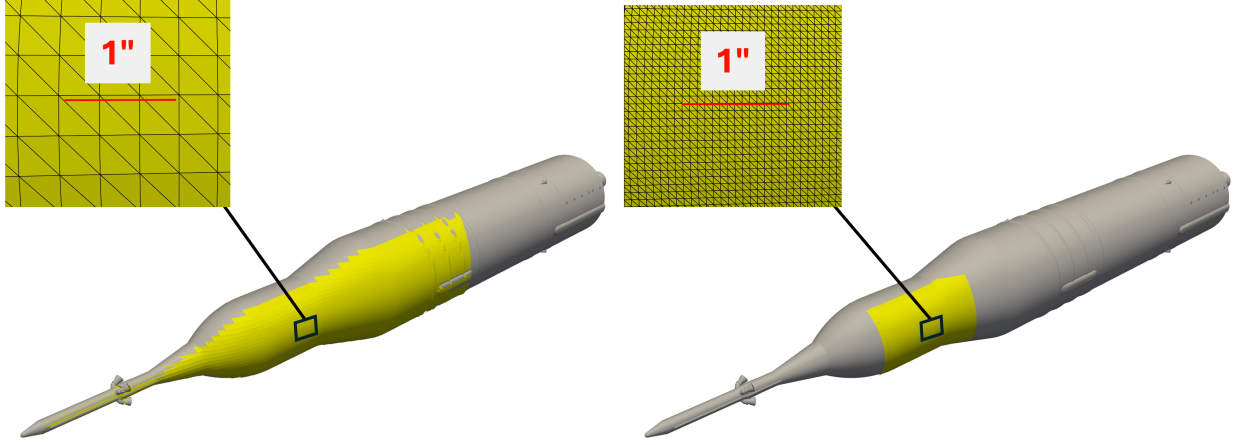


Fig. 4 Comparison of surface area coverage between sidewall camera equipped with 35 mm (left) vs 180 mm (right) lenses. Insets show grid resolution relative to 1 inch on the model surface. Each grid point corresponds to the center of a 7×7 super-pixel in the camera plane.

B. Signal Processing

A brief summary of processing high-speed video recordings of luminescent PSP is included here. For additional detail and alternative methods, we refer the reader to work by Sellers [6] and Powell [17].

1. Theory

Each uPSP camera records a set of frames—denote $s_i[k]$ as the counts measured by the i th camera pixel at the k th sample time. $i = 0, 1, \dots, N_P$, where N_P is the total number of pixels (our convention is to enumerate pixels in row-major fashion, where ‘0’ is the upper-left corner and ‘ N_P ’ is the lower-right corner) and sample times are $k\Delta t$, $k = 1, 2, \dots, N_T$. For this test event, the cameras were run at 10,000 frames per second so $\Delta t = 100 \mu\text{s}$.

For this discussion, we ignore several corrections to the raw pixel counts that must be performed in preprocessing including black level correction and pixel response nonlinearity, and simply state that s_i is linearly related to the (time-varying) luminosity of the painted surface.

Let $r_i[k] = \bar{s}_i[k]/s_i[k]$ represent an intensity *ratio* where $\bar{s}_i[k]$ is the intensity corresponding to the local steady-state surface pressure (and possibly slowly time-varying itself; see IV.B.2). It has been shown previously in [6] that small fluctuation in the value of r_i around its mean value are linearly related to the local surface pressure fluctuation. More precisely, if dr_i is the fluctuation in intensity ratio measured by the i th pixel, and dp_i is the fluctuation in surface pressure, then

$$dp_i[k] = G(\bar{p}_i, \bar{T}_i) \cdot dr_i[k] \quad (1)$$

where G is a linear gain factor that is a function solely of the local steady-state surface pressure $\bar{p}_i$ and local steady-state surface temperature $\bar{T}_i$.

In this paper, we focus primarily on spatio-temporal content of the uPSP data that can be obtained directly from dr without requiring knowledge of the pressure calibration factor G . For example, normalized quantities such as the coherence function γ and cross-spectral phase φ can be obtained from intensity ratios without calibrating to pressure. Considering the surface pressure fluctuation measured by two different pixels i and i' , with corresponding power spectral densities $\Phi_{p,i}$ and $\Phi_{p,i'}$, and cross-spectral density $\Gamma_{p,ii'}$, we have:

$$\gamma_{p,ii'} = \frac{|\Gamma_{p,ii'}|}{\sqrt{\Phi_{p,i}\Phi_{p,i'}}} = \frac{\mathcal{G}^2 |\Gamma_{r,ii'}|}{\mathcal{G}^2 \sqrt{\Phi_{r,i}\Phi_{r,i'}}} = \gamma_{r,ii'} \quad (2)$$

$$\varphi_{p,ii'} = \arg(\Gamma_{p,ii'}) = \arg(G^2 \Gamma_{r,ii'}) = \arg(\cancel{G^2})^0 + \arg(\Gamma_{r,ii'}) = \varphi_{r,ii'} \quad (3)$$

In light of Equations (2) and (3), for non-dimensional quantities we drop the r and p subscripts and use simply $\gamma_{ii'}$ and $\varphi_{ii'}$ respectively. In addition, we compute these quantities using the fluctuating intensity ratio without calibrating to units of pressure.

2. Practical Considerations

There are several practical challenges with implementing the signal processing strategy outlined in the previous section:

- 1) **Measurement of local steady-state conditions:** The processing strategy requires a measurement of steady-state conditions at each point on the surface for determining the linear gain factor relating fluctuations in intensity ratio and fluctuations in surface pressure. Steady-state conditions can be acquired from time-averaged sampling of the fast-response PSP.*
- 2) **Time-varying PSP lamp emission:** In theory, $\tilde{s}_i[k]$ would be a constant (mean) intensity, but in practice, the Ames uPSP system lamps exhibit a slow decay in emitted light intensity which causes a subsequent decay in paint luminescence. We account for this by fitting a low-order polynomial (6th-degree) to the time series (least-squares fit) and evaluating it at each time point to obtain $\tilde{s}_i[k]$.
- 3) **Vibration and model motion:** Prior to testing, the cameras were calibrated with a standard checkerboard pattern to obtain camera intrinsic parameters (lens distortion coefficients and exact focal length). Then, each frame is registered to the first frame using image registration (OpenCV `transformECC` method [20, 21] solving for an affine transformation) and then the transformation is applied using bilinear interpolation (sub-pixel).
- 4) **Camera shot noise:** The topic has been covered previously in the literature, see [14, 16, 22]. To mitigate the effect of shot noise, the frames are down-sampled to lower-resolution “super-pixels” as follows:
 - 1) Apply an $N \times N$ boxcar average (for odd number N) to each frame. In the case of this study, $N = 7$, which for the 180 mm lens corresponded to a surface area similar to the cylindrical housing of nearby miniature pressure transducers
 - 2) Select every N th pixel from the filtered frame (so there are no overlapping source pixels in each super-pixel[†]). For the 180 mm lens, the source frames were 1280×800 and the super-pixel frames were 183×115 ; for the 35 mm lens, the source frames were 1280×400 and the super-pixel frames were 183×58

V. Results and Discussion

We first define several coordinate systems used in the analysis process. Then, we present a brief validation of the uPSP data using collocated pressure transducers. Finally, we present an analysis of the 35 mm and 180 mm lens uPSP datasets and discuss the results.

A. Coordinate System Definitions

The majority of the results in this report make use of a spatial projection to map the 3D surface of the SLS Block 1B Crew configuration wind tunnel model into a 2D coordinate system aligned with the streamwise- and spanwise-directions of the tunnel free-stream flow. All test conditions are at $\alpha = \beta = 0$ so the free-stream flow aligns with the rocket centerline.

*Previous work at NASA Ames relied on a separate data acquisition system of eight Photometrics® CoolSNAP K4 cameras and associated processing hardware and software, originally developed at the Air Force’s Arnold Engineering Development Complex [18]. Most recently, NASA Ames has developed a new method of operating the high-speed camera system for providing comparable data sufficient for calibration of unsteady data (see companion paper [19])

[†]Note: some overlap is unavoidable due to the frame registration process that uses bilinear interpolation, however, the effect is minimal compared to the boxcar average size.

The SLS vehicle coordinate system is documented in Ref. [23] and reproduced for convenience in Figure 5. Data in this paper are presented in an “unwrapped” cylindrical coordinate system where each 3D surface point $(X_{SLS}, Y_{SLS}, Z_{SLS})$ in the SLS coordinate system is mapped to (X_1, X_3) where $X_1 = X_{SLS} - X_o$ and $X_3 = R\Theta$. X_o is a reference position on the surface of the Orion Service Module fairing; $R = \sqrt{Y_{SLS}^2 + Z_{SLS}^2}$ is the local rocket radius; and Θ is an angle starting from the $-Z_{SLS}$ axis and right-handed relative to X_{SLS} and X_1 . The surface coordinate system is established so that $(X_1, X_3) = (0, 0)$ corresponds with a point near the horizontal centerline of the field of view of the camera equipped with the 180 mm lens (at nominal model position, the $+Z_{SLS}$ -axis was aligned with the opposite sidewall to the one containing the camera). In this report, X_1 , X_3 , and other surface coordinates are reported normalized relative to the Service Module fairing outer diameter, D . The (X_1, X_3) system simplifies spatial analysis so that for any surface point, we can establish a local stream-wise/span-wise coordinate system (ξ_1, ξ_3) where the values for ξ_1 and ξ_3 correspond with straight-line displacements in X_1 and X_3 , respectively.

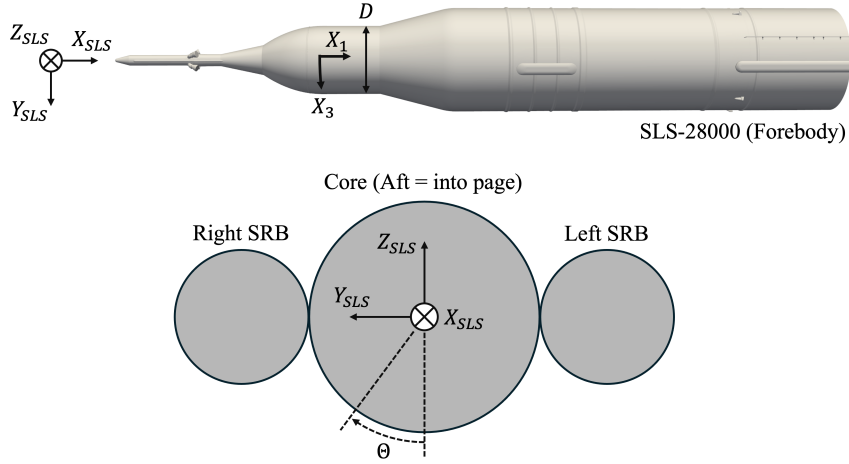


Fig. 5 Space Launch System (SLS) coordinate system and relation to projected surface coordinates (X_1, X_3) used in this report. Surface coordinates originate at a point on the surface of the Orion Service Module fairing and are normalized by its diameter, D .

B. Side-by-side of 35 mm and 180 mm uPSP data

Figure 6 compares the intensity ratio variance measured by the sidewall camera when equipped with 35 mm and 180 mm lenses. The 180 mm lens provides a significantly higher resolution view of the spatial details of the signal variance, for example, resolving the FSP under the shock foot near $X = 45$ to its true width, about a third the extent reported by the 35 mm data. Circular dots of higher signal variance in the 180 mm data correspond to known, unpainted areas around pressure transducers and 3D registration targets—interpolation over these artifacts is not yet completed for the 3D projection strategy used here (see Section IV.A) so they were manually noted and avoided during data analysis.

C. Validation with Collocated Pressure Transducers

Figure 7 compares 180 mm uPSP coherence data with measurements from nearby pressure transducers (PTs). Results are shown for four test conditions ($M = 1.0, 1.1, 1.2, 1.3$, $\alpha = \beta = 0$). We refer to the upstream location as ‘0’ and the downstream transducer as ‘1’. One super-pixel ($N = 7$) was chosen nearby each transducer and the pairwise discrete cross-spectral density, Γ_{01} (complex-valued), was computed. Then, the discrete coherence function γ_{01} and cross-spectral phase φ_{01} were plotted. The uPSP and transducer time series were not time-synchronized, but they were collected at the same sample rate (10 kHz) and consist of the same number of samples. Both were processed using a Welch-like method from the Python `scipy.signal` package[‡]. The window size must be a minimum size to ensure sufficient overlap in signal content that is convected downstream; we refer the reader to Palumbo [24] for a more comprehensive discussion. Overall, the plots show PSP coherence and cross-spectral phase matches the PT data with

[‡]`scipy.signal.csd`, with series consisting of 29,696 time samples, Hann window, `nperseg=512`, `noverlap=256`

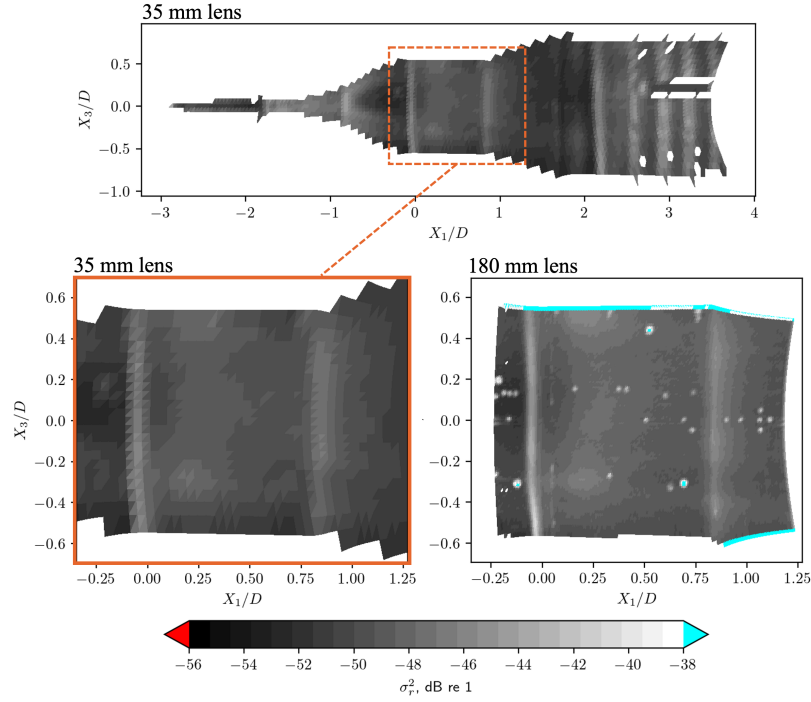


Fig. 6 Comparison of measured intensity ratio variance between sidewall camera equipped with 35 mm (left) vs 180 mm (right) lenses. The variance is computed for each super-pixel time series, projected onto the 3D wind tunnel model, and then displayed in an “unwrapped” cylindrical coordinate system.

some divergence at higher frequencies (>4 kHz).

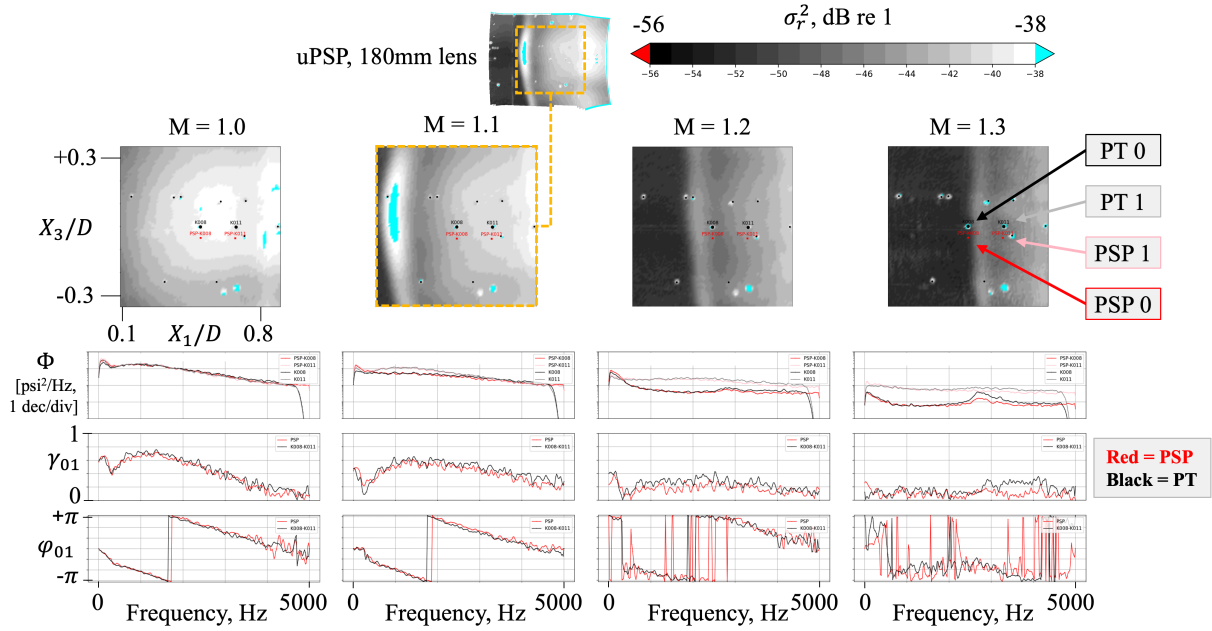


Fig. 7 Validation of uPSP-reported longitudinal coherence with nearby pressure transducers (PTs).

D. Convection Velocity Measurements

A common method of summarizing turbulent boundary layer behavior for engineering analysis uses Taylor’s “frozen turbulence” hypothesis [25]. Taylor posited that turbulent flow over a surface point can be modeled as a fixed spatial pattern moving downstream at a constant “convection velocity”, denoted here as u_c . Fast-response PSP provides a unique opportunity to validate this hypothesis and to understand its limitations. There are several methods for estimating u_c ; the one we use here treats the uPSP data as a dense grid of wall pressure sensors and derives u_c from the cross-spectral phase between upstream- and downstream- grid point pairs. The convection velocity can be estimated as $u_c = -2\pi f \xi / \varphi$ where ξ is the displacement from the upstream position to the downstream position, and the negative sign adopts the convention that $+u_c$ corresponds to downstream convection.[§]

Figures 8 and 9 show the relationship between u_c and the cross-spectral phase at a position approximately 1-inch downstream of the shock established on the service module at $M = 1.2$. Estimation of u_c at larger stream-wise displacements is complicated by rollover of the phase at $-\pi$ and $+\pi$. Results are improved with robust phase unwrapping strategies—in comparison to individual pairs of point sensors such as pressure transducers which provide 1-D cross-spectral phase signals, spatially-dense uPSP data covers the 2-D $\xi - f$ domain and benefits from significantly more robust 2-D phase unwrapping techniques. Here, we show results leveraging the Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping (SNAPHU) [26], an algorithm developed primarily for unwrapping interferograms from Synthetic Aperture Radar (SAR). SNAPHU is a maximum a posteriori (MAP) estimation technique that can leverage the measured signal coherence γ , resulting in better performance than naive phase unwrapping based solely on 2π jump detections. In Figure 9, u_c is estimated from φ using 29 uPSP grid points along a downstream line of $(X_1/D, X_3/D) = (0.58, 0)$. Samples from the red, rectangular regions in the φ plot are highlighted in red in the corresponding u_c plot, along with their mean value vs. frequency. In the highlighted frequency region, u_c appears mostly constant, but slightly increasing, with frequency. At lower frequencies (less than 1000 Hz), there is variation with choice of ξ but some trend exists showing decreasing u_c with decreasing f , consistent with the literature (for example, see measurements made by LeClerc [27]).

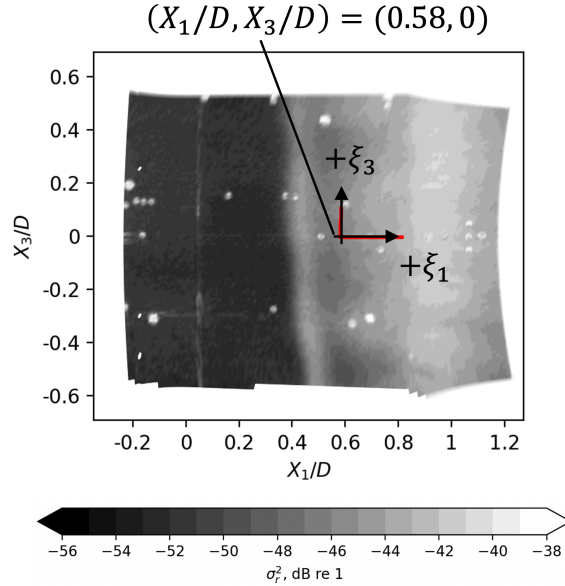


Fig. 8 Surface location and local coordinate system for convection velocity estimates in Figure 9. Grayscale map corresponds to intensity ratio variance for test condition $M = 1.2$, $\alpha = \beta = 0$.

Figure 10 shows the unwrapped cross-spectral phase and mean convection velocity estimate for three surface locations at $M = 1.1$. In the two downstream positions, a mean convection velocity normalized to the free-stream velocity, u_∞ , is measured between 0.83 and 0.89. In general, u_c tends to slowly increase with frequency and is insensitive to the value of ξ_1 . The upstream point illustrates the challenges of fitting the simplified flow model to behavior at a

[§]The downstream signal lags the upstream signal, producing, in general, negative values of φ .

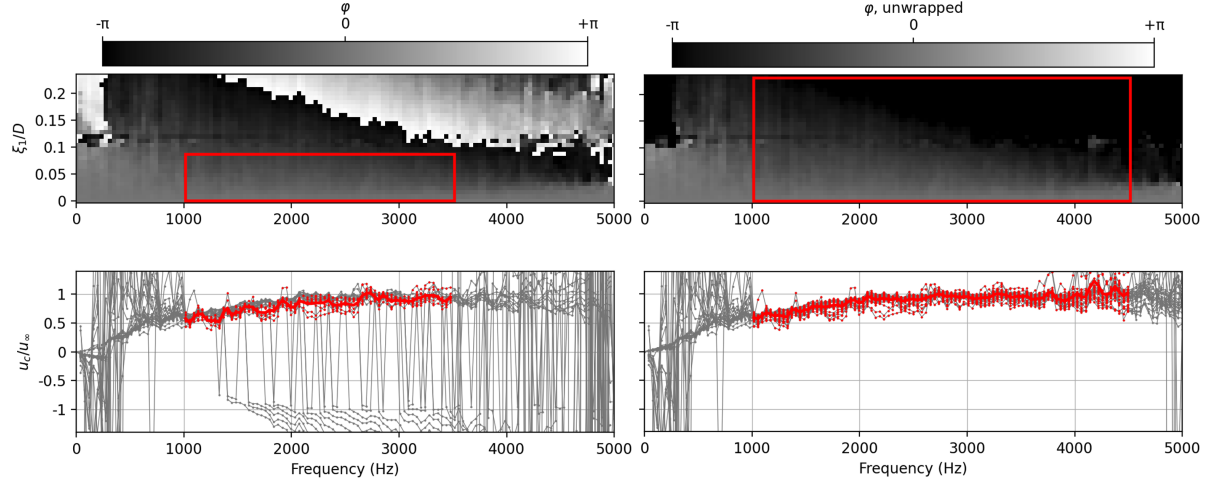


Fig. 9 Convection velocity estimate using cross-spectral phase at location shown in Figure 8. 29 downstream uPSP grid points are used. Right-hand plot shows results of robust 2-D phase unwrapping with SNAPHU.

location where a shock foot meets the boundary layer—no clear mean convection is observable using this analysis technique.

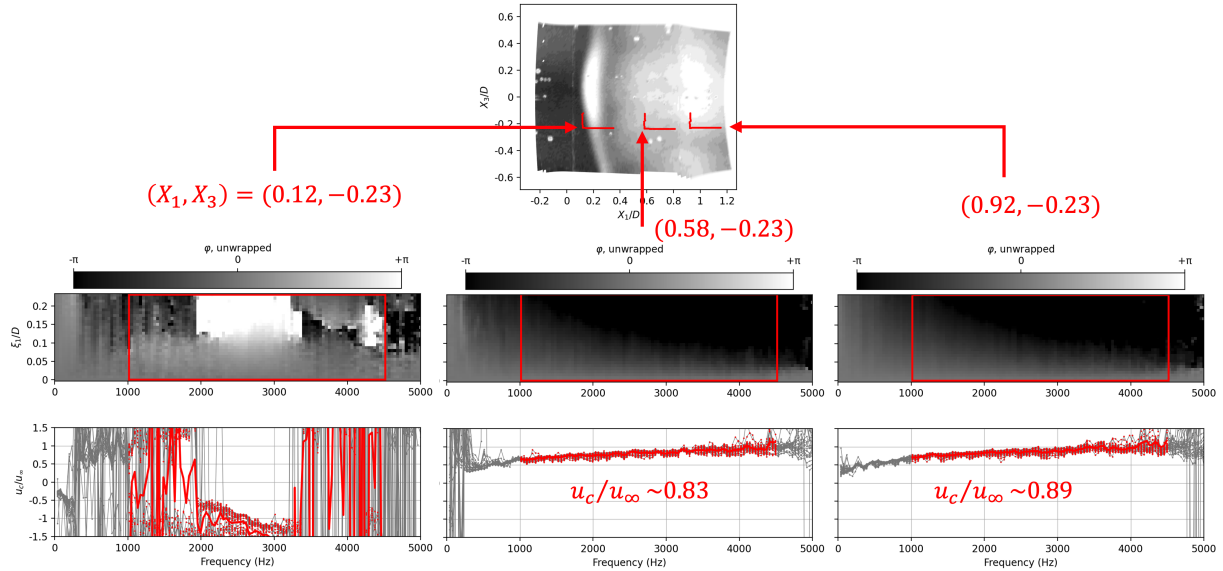


Fig. 10 Convection velocity estimate using cross-spectral phase at three locations for test condition $M = 1.1$.

E. Spatially-dense fit to Corcos Model

Corcos [10] proposed a simplified model for the wall pressure cross-spectral density function as a separable function in the stream-wise and span-wise directions as follows:

$$\Gamma(\xi_1, \xi_3, \omega) = \Phi(\omega) A(\xi_1 \omega / u_c) B(\xi_3 \omega / u_c) e^{i \omega \xi_1 u_c} \quad (4)$$

$$A(\xi_1 \omega / u_c) = e^{-c_1 |(\omega \xi_1 / u_c)|}, \quad B(\xi_3 \omega / u_c) = e^{-c_3 |(\omega \xi_3 / u_c)|} \quad (5)$$

The original intent of the model was to produce corrections to wall pressure spectra reported by finite-size pressure transducers that exhibit some loss in measured power due to decorrelation of the flow over the sensor response surface. However, it has since proven useful as a simplified model for engineering design and analysis.

Corcos originally posited that u_c was primarily a function of frequency and invariant with the separation vector (ξ_1, ξ_3) ; this assumption is validated by the results shown in the previous section (see Figure 9).

Using the same data as was used to estimate $u_c(f)$ in Figure 9, we can estimate the stream-wise and span-wise decay coefficients (c_1 and c_3 , respectively) by fitting exponential functions to $\gamma_1(\omega\xi_1/u_c)$ and $\gamma_3(\omega\xi_3/u_c)$. The results are shown in Figure 11. The left-hand plots show the coherence function distribution at each value of spatial displacement; the right-hand plots show the collapse of the data onto a single curve when plotted against $\omega\xi_1/u_c$ and $\omega\xi_3/u_c$. As expected, the stream-wise decay is slower than the span-wise decay. The results are slightly higher decay rates than Blake [28] who quotes $c_1 = 0.116$ for smooth walls, $c_1 = 0.3$ for rough walls, and $c_3 = 0.7$ for smooth and rough walls.

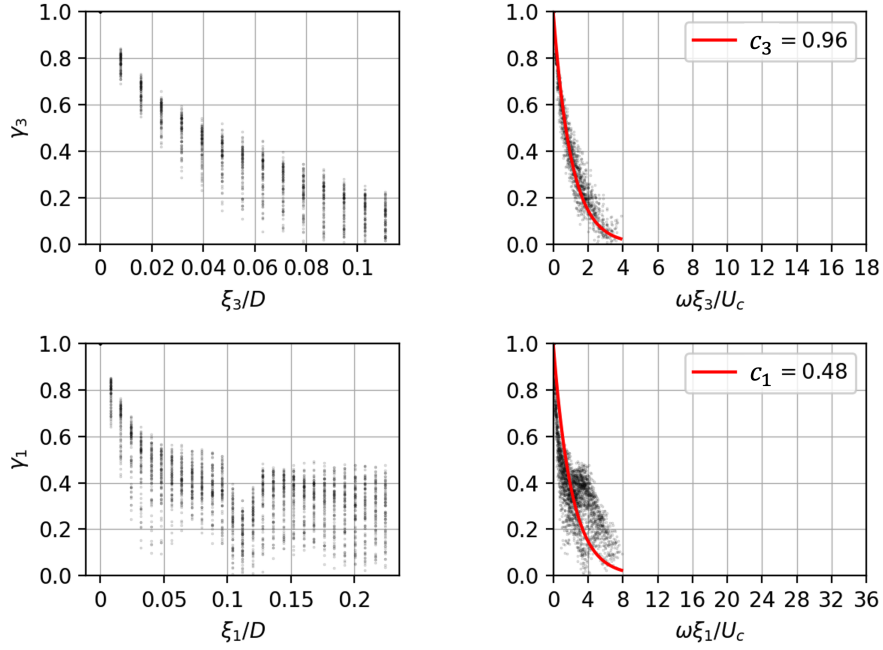


Fig. 11 Corcos decay coefficient estimates using coherence function samples at location shown in Figure 8. 29 downstream uPSP grid points are used. Left-hand plots show distribution of coherence samples at all frequencies, ranging over ξ_1/D and ξ_3/D ; right-hand plots show same samples collapsed to non-dimensional similarity variables $\omega\xi_1/u_c$ and $\omega\xi_3/u_c$.

We now extend the technique shown in Figure 11 to each point on the uPSP grid in a rectangular subregion of the 180 mm lens field of view. The results are shown in Figure 12. Note that the quality of fit of the Corcos exponential decay model is not shown, and the domain has been limited to a region that avoids artifacts of sampling “off the edge” of the uPSP camera coverage area. We make several observations:

- u_c/u_∞ generally increases with increasing Mach number
- u_c/u_∞ is not resolved by the uPSP data upstream of the shock on the Orion SM (evidenced by dark red/speckled areas on the left side of $M = 1.2$ and $M = 1.3$ plots). These areas correspond to where c_1 and c_3 take on unrealistic values much larger than one.
- Both stream-wise and span-wise decay coefficients vary significantly in the span-wise direction at most Mach numbers. In particular, the “diamond” pattern in c_3 at $M = 1.3$. A hypothesis for this behavior is disturbances due to the Orion launch abort nozzles which are further upstream.

VI. Conclusion

Recent uPSP data collected in April 2024 at the ARC TWT on a scale model of the SLS Block 1B vehicle demonstrated unprecedented spatial resolution of the fluctuating surface pressure under a transonic turbulent boundary

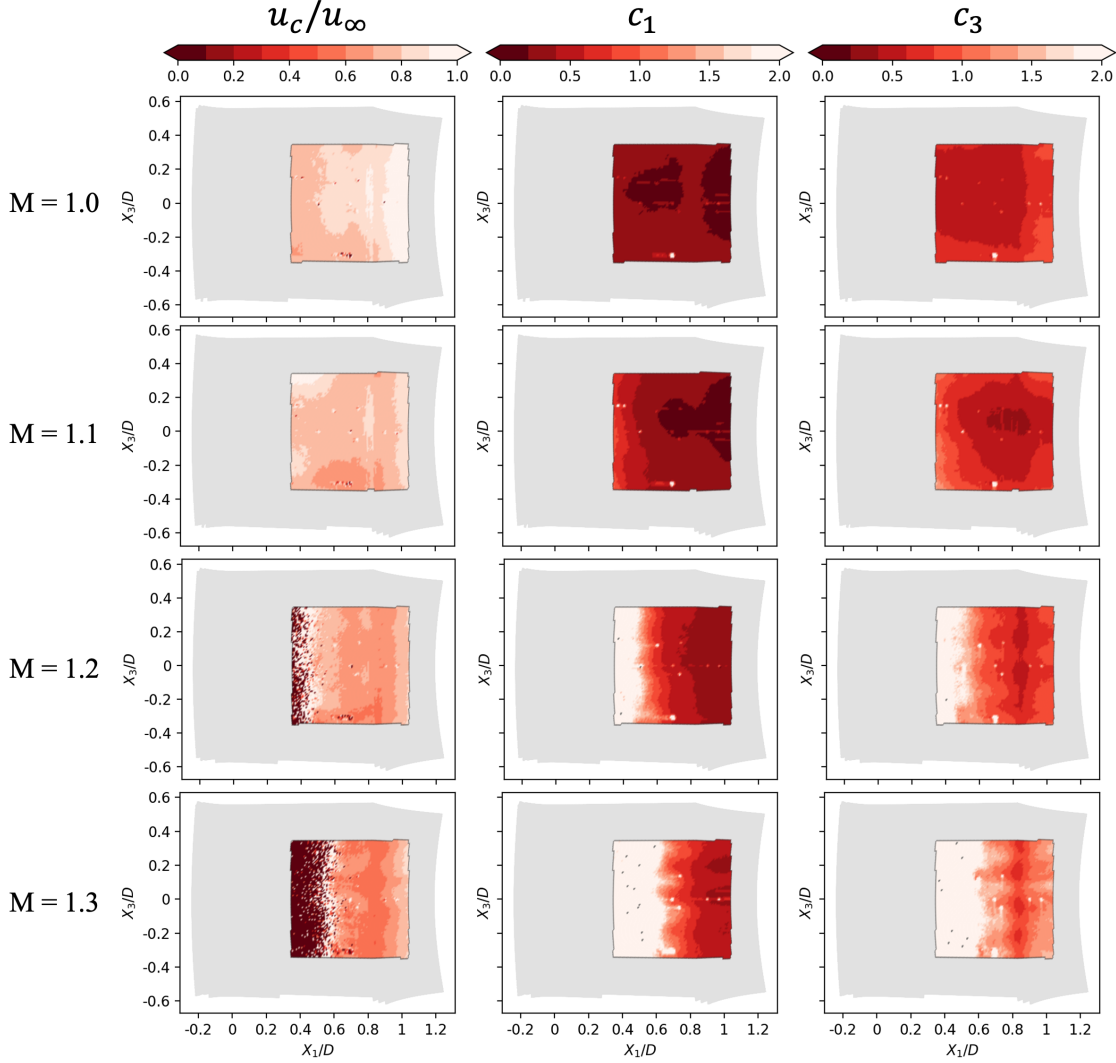


Fig. 12 Corcos model parameters (convection velocity u_c , stream-wise decay coefficient c_1 ; span-wise decay coefficient c_3) for $M = 1.0, 1.1, 1.2, 1.3$ and a dense, rectangular subregion of the 180 mm lens field of view.

layer by installation of a 180 mm lens for a portion of the test event. The data were processed into non-dimensional spatio-temporal statistics—without relying on calibration to exact physical pressure amplitude—that enabled determination of first-order Corcos model coefficients across a broad area of the scale model on and around the Orion service module. After validating against collocated pressure transducers, the data confirm Corcos’ original hypothesis that the convection velocity is independent of stream-wise separation; however, it is clearly dependent on frequency. Determination of the convection velocity using uPSP data is shown to be more robust than pairs of point sensors because a linear array of uPSP grid points provides an additional dimension to the cross-spectral phase signal and can leverage 2-D phase unwrapping techniques matured in related signal processing disciplines. Finally, the Corcos model coefficients computed across the entire surface were shown to vary significantly, indicating that uPSP data provide a higher fidelity solution for characterizing the flow in comparison to strategically-placed pressure transducers.

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