

# NASA's Unsteady Pressure-Sensitive Paint Phase I Development Overview

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Since 2019, a group out of NASA Ames Research Center (ARC) has been focused on implementing systematic updates to make unsteady pressure-sensitive paint (uPSP) a more viable capability for production wind tunnel testing. Focusing on the general categories of data acquisition, data transfer, data processing, and data visualization, the uPSP Development Team has made several improvements to increase data quality and innovate a more workable system that would provide valuable surface pressure data to customers. As a result of the COVID-19 pandemic and several initial demonstration tests prior to the formal start of the development effort, the decision was made to focus on launch vehicles as the test article. To-date this development has focused on implementation in the ARC Unitary Plan Wind Tunnel 11-by 11-foot Transonic Wind Tunnel due to the large optical access of the test section and that the NASA Advanced Supercomputer is located at ARC. This paper summarizes the project origins and the results of four years of development effort, which will all culminate in a final demonstration test in the first half of 2024.

## Notice to Readers

Certain features and characteristics of the Space Launch System (SLS) vehicle are defined by the U.S. Government as Export-Controlled, Controlled Unclassified Information (CUI). To comply with CUI restrictions, values in some plots and figures have been either removed or normalized to arbitrary values. It is the opinion of the authors that these alternations do not detract from the relevant technical discussions.

## I. Introduction

Starting in October 2019 (fiscal year [FY] 2020), a concentrated effort at NASA Ames Research Center (ARC) began to make unsteady Pressure-Sensitive Paint (uPSP) a turnkey capability at NASA facilities. This effort is sponsored by the Aerosciences Evaluation Test Capability (AETC) Portfolio Office under the Aeronautics Research Mission Directorate (ARM) within NASA as the uPSP Test Technology Capability Challenge. AETC oversees many of the large ground test facilities across NASA. Scaling up uPSP to be compatible with production wind tunnels involves redesign of data acquisition, data transfer, data storage, data processing, and data visualization. From October 2019 – September 2023, the uPSP Development Team at ARC worked to meet this challenge. AETC's goals are to provide the tools to deliver the technology innovations and breakthroughs necessary to address increasingly complex research and development challenges in wind tunnel testing facilities at NASA. Prior to the formal start of the capability challenge, two demonstrations of the uPSP system at the NASA Ames Unitary Plan Wind Tunnel (UPWT) 11-by 11-ft Transonic Wind Tunnel (TWT) using two different NASA Space Launch System (SLS) models were performed. In 2017, the first multi-camera test was conducted during SLS's Ascent Unsteady Aerodynamics Test

(AUAT)<sup>[1]-[3]</sup> and in 2019, SLS’s Ascent Transient Aerodynamics Test (ATAT)<sup>[4],[5]</sup> was conducted. The close collaboration with the SLS program resulted in these two “piggyback” tests to demonstrate the improvements to the uPSP system, while traditional dynamic pressure transducers were the primary diagnostic acquiring surface pressure measurements.

Phase I of the uPSP Test Technology Capability Challenge will conclude with a full-system Launch Vehicle Demonstration Test (LVDT) at NASA ARC in the UPWT 11-by 11-ft TWT, currently scheduled for the first half of 2024. To date, the primary focus of the system development has been on launch vehicles, and this test will consist of a generic launch vehicle. This will be the first time several updated and integrated components of the overall system will be in place and tested. For example, eight high-speed cameras will be used to acquire the data. In the 2019 SLS ATAT demonstration test, Project: Red Rover<sup>[1],[6]</sup> was implemented as a connection between the UPWT and a high-performance computational facility, the NASA Advanced Supercomputing Division (NAS), also located at NASA ARC. This Red Rover pipeline has been improved and this future demonstration will include the transfer, processing, and visualization of the data in near-real time. Finally, the processing software will be run as each test data point is completed with data products available in near-real time for those with an active NAS account, or for anyone on site to visualize on a local computer or on the Hyperwall within the NAS facility<sup>1</sup>. The Hyperwall provides the display of image data over a matrix of computer monitors, allowing detailed representation of these data for three-dimensional environments. We invite the community to participate in this demonstration test by either accessing the data from the NAS from a remote location, or by travelling to Ames during the test and interacting with the system on site. The uPSP processing software is also now open source<sup>2</sup> and available for anyone to apply to their own data sets.

This paper serves as a summary and overview of Phase I of the uPSP Test Technology Capability Challenge at NASA Ames Research Center, covering obstacles, improvements, and the state of the art in uPSP as a diagnostic for production wind tunnel experiments from October 2019 (FY 2020) - December 2023 (FY 2023). It motivates the necessity of uPSP in the study of aerosciences, the challenges with leveraging the uPSP technology, and how the uPSP Development Team at NASA ARC produced a system to increase the functionality of uPSP at NASA wind tunnels. This paper also provides details about the uPSP processing software and how certain errors and corrections are implemented to increase the data quality. Finally, this paper describes future work for uPSP development, with the assumption the capability challenge will continue with a Phase II. Some additional prior technical work published by the uPSP Development Team may be found in Refs. [7]-[13].

## II. Unsteady Pressure-Sensitive Paint

Pressure-sensitive paint (PSP) has been in development in earnest at NASA since the 1990s<sup>[14],[15]</sup>, however, it has primarily focused on the steady-state acquisition as camera technology to acquire images at fast sample rates precluded the usefulness of having a fast-responding paint<sup>[16],[17]</sup>. The paint formula used for this development work was the porous, fast-response PSP purchased from Innovative Scientific Solutions Inc<sup>3</sup>. In the theme of making as much of the results of development as accessible as possible, the uPSP Development Team consistently used commercially available resources. The paint has response rates up to 20 kHz with a polymer ceramic base coat with a platinum tetra (pentafluorophenyl) porphine (PtTFPP) pressure-sensitive component that is a permeable biner with luminescent molecules that sit on top of the base coat. The absorption of 400-nm light energy by the luminophore excites the molecules so they either emit a photon or return to the ground state through oxygen quenching. Given that quenching due to oxygen competes with relaxation via emission of a photon, the resulting light intensity measurements collected by the camera at 650-nm are inversely proportional to the partial pressure of oxygen in the flow and can be converted into quantitative pressure values given a calibration curve. The calibration curves are generated through a combination of laboratory benchtop and in-situ data collection<sup>[18]</sup>. A more refined methodology for in-situ data calibration will be implemented as a part of the LVDT in Spring 2024.

## III. Project Origins

In 2013, the Department of Energy published an Advancing Scientific Knowledge Discovery Working Group report<sup>[19]</sup> emphasizing that to accelerate scientific discovery, data must be processed as quickly as it is acquired. Often this is a challenge for optical data sets due to the system complexity requiring input from other instrumentation systems and traditionally large data sets, which require human interaction for processing. The deployment of uPSP for the

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<sup>1</sup> [https://www.nas.nasa.gov/hecc/resources/viz\\_systems.html](https://www.nas.nasa.gov/hecc/resources/viz_systems.html)

<sup>2</sup> <https://github.com/nasa/upsp-processing>

<sup>3</sup> <https://innssi.com/fast-pressure-sensitive-paints/>

2017 SLS AUAT (described below) demonstrated the operational capability of the data acquisition system but also highlighted the enormous challenge large data sets would present experimental facilities. During the 2019 SLS ATAT, the operational connection between the UPWT and the NAS was demonstrated with the transfer, processing, visualization, and distribution of 150 terabytes of uPSP data in near real-time. More details on the SLS ATAT demonstration are also provided below.

Characterizing unsteady, separated flow will continue to be a focus in the advancement of aerosciences. In a 2017 Future of NASA’s Aerosciences Capability Report<sup>[20]</sup>, Schuster and D’Agnostino highlighted unsteady flows as the “performance limiting factor for many flight vehicles”. To understand unsteady aero-physics, the unsteady surface pressure must be measured. The ability to measure and compute these flows is a challenge. The future is also optical. Optical measurement technologies are being developed and employed to address challenges in astrophysics, medicine, and autonomous vehicles. In addition, cross-disciplinary teams will be needed to leverage skills to acquire and process large data sets, develop robust processing routines, and use and create open-sourced applications to share data and efficiently meet customer requirements<sup>[8]</sup>. All of this motivated the uPSP Test Technology Capability Challenge development effort, which had three primary objectives:

1. Reduce the noise floor of the system to  $\leq 128$  dB
2. Reduce processing time to  $< 24$  hours for a uPSP test conducted at ARC UPWT TWT
3. Show decrease in required Kulites by  $\sim 25\%$  in uPSP highly visible areas

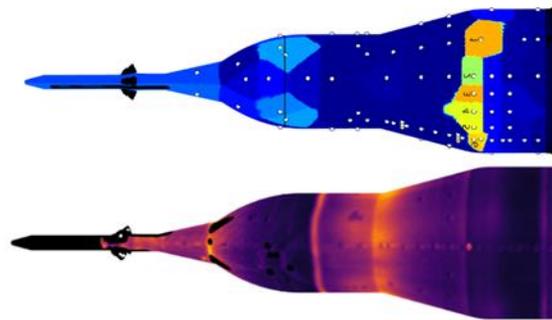
With the successful completion of the planned LVDT and post-processing of the data, the uPSP system will demonstrate that it meets all these requirements, proving the project objectives were achieved.

### A. SLS AUAT 2017 Demonstration Test

In 2017, the SLS AUAT was conducted at the NASA Ames UPWT<sup>[2]-[3]</sup>. This test served as a major launching point in evaluating the feasibility of uPSP being implemented for a production-level wind tunnel facility as a “piggyback” demonstration test. A photo of the AUAT model installed in the NASA ARC UPWT is provided in Figure 1. This test was the first time multiple high-speed cameras were used to collect uPSP data, one in each of the four sides of the test section. This test highlighted the conservative nature of traditional unsteady pressure load analysis when using pressure transducers (Kulites<sup>TM</sup>). When looking at the impact of the wake from the launch abort nozzles, for example, the pressures between each Kulite needs to be interpolated as opposed to directly measured over the entire surface in uPSP data, as shown in Figure 2.



**Figure 1.** SLS AUAT model with uPSP in the 11-by 11-ft TWT at the NASA ARC UPWT [2].

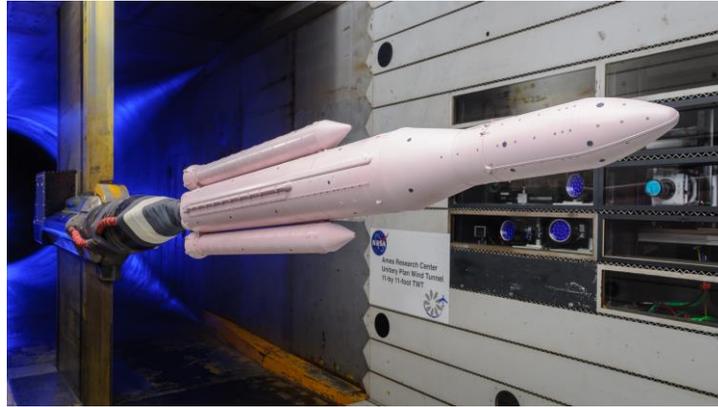


**Figure 2.** Qualitative comparison of surface pressure results between interpolating pressure between Kulites (top, Ref. [3]) and calculating directly using uPSP (bottom, Ref. [9]).

### B. SLS ATAT 2019 Demonstration Test

After the successes of SLS AUAT, a supplemental demonstration was conducted in 2019, the SLS ATAT<sup>[4],[5]</sup>, to implement lessons learned and take additional steps in the advancement of the uPSP system, including the first iteration of Project Red Rover. A photo of the ATAT model installed in the NASA ARC UPWT is provided in Figure

3. Project Red Rover leveraged the need for a management system for large uPSP data sets to foster a connection between a ground test facility, UPWT, to the NAS. This successful demonstration led to Red Rover 2.0, which is outlined in more detail in Section V. ATAT focused on aspects such as paint roughness effects<sup>[21]</sup>, noise sources and their mitigation<sup>[5]</sup>, and how to build a sustainable, production level data acquisition, processing, and storage system, which led to the uPSP Capability Challenge.



**Figure 3.** SLS ATAT model with uPSP in the 11-by 11-ft TWT at the NASA ARC UPWT.

The combination of the two SLS demonstration tests helped define the scope of work and requirements necessary to develop the uPSP system for production wind tunnel tests. This served as the last major demonstration of the technology prior to the formal effort of developing an overall system.

#### **IV. Data Acquisition and Calibration**

With the incorporation of eight high-speed cameras (Phantom v2512) as a part of the uPSP data acquisition leg of the system, and with a new process to acquire uPSP lifetime data with high-speed cameras<sup>[10]</sup>, significant upgrades have been made to the acquisition of pressure-sensitive paint data points. In addition, better camera and paint calibration procedures have been introduced that not only reduce the uncertainty of projecting the uPSP data onto a surface grid, but also allow for the calibration and incorporation of additional optical diagnostics in conjunction with uPSP data products.

Internal and external calibrations of the high-speed cameras allow for a point on the 3D model surface to be associated with a pixel on the 2D camera image. These calibrations ensure that flow features are associated with the correct physical location on the test model. Improvements have been made to the camera setup procedure using more robust calibration algorithms, operational changes to the measurement of the 3D targets, and a new internal calibration board<sup>4</sup>. These improvements have reduced noise-to-pixel error to less than 0.1 pixels while additionally reducing the test setup complexity<sup>[13]</sup>.

The incorporation of four additional cameras creates a trade-off between higher overall resolution of the model surface and better camera coverage/overlap of the model surface<sup>[22]</sup>. Analysis was performed to determine the benefits and drawbacks of different camera placement options in the UPWT so that the uPSP Development Team could make timely, informed decisions on said trade-off. There are several calibration-related updates that have been incorporated into the data acquisition and included as a part of the processing software. For example, camera-to-tunnel calibration has been accounted for and automated. The flatfield calibrations of the camera sensors to account for any non-linear or non-uniform pixel response has been included. Finally, methodologies for improving the overall focus of each camera were also developed to improve the resolution compared to prior experiments and make better use of the full range of model motion (alpha-beta angles) during a test.<sup>[22]</sup>

Future improvements that will be investigated and implemented after the planned LVDT event include using new optical filters on the high-speed cameras. Initial tests had >30% illumination on the camera sensor compared to filters purchased in 2016. This will require further development to address excess signal leakage from unwanted sources. We

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<sup>4</sup> <https://calib.io/>

also plan to improve sensor utilization. The maximum resolution of the Phantom v2512 cameras is 1280 x 800 pixels. For elongated wind tunnel models such as launch vehicles, tilting the camera to use the diagonal of the camera sensor will be evaluated as a possible option. In addition, longer focal length of the lenses used on the cameras would maximize the number of pixels used on the sensor but would require tighter tolerances on camera positioning during setup and possibly limit the range of model alpha-beta.

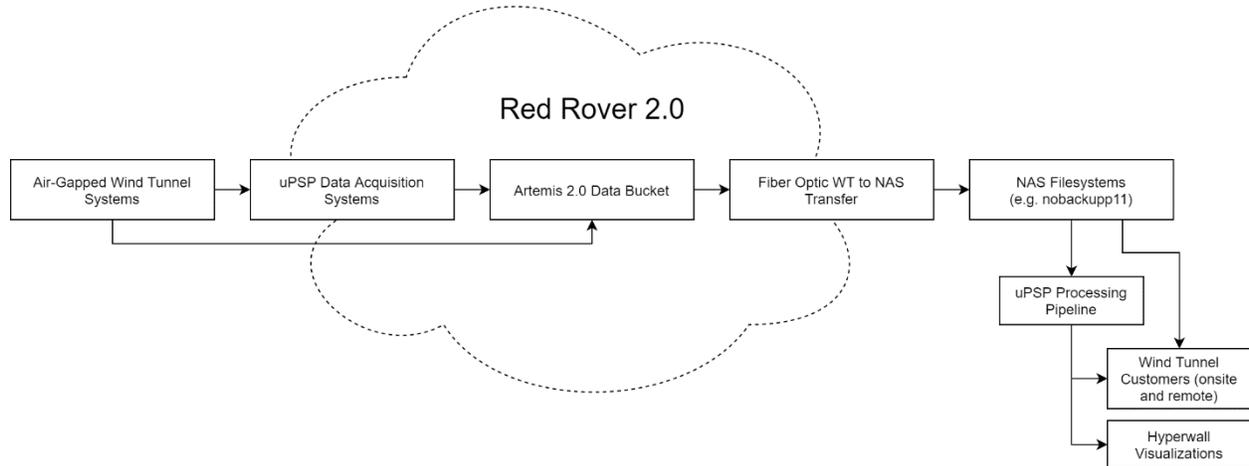
## V. Project: Red Rover

The original Red Rover project supported a proof-of-concept demonstration of near-real time processing and visualization of uPSP data for the September 2019 SLS ATAT<sup>[4],[5]</sup> wind tunnel test. The feasibility of this approach was established, and the scope of work required for a follow-on production level system was determined. Red Rover 2.0 project builds upon previous work to create a production-ready capability through additional fiberoptic cabling and data transfer procedures have been implemented to ensure an even faster and more secure data transfer from the high-speed cameras in the UPWT test section to the NAS. Among the wind tunnel data systems at the UPWT, uPSP is unique in the quantity of data that it produces and the computational processing power required. Data sets from other wind tunnel systems are typically managed by small servers located locally and easily backed up on a small number of external hard drives. This method was barely workable for earlier proof-of-concept tests and was quickly realized to not be scalable to production-level uPSP. The approach to this problem was to connect the UPWT to the NAS, which operates NASA's supercomputers, and is a few blocks down the street from the UPWT. This idea of connecting Ames' wind tunnels and supercomputers was explored in the late 90's through the DARWIN project<sup>[23]</sup>, and the uPSP project was able to reuse the fiber optic infrastructure that had already been installed. This connection is called "Red Rover", mnemonically named because it 'sends data on over'. Through this connection, the uPSP team is able to leverage the world-class supercomputing capabilities of the NAS and produce processed results as the wind tunnel test is occurring, in near-real time. Because the data is hosted on the NAS and not stored on external drives, it is also much more accessible to remote customers (by logging in to the NAS). The NAS also hosts a customer facility called the Hyperwall, which allows customers to interactively visualize data, as shown in Figure 4.



**Figure 4.** Engineers discuss the preliminary data transferred from the 11-by 11-foot TWT of the UPWT for processing at the NAS facility and visualized at the NAS Hyperwall facility in near real-time [4].

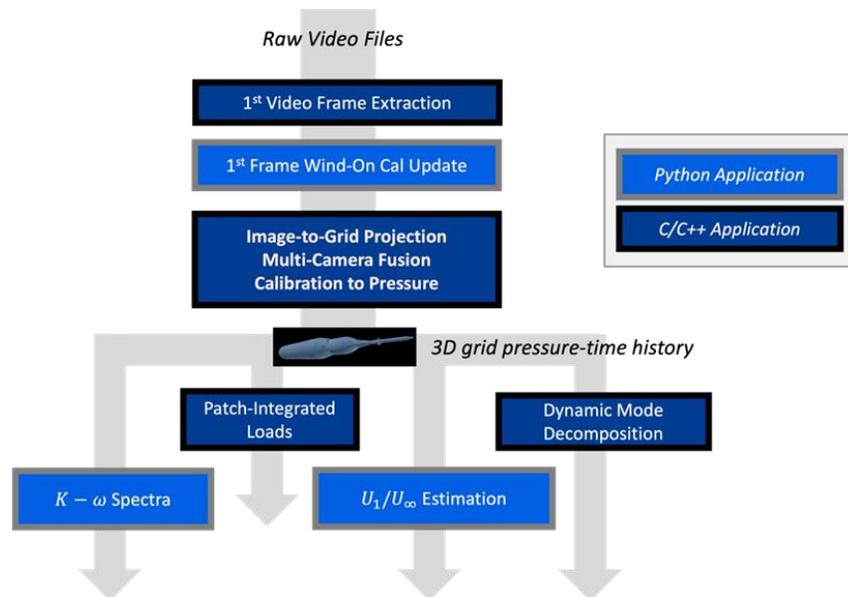
The overall data flow through the system is described in Figure 5, below. Test data from the air-gapped wind tunnel systems, including tunnel conditions and other experimental diagnostics such as shadowgraph or infrared thermography imaging, and uPSP data acquisition systems are transferred into Artemis 2.0. Artemis 2.0 is a pair of servers (like a 'bucket') connected to a Network Attached Storage system with over a petabyte of storage. The system offloads data from the high-speed cameras and acts as a buffer for transferring data to the NAS and has enough capacity to locally store all data from a typical wind tunnel test if data transfer to the NAS is unavailable or not desired. Upload to the NAS occurs over a fiber-optic connection, and data is accessed and processed using NAS user accounts. A full demonstration of Red Rover 2.0 is included in the LVDT.



**Figure 5.** Simplified schematic of how Red Rover 2.0 connects the wind tunnel systems to the NAS.

## VI. uPSP Data Processing Software

In January of 2023, the uPSP Data Processing Software was released to the general public under the NASA Open-Source Agreement Version 1.3 (<https://github.com/nasa/upsp-processing>). The software, in development since 2015<sup>[24]</sup>, has enabled uPSP technology to operate in a production wind tunnel environment and efficiently incorporates necessary data acquisition improvements, such as camera calibration routines described above. The latest software comprises a suite of mixed Python/C++ applications that operate on raw, high-speed video to produce surface pressure time series useful for engineering analysis. The data flow is outlined in Figure 6. The highest-fidelity output is the measured fluctuating surface pressure at each point on a 3D surface grid model of the wind tunnel test subject, which can then be post-processed into more useful engineering data such as surface patch time series and dominant surface pressure spectral modes. The software accounts for small frame-to-frame motion of the test subject and is most suited for rigid-body test models. Active development effort is focused on upgrades to support deformation test models (such as aircraft wings), enhanced signal processing for measurement noise suppression, and tailored data products to fit end-user engineering workflows.

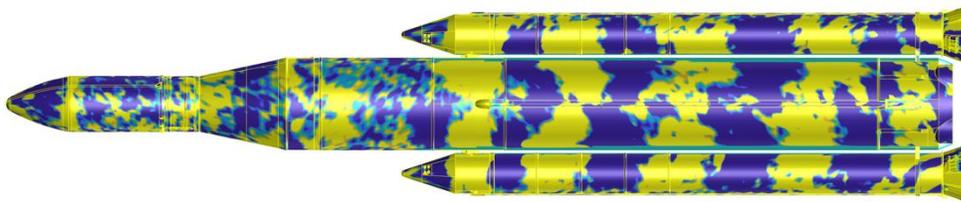


**Figure 6.** Functional data flow implementation by the NASA uPSP Data Processing Software, available for public use at: <https://github.com/nasa/upsp-processing>.

## VII. Data Products and Visualization

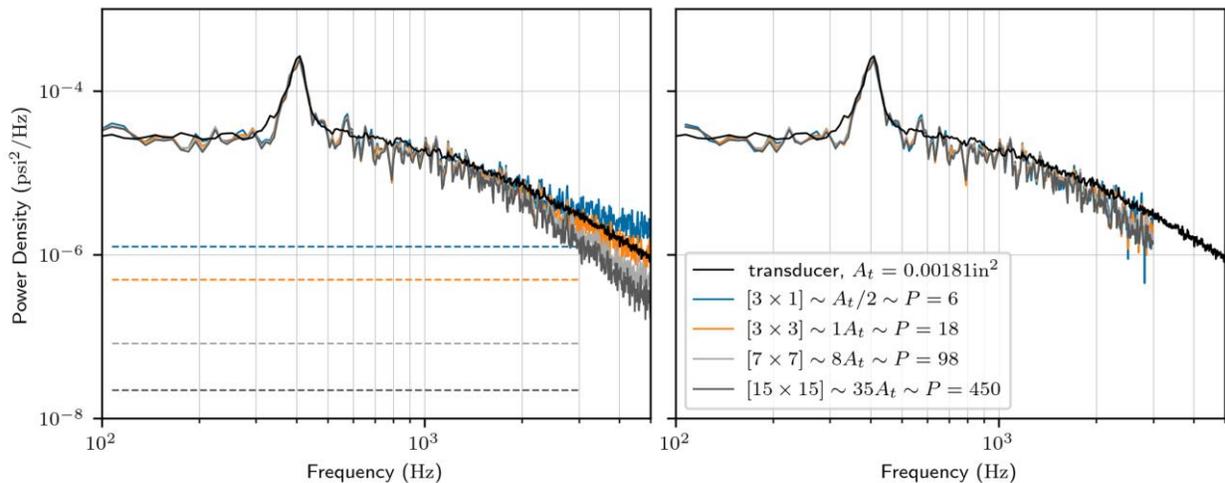
The most basic output from the processing software is the pressure-time-history on the model surface grid. However, this data product is often not useful in and of itself when considering the aero and vibro-acoustic analysis possibilities of high spatio-temporal surface pressure data.

The reader is directed to Ref. [8] for a more detailed discussion of some of the outputs and visualization tools, but some highlights are provided here. For example, dynamic mode decomposition (DMD) has been used to analyze aeroacoustics associated with the two SLS demonstration tests that heavily relied on the visualization aspects this technique provides.<sup>[7],[25]</sup> DMD was used to further investigate the vortex shedding tone generated by the forward attachment of the solid rocket boosters (SRBs) to estimate the shedding frequency, the wavelengths, and propagation speeds. DMD also verified the propagation direction, proving that one component of the aeroacoustics is moving upstream. Figure 7 shows the real component of the DMD mode from the uPSP data collected at a subsonic Mach number from the SLS ATAT at the vortex shedding frequency.<sup>[25]</sup>



**Figure 7.** Visualization of the DMD real mode of uPSP in a subsonic test condition from the SLS ATAT test [25].

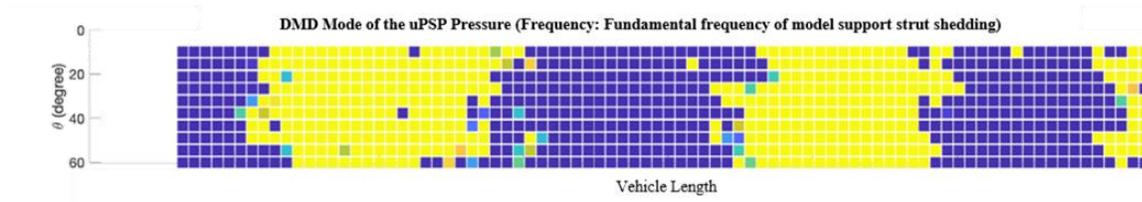
Knowing that Kulite pressure transducers are the industry standard in measuring unsteady surface pressure, simple point-source comparisons are available using a refined uPSP-Kulite method as outline in Ref. [9] and shown in Figure 8. Recognizing that uPSP is not well-suited for point-source measurements, an improved method to reduce the noise in the uPSP data to allow for better comparisons to Kulites was developed.



**Figure 8.** Power spectral density estimated from an area-averaged virtual transducer (uPSP data) signal before (left) and after (right) noise correction for comparisons to a pressure transducer [9].

The uPSP may also be used as a wind tunnel diagnostic tool after shot noise and local aerodynamic flow features are attenuated. Previous acoustic surveys at the NASA ARC UPWT<sup>[26]</sup> have been documented, with a comprehensive characterization of transonic and supersonic conditions of the facility. Characterization studies occur periodically to ensure consistency and track down the source of some phenomena that remain unknown. The uPSP technology may

be used as a complementary acoustic survey to evaluate tunnel acoustics. In Figure 9, a discrete Fourier transform (DFT)-based dynamic mode decomposition (DMD) of a small region of pixels highlights a known tunnel tone that moves upstream the test model.

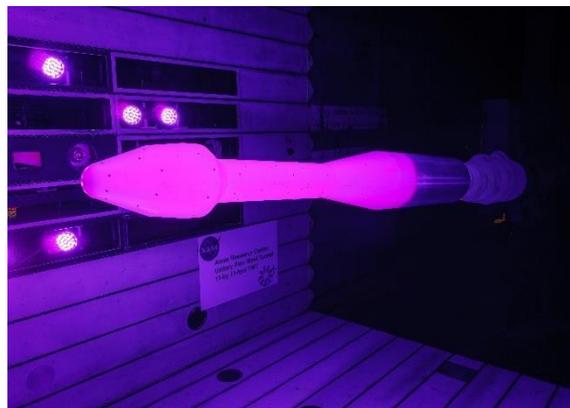


**Figure 9.** Dynamic mode decomposition of a wind tunnel tone in the uPSP data [8].

### VIII. Conclusion & Future Work

For the past four years, the uPSP Development Team at NASA Ames Research Center has worked to make unsteady pressure-sensitive paint (uPSP) technology a turnkey capability that is accessible to production-level wind tunnel facilities at NASA. As a by-product of this effort, an open-source processing code has been released that is not limited by the uPSP formula or facility the data is acquired. The final demonstration of the Phase I development effort will occur in Spring 2024 in the Ames Unitary Plan Wind Tunnel 11-by 11-ft Transonic Wind Tunnel as a Launch Vehicle Demonstration Test (LVDT) that highlights each of the components of the system outlined in this work.

The LVDT will use a test model previously used in 2015<sup>[27]</sup> as a part of the series of uPSP demonstrations at NASA Ames that was designed to generate buffet loads around a hammerhead payload nose based on a launch vehicle designed by Charles Coe<sup>[28]</sup>. An image from that test is provided in Figure 10. With all the system development since previous demonstration tests, the operational capability will be a key factor of LVDT in addition to the technical and data quality improvements highlighted in this work. For example, given that PSP is applied after the model is fully installed on the support strut, any model changes that need to occur will damage the paint surface, this test seeks to find ways to minimize that damage. To streamline this and establish the proper procedure to ensure continued high data quality with any configuration changes during testing, a new ogive nose to replace the existing hammerhead nose will also be tested. Furthermore, to highlight the greater versatility additional high-speed cameras provide, an optics change where two cameras on the same test section sidewall will occur to magnify (thus increasing the resolution) on a smaller region of the model. This test will also be the first production-scale test of the high-speed lifetime methodology where steady-state PSP data is collected using the unsteady paint formula and the high-speed cameras as a follow on from Ref. [10]. Simultaneous shadowgraph and infrared (IR) thermography imaging will be conducted to integrate already turnkey capabilities at the UPWT into the uPSP analysis. Finally, this model in both its configurations is completely open-source and it is our aim to share as much as the data as possible with the wider community to foster continued and new collaboration in using uPSP for wind tunnel testing.



**Figure 10.** Image of Coe model with hammerhead nose installed in ARC UPWT 11-by 11-ft TWT in 2015 [27].

There is the intention for a Phase II of development, which will focus on the greater integration of data products and visualization into the open-source version of the processing software, integration of additional data collection systems (such as shadowgraph and IR thermography<sup>[12]</sup> as described with LVDT), and transition to deployment at other NASA wind tunnels other than the ARC UPWT. Future use of the system will also leverage cloud computing and visualization tools in conjunction with parallel AETC efforts. Finally, future work will account for those added complexities of testing aircraft in wind tunnels that were of little concern when evaluating launch vehicles.

### Acknowledgments

This work was funded by the NASA Aeronautics Research Mission Directorate's (ARMD) Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office. A special thank you to NASA's Space Launch System (SLS) program and the Multi-Purpose Crew Vehicle (MPVC) program for the time and interaction to pursue technical excellence and improve data quality. Thank you to the staff at NASA Ames Research Center's Fluid Mechanics Lab (FML) for support of small-scale testing to develop the uPSP technology. Thank you to NASA Ames Research Center's Tech Transfer Office to enable the ability to open-source the uPSP software. Thank you to the key collaborators at the NASA Ames Research Center's Wind Tunnel Division (Code AO) and NASA Advanced Supercomputing Division (Code TN) whose cross-discipline expertise demonstrates the future of Aerosciences. Lastly, the authors would like to thank the contributions from several key individuals over the past four years: Alan Landmann & Jaffar Iqbal from The Boeing Company; Paul Bremner from AeroHydroPLUS; James Ross, and Ted Garbeff III from NASA Ames; Thomas Steva, Bruce LaVerde, and John Blevins from NASA Marshall Space Flight Center; and Ron Colantonio, Stephen Helland, David Stark, Lori Arnett, and Erik Lopez from NASA AETC.

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