NASA's Unsteady Pressure-Sensitive Paint Research and Operational Capability Developments

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To address challenges in the field of unsteady aerodynamics, NASA has developed a new state-of-the-art capability called Unsteady Pressure-Sensitive Paint (uPSP). It has been developed as an operational surface-pressure measurement capability for deployment in NASA's AETC ground test facilities. Offering unprecedented spatiotemporal resolution, uPSP is an extremely powerful tool for investigating unsteady separated flows. To accelerate scientific discovery, uPSP data is to be processed and distributed as rapidly as it is acquired. Several demonstrations of the technology collected valuable data that has been used to develop data products, a robust processing pipeline, and other computational capabilities. A collection of papers documents the most recent research and development work on the uPSP technology and capability. This paper summarizes the current state of this effort at NASA.

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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

In the last three years, several advancements have been made to produce a new state-of-the-art capability in the field of aerosciences. NASA's Aerosciences Evaluations and Test Capabilities (AETC) Portfolio Office has funded a multi-year project to mature unsteady Pressure-Sensitive Paint (uPSP) technology into an operational capability in key ground test facilities at NASA. The research and development have primarily been conducted at NASA Ames Research Center's (ARC) Unitary Plan Wind Tunnel (UPWT) 11-by 11-ft Transonic Wind Tunnel (TWT), as well as several small-scale development tests[1] at NASA ARC's Fluid Mechanics Lab. The NASA ARC UPWT is one of the ground test facilities under NASA AETC's Portfolio Office. AETC's goals are to provide the tools to deliver the technology innovations and breakthroughs necessary to address increasingly complex research and development challenges. AETC's integrated approach will consider the complementary high-end computing capabilities necessary to advance analysis in conjunction with ground experimental capabilities.

Before the multi-year project was funded, two increasingly sophisticated demonstrations of the uPSP technology were conducted through close collaboration with NASA's Space Launch System (SLS) Program. In 2017, the first multi-camera demonstration was conducted during SLS's Ascent Unsteady Aerodynamics Test (AUAT)[2,3] and in 2019, SLS's Ascent Transient Aerodynamics Test (ATAT)[4,5] was conducted. For both tests, the uPSP technology was a "piggyback" effort and traditional unsteady pressure transducers were the primary sensor used to collect time-resolved pressure measurements.

Over the past three years, the research and development has focused on two key areas: 1) developing accurate data and data products and 2) producing a robust, modifiable, maintainable processing pipeline to produce a turn-key capability for AETC's ground test facilities.

This paper is one of five in a special session, cross-listed across the AIAA Aerodynamic Measurement Technology (AMT), Ground Testing (GT), and Structural Dynamics (SD) Technical Committees, dedicated to the development of the uPSP technology. The session is intended to serve as an overall update for the project and to link the bodies of work together[6,7,8,9, 10].

II. Methodology

A key motivator for the uPSP research and development was the Department of Energy's 2013 Advancing Scientific Knowledge Discovery (ASKD) Working Group report[11], which highlighted 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 2017 SLS AUAT demonstrated the operational capability of the data acquisition system but also highlighted the enormous challenge large data sets would present experimental facilities, like the ARC UPWT. The deployment of uPSP for the 2019 SLS ATAT demonstrated an operational data "pipeline", called Project: Red Rover[4, 12], which connected the ground test facility (ARC UPWT) to a high-performance computational facility (the NASA Advanced Supercomputing Division [NAS]), also located at NASA Ames Research Center. A key piece of this demonstration was the transfer, processing, visualization, and distribution of 150 Terabytes (TBs) of uPSP data in near real-time. Future uPSP demonstrations will leverage the Red Rover data pipeline to accelerate scientific discovery. There are several points to keep in mind as we move forward in the broad field of aerosciences.

The future of aerosciences will continue to explore unsteady, separated flow. In the 2017 Future of NASA's Aerosciences Capability Report[13], Schuster and D'Agostino 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. To enable Space Economy 2.0 and achieve the bold vision of next-gen aviation, advanced, time-resolved measurement technology will be needed.

The future is optical. Like many other sciences, the frontier of discovery is based on the complex evolution of phenomena in space and time[14]. Optical measurement technologies are being developed and employed to address these challenges in astrophysics, medicine, and autonomous vehicles.

Lastly, the future is cross-disciplinary. As data sets volumes continue to increase in size and capability of answering challenging questions, teams will need to be ever-more cross-disciplinary to leverage skill sets that acquire and process large data sets, develop robust processing routines that ideally use or produce open-sourced applications, enable enterprise-level tools for sharing data, and efficiently visualize the data meeting customer requirements.

III. Key Research and Development

The data products highlighted below have helped the uPSP development team understand the measurement system much better and its sensitivity to critical factors like pixel spatial resolution, grid resolution, model surface temperature, and camera noise and nonlinearity. In some sense, we are writing the uPSP processing handbook as we develop each product. Our robust data pipeline has facilitated the data reduction and analysis process, simplifying data reuse and configuration management. As we developed data products, we learned about what critical metadata would aid our diagnosis of any given plot. Below is a list of current data products developed by the team and several pieces of work that have produced and continue to develop the robust uPSP data processing pipeline.

A. Accurate uPSP Data and Data Products

At the lowest level of processing, our uPSP software reads raw data (high-speed camera video files along with camera calibration files, wind tunnel conditions and wind tunnel model orientation) and produces "intensity-time histories" at each vertex on the PSP grid that quantify pressure fluctuation in units of camera digital counts. From there, the intensity-time histories are converted to pressure-time histories using a physical calibration of the paint response to pressure. The validation of laboratory-based paint calibration continues to be an active area of research, and the process can be made more robust using "in-situ" corrections to match co-located pressure transducers. In addition, the pressure-time histories are large files and not the preferred data product desired by customers. To address both data validation and customer requirements, we have developed a series of data products derived from the low-level intensity- and pressure- time histories.

1) **uPSP to Kulite comparisons**: The most essential data product for the uPSP technology to gain acceptance by the community-at-large is comparison of the uPSP data to traditional discrete unsteady pressure transducers. However, since the two technologies are inherently different, it is difficult to correctly compare the two measurement systems. There are several companies that manufacture unsteady pressure transducers. For this work, the manufacturer was Kulite, and the brand name will be used when discussing unsteady pressure transducers.

   Kulites are discrete, point-source sensors and give accurate, time-resolved pressure measurements at a known location; however, this point source measurement is often used to estimate an integrated load over some area. On the other hand, given the high spatial resolution, the uPSP technology is best used as an integrated measurement and provides a continuous measurement over an area allowing for integrated loads to be directly computed. It has been challenging in the past to provide accurate discrete measurements from the paint that compare with Kulite measurements due to the shot noise that is inherent to any optical technology and often low SNR seen in previous demonstrations while developing the uPSP technology. Recent work has matured the analysis required to compare these two data sources.

   A single uPSP measurement (either a grid node or single camera pixel) is dominated by camera shot noise. The integration of the uPSP data over an area has shown benefits to reduce camera shot noise, however, aerodynamic flow-features are also attenuated with integrations over an area. Fig. 1 displays previous uPSP integrations from December 2020. The two Kulites shown in the figure are positioned on the same patch and produce very similar measurements since they are measuring the same flow. The individual uPSP Point Source Measurements (grid nodes) for a given uPSP patch, shown on the right, are dominated by shot noise and relatively flat and above the Kulite measurement. If the uPSP measurements for a given patch are integrated, the shot noise is reduced. However, the uPSP measurement levels are then far lower than the Kulite measurements since the integration is attenuating local variations in the measured surface pressure.

   Over the past two years, through a close collaboration between the uPSP development team and the NASA SLS Unsteady Aerodynamics Team, we have been able to refine how we compute virtual transducers to compare to discrete pressure transducers, enabling calibration to the Kulite level. The details are of our progress to correctly compare the well-accepted transducer measurements to the uPSP measurements are well documented in the Shaw-Lecerf et al. paper[6]. In Fig. 2, nine uPSP grid nodes were averaged at four locations to produce the uPSP point source measurement.

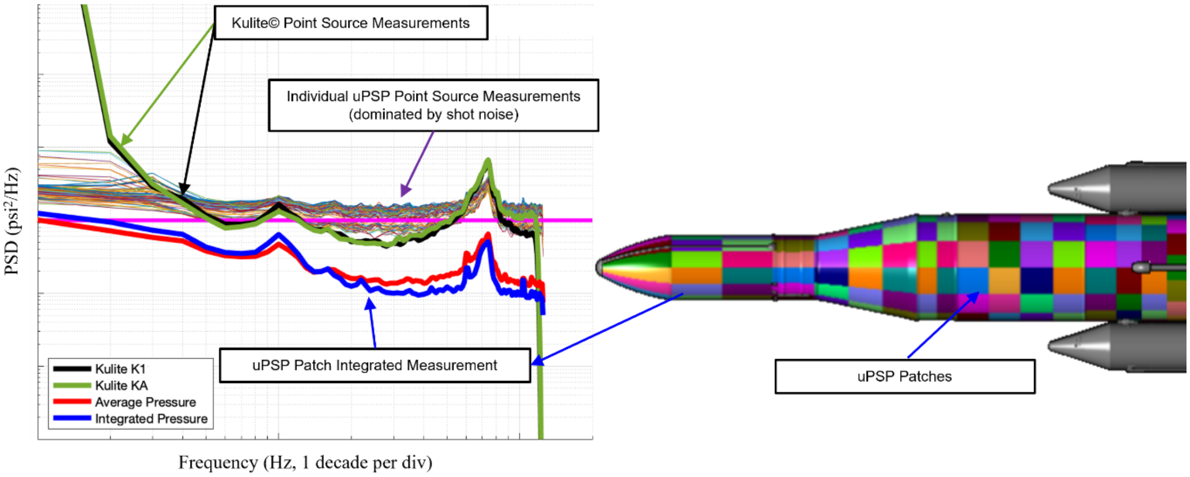


Fig. 1 Previous uPSP Patch Integration Comparison to Kulite Point Source Measurements

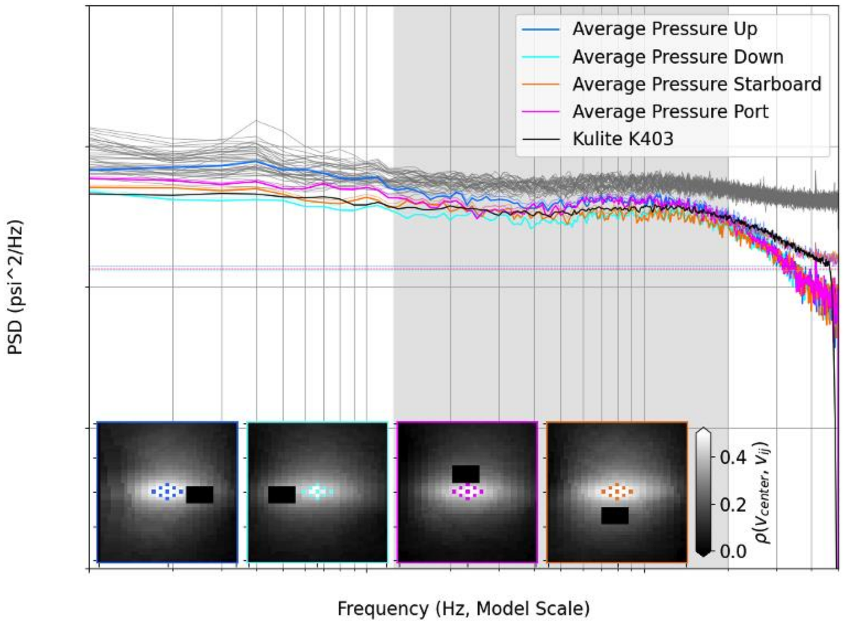


Fig. 2 uPSP Point Source Measurement Compared to Kulite Point Source Measurements[6]

2) **Patch Integrations for Structural Analysis:** Full-body aero-structural analyses such as launch vehicle buffet analysis[15] are most often performed using a lower-fidelity vehicle model than what is used for processing and projection of uPSP video files. Fig. 1 illustrates how uPSP data can be integrated over a user-defined area, or patch, to produce a lower-fidelity representation of the full-body fluctuating surface pressure. This is a data product desired by the structural dynamics community and demonstrates the power of spatially dense uPSP compared to the comparably complex network of transducers that would be needed to provide similar coverage of the vehicle surface. uPSP has shown promise particularly for launch vehicle buffet analysis due to the lower frequencies of structural excitation that can be resolved even in low-signal environments where large area averages are needed to mitigate broadband noise from the uPSP camera system.
3) **Joint Acceptance Attenuation Factor:** Li et al[7] discuss the Joint Acceptance Attenuations Factor (JAAF) of the integrated pressure with the uPSP measurements. The closed-form formulas of the JAAF of the integrated pressure on rectangular patches derived in the paper provide an efficient method to estimate the attenuation of integration by the decorrelation of the flow pressure field. They show explicitly how the parameters of the model of the pressure field and the parameters of the grid affect the spectrum of the integrated pressure on the patches. The results computed with the closed-form formulas set references for the comparison of the spectrum of the integrated uPSP measurements and the conventional pressure transducer measurements.
4) **IR Thermography:** Another challenge the uPSP technology must overcome is the sensitivity to temperature. NASA ARC UPWT purchases pressure-sensitive paints from Innovative Scientific Solutions, Inc. The ISSI porous, fast-response PSP has a higher temperature sensitivity[2,16] than the steady-state formula of the paint[17] due to the absence of the binder to allow for the fast response. Infrared (IR) radiometry measurements using IR cameras allow for high-spatial-resolution temperature measurements on a model during a wind tunnel test. The uPSP development team has previously used four to six thermocouples embedded near the surface of the wind tunnel model to gain understanding of the surface temperature during testing. However, a global temperature measurement is highly desired. Infrared (IR) radiometry[18] measurements using IR cameras allow for high spatial resolution thermal measurements of a model during a wind tunnel test. Development is ongoing for simultaneous uPSP and IR radiometry to would allow for temperature correction of uPSP measurements. Currently, IR camera temperature measurements have high uncertainty due to the reflective nature of the uPSP surface coating. IR camera signal from the model thermal emission is indistinguishable from that of reflection of the tunnel environment, namely the tunnel walls. Califano et al.[9] document one method to attempt to remove these undesirable reflections but faced challenges in doing so.

5) **Wind Tunnel Diagnostics Tool:** During the development of the patch integration methodology for structural analysis, the data showed that the uPSP technology is an excellent tool for tunnel acoustics diagnostics to measure what tones, or noise, are generated by the wind tunnel and how they change as wind tunnel conditions change. During the first round of patch integrations, we kept the number of patches relatively small, but the patch areas covered a large area. By averaging over large patches of the uPSP data, all shot noise and local aerodynamic flow features are attenuated and the remaining signals are predominantly acoustic noise generated by operation of the facility. These types of acoustics are inherent to any ground test facility, although some wind tunnels have been designed or modified to reduce them to a certain extent.

Previous acoustic surveys[19] at the NASA ARC UPWT have been documented, but recent studies have shown these results are sufficient for subsonic conditions only. Due to measurement limitations, transonic and supersonic conditions are not adequately characterized. This is not a critique of the previous work, but rather, a proposal for complementary acoustic surveys to be conducted using the uPSP technology, and other optical technologies, to support advanced aerospace vehicle testing. Optical technologies measure and record the traveling acoustic waves, which is what is desired and now made possible with current high-speed camera technology. Powerful analysis tools like the Dynamic Mode Decomposition (DMD) and wavenumber-frequency analysis (described below) can be used to show phase and direction of an acoustic or turbulent feature.

With the boom in launch-vehicle design and development to support NASA and other public and private space industry needs, there is a surge in wind tunnel testing to assess low-frequency buffet loads. In these tests, it is crucial to know what tones are acoustic (facility-generated) and what tones are turbulent (model-generated). Oftentimes, lower frequency acoustic tones overlap the buffet frequencies of greatest interest. The uPSP can be applied to walls of the facility to act as an acoustic survey to collect the requisite data.

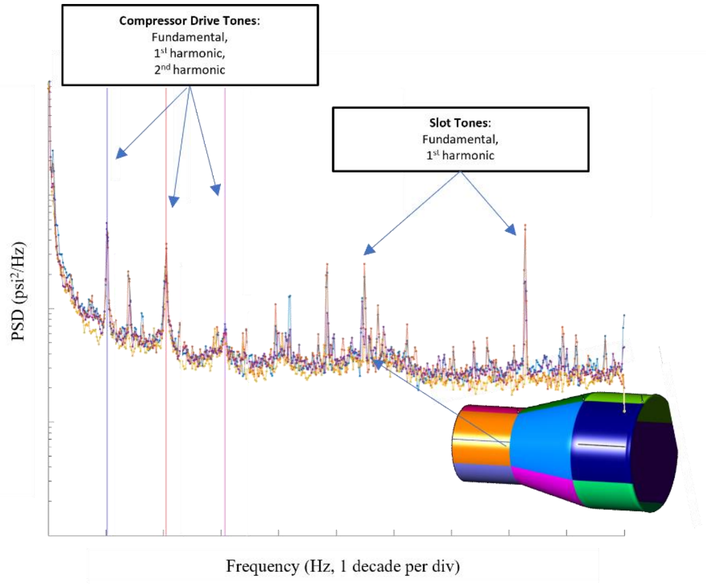


Fig. 3 Tunnel Tones detected by uPSP Patch Integrations

6) **Dynamic Mode Decomposition:** Work previously published by Li et al.[20] demonstrated the use of DMD using uPSP measurements. During the development of this data product, we noticed results that challenged our original thinking about flow in wind tunnels. Several of the DMD videos displayed pressure disturbances moving opposite to the tunnel free-stream flow for frequencies model-generated and tunnel-generated. Recent work, currently unpublished, derives and supports the fact that noise, even in a ground test facility, does not flow in a single direction during subsonic conditions, but rather, sound waves are dispersed in all directions from the source. The DMD data product has also proven to be an excellent tool for tunnel diagnostics to determine the direction of the wave propagation at a given frequency. Fig. 4 is a still image of the DMD mode the fundamental frequency for the model support strut shedding in the top image and the first harmonic in the second image. A video is shared in the recorded presentation showing the upstream propagation of noise from the model support system.

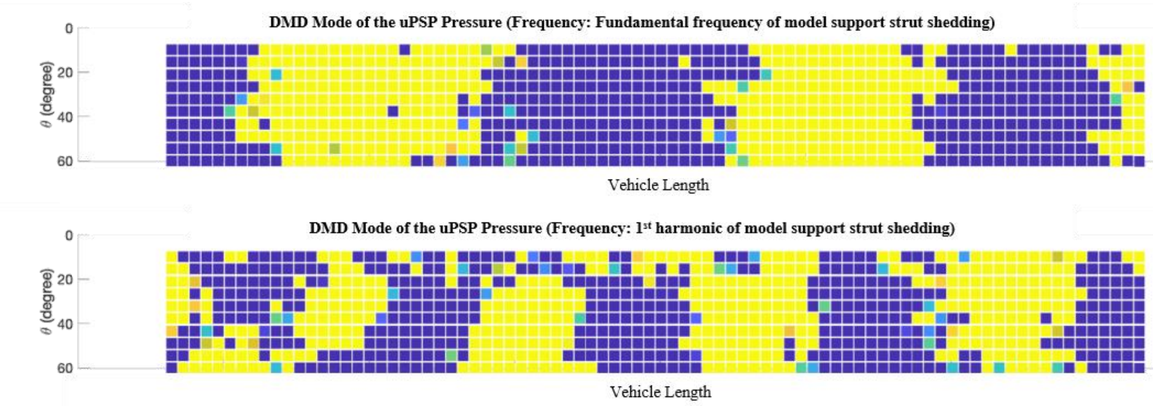


Fig. 4 Dynamic Mode Decomposition Produced from uPSP Data for Tunnel Tone Diagnostics

7) **Wavenumber-Frequency Analysis:** The time histories on the uPSP dense, equally spaced, structured grid allow for the direct calculation of wavenumber-frequency spectra by the means of the Fourier transform. This data product is valuable for the buffet and vibroacoustic analysis teams. Wavenumber-frequency analysis has also shown to be advantageous for tunnel diagnostics [21, 22]. The model support system generates acoustic noise which radiates in all directions in the wind tunnel. Fig. 5 plots the wavenumber-frequency spectra for the same area and same fundamental and first harmonic frequencies shown in Fig. 4. The red arrow on the plots confirms pressure disturbances traveling upstream through the boundary layer, indicated by the negative linear wavenumber, υ_x, value.

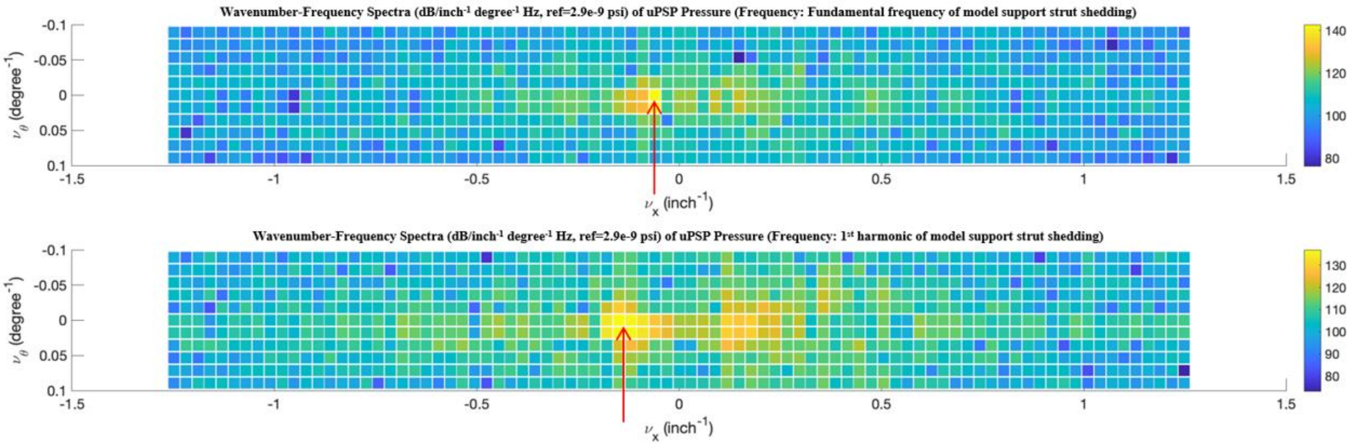


Fig. 5 Wavenumber Frequency Spectra from uPSP Data for Tunnel Tone Diagnostics

8) **Turbulent Boundary Layer Convective Velocity:** The uPSP system can resolve the bulk convective velocity of the turbulent boundary layer across large areas of the model surface. If we consider two points on the model surface positioned closely together but separated by a small streamwise distance, then the convective velocity is proportional to a linear phase delay in the cross-spectral phase between the uPSP signals. In practice, a small area average around each point is needed to sufficiently mitigate noise from the uPSP cameras. The measurement does not rely on the pressure amplitude calibration of the system and relies solely on the time-synchronization and spatial density of the uPSP data set. The data product is unique to uPSP in that it can be provided across a spatially dense area of the model surface compared to using a single pair of Kulite pressure transducers.

The convection velocity estimation process has been demonstrated for several test events in the Ames 11-ft wind tunnel. Fig. 6 illustrates the process applied to the 2017 ARC SLS AUAT, and we also refer the reader to a previous demonstration of uPSP-measured cross-spectral phase delay during a test of a generic “hammerhead” launch vehicle geometry[22].

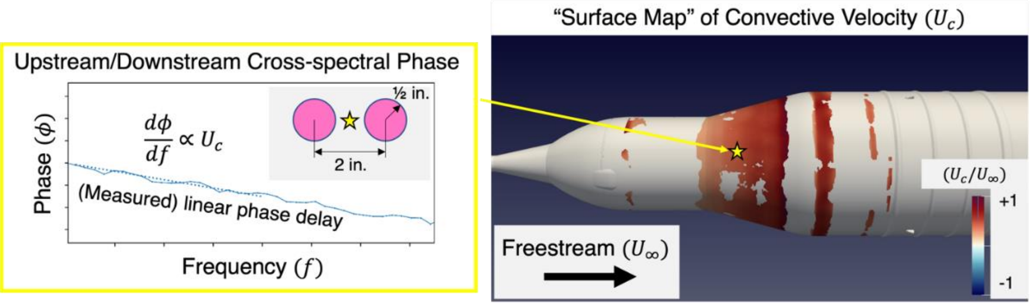


Fig. 6 Estimation of turbulent boundary layer convective velocity over a wide surface region with uPSP

B. Robust Processing Pipeline

The main motivation behind the multi-year project, funded by AETC, is to produce a turn-key capability at NASA AETC-managed wind tunnels. Many of these facilities operate as a production facility, meaning a test matrix is produced by the customer and the wind tunnel facility aims to complete the testing requested by the customer as efficiently as possible within the time and budget allotted. The uPSP technology is extremely powerful given the high spatiotemporal resolution, and gained interest from the aerosciences community, once the paint, camera, and lighting technology were available, after decades of issues involving separated flow on aerospace vehicles. In 2017, Schuster and D’Agostino’s Future of NASA’s Aerosciences Capability Report [13], highlighted several NASA programs that had experienced great challenges because of unsteady, separated flow, mainly in the transonic flight regime: Delta II Heavy, Ares I-X, and SLS. In the 1990’s, the Navy’s F-18 program faced delay in funding due a highly-publicized “wing drop” problem [23] due to unsteady aerodynamics. As stated previously, unsteady flow is difficult to measure and compute, but the uPSP technology is a promising tool that can optically measure, visualize, and aid in the understanding of these complex phenomena. However, if the data is not processed as quickly as it is acquired, its value and impact decreases with time. Therefore, the uPSP project prioritized leveraging high-performance computing available through NASA’s HECC and building the infrastructure required to enable real-time processing, visualization, and distribution of the uPSP data. Below are several vital pieces of work that have been produced to enable real-time delivery of uPSP data.

1) **Leverage High-Performance Computing:** Given the large data sets produced by the multiple high-speed cameras used, a sustainable, digitally transformed capability to process, share, visualize, and distribute the uPSP data was required. The uPSP processing pipeline has seen several operational improvements allowing for uPSP data from multiple high-speed cameras for a single wind tunnel condition to be processed in minutes rather than hours. This software[24] has been in development since 2015.

   The uPSP team has further developed an operational data processing pipeline capability to process dense uPSP surface pressure measurements (1000x higher resolution than traditional pressure transducers) at a speed 10,000x faster than the initial baseline capability from 2018. This notable achievement leverages the NASA HECC resources to store, process, transfer, and share the high-spatial resolution surface pressure data in near real-time. The software is modular and flexible to handle multiple wind tunnel events.
2) **Lifetime PSP Acquired with High-Speed Cameras:** Previous demonstrations have relied on steady-state pressure measurements[17] acquired from a separate lifetime PSP system (including separate cameras, timing hardware, and other data processing hardware and software). This system is installed and operated in parallel with the uPSP system. The steady-state pressures are required to determine the gain[25] in the intensity ratio to fluctuating component of pressure conversion. This introduced a separate data product required to produce uPSP data and lacked the traceability the team desired for the uPSP technology. The team undertook efforts to acquire uPSP lifetime data with the high-speed cameras in a series of small-scale tests. Murakami et al.[8] document the development of this capability. If successful, this would streamline the acquisition system by eliminating some experimental hardware, shorten setup time, and leverage existing software processing tools.
3) **Digital Twin Capability:** The team developed a digital twin capability of the uPSP system with the Blender 3D rendering software [26] to simulate videos of a wind tunnel model with an arbitrary wall pressure time history at each point. With exact control over extrinsic and intrinsic camera parameters, pressure-to-intensity mapping, and model geometry, this tool enables verification of the unsteady processing code as

well as analysis of various non-ideal effects. The tool was initially validated by generating videos for several overlapping views of a flat plate model with a sinusoidal pressure field moving downstream, and pressure time histories as well as RMS pressures were found to match the specified inputs. The simulation capability has also been used to quantify the effects of camera shot noise as well as errors in model surface temperature estimates. The digital twin maintains "ground-truth" physics-based parameters and enables the team to support wind tunnel customers with analyses such as Monte-Carlo-based uncertainty quantification studies.

While the tool has been primarily used to test and characterize sources of noise and error in the uPSP measurement and processing systems that are difficult to isolate experimentally, it may in the future serve as a digital twin[27] of a wind tunnel such that camera, lighting, and model configurations can be interactively visualized and tuned prior to physical testing.

4) **Improved Camera Calibration Routines:** New techniques were needed to meet new requirements on robustness and accuracy introduced by higher camera resolution, large wind tunnel models, and large variation in model position during a given wind tunnel test. Califano et al.[10] outlines several techniques and improvements for intrinsic and extrinsic camera calibrations that have leveraged open-source software, like OpenCV[28], and off-the-shelf tools, like Calib.io calibration software to decrease calibration uncertainty.

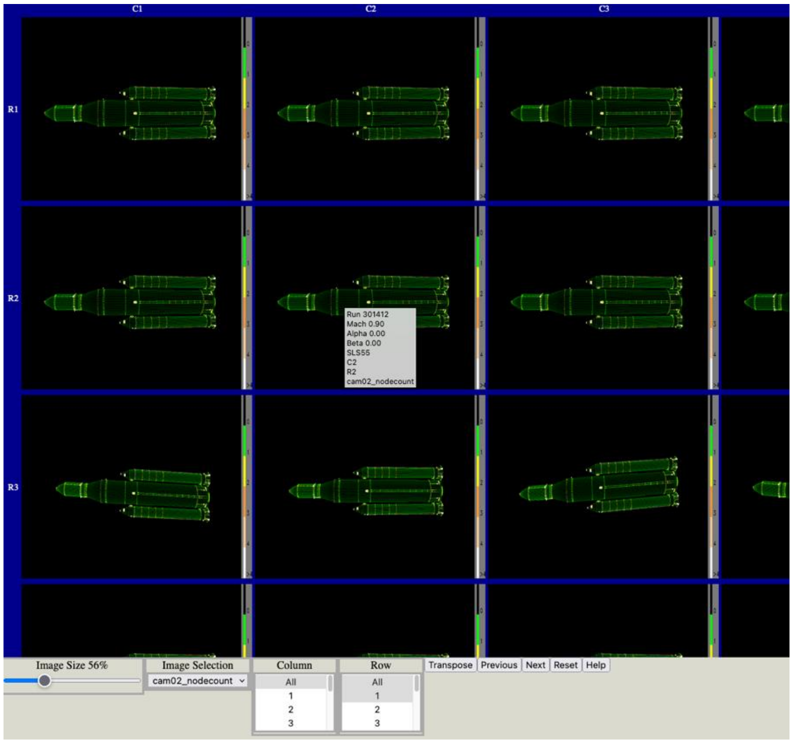
C. uPSP Data Visualization Tools

Throughout the entire uPSP process from model preparation, camera calibration, testing and data acquisition, and data reduction, an important challenge of the uPSP process remains. This challenge is the visualization of the data. While the testing of the model is conducted in three-dimensional space, the visualization of the data can be insufficient to orient the user with the presented data. Simple two-dimensional data plots represent the results at a specific location on the model for specific test conditions. The user is left to organize these plots to provide an understanding of the data variation as a function of locations on the model surface. Several visualization tools have been developed to overcome this deficiency. These tools include the MiniWall, Interactive MiniWall, and the pyVista applications. These tools will be discussed in the following sections.

1) **MiniWall Application:** The MiniWall application is a software version of the Hyperwall system at the High-End Computing (HEC) facility at the NASA Ames Research Center. The Hyperwall provides the display of image data over a matrix of computer monitors allowing detailed representation of these data for three-dimensional environments. The MiniWall replicates the Hyperwall system in HTML. The MiniWall application is fully customizable to display data for variables of interest over desired test conditions. The application has been used for visualization of uPSP camera data, for diagnostic purposes, and for the presentation of processed data. An example of the MiniWall representation for camera diagnostics is shown in Fig. 7.

In Fig. 7, images of the camera data for the installed test vehicle are presented. The figure depicts a portion of the MiniWall presentation. In this representation the user can quickly verify all the diagnostics for all the uPSP cameras and all test conditions. Two of these diagnostics include the surface normal vectors and targets associated with each camera for all test conditions. An example of the MiniWall representation for surface patch and Kulite data is shown in Fig. 8.

In Fig. 8, uPSP images of patch and Kulite data for the installed test vehicle are presented. The figure depicts a portion of the MiniWall presentation and represents the surface patch and Kulite images as a function of X (downstream) and Phi (azimuth) vehicle surface locations. The patch data are created from user defined surface patches integral to vibration or structural analysis. The Kulite images represent the processed data for the installed Kulite sensors. The proximity of the patch and Kulite locations is preserved in the MiniWall representation. In this representation, the user can quickly compare the processed data for the user defined patches (red border) with the adjacent Kulite (green border) data for all test conditions. The presentation depicts the "unwrapped" surface of the test vehicle.



Run 301412
Mach 0.90
Alpha 0.00
Beta 0.00
SLS55
C2
R2
cam02_nodecount

Fig. 7 MiniWall Application for Camera Diagnostics

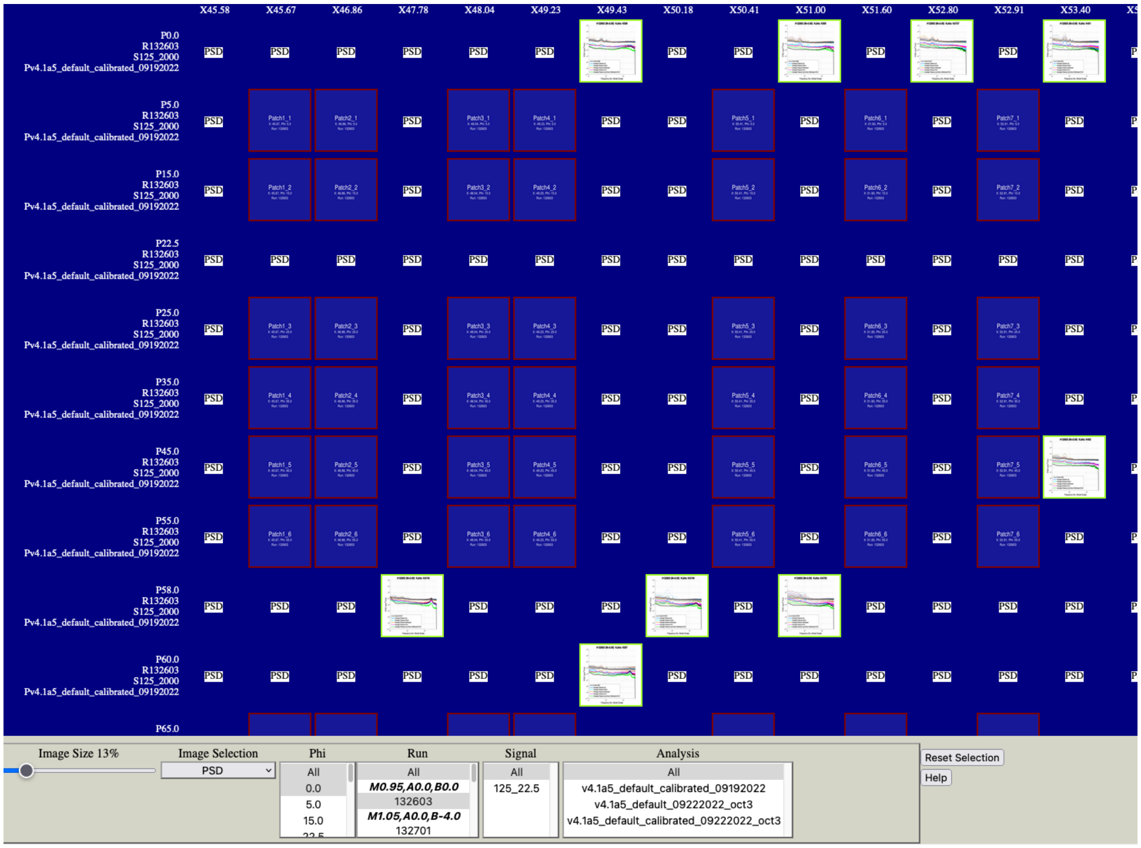
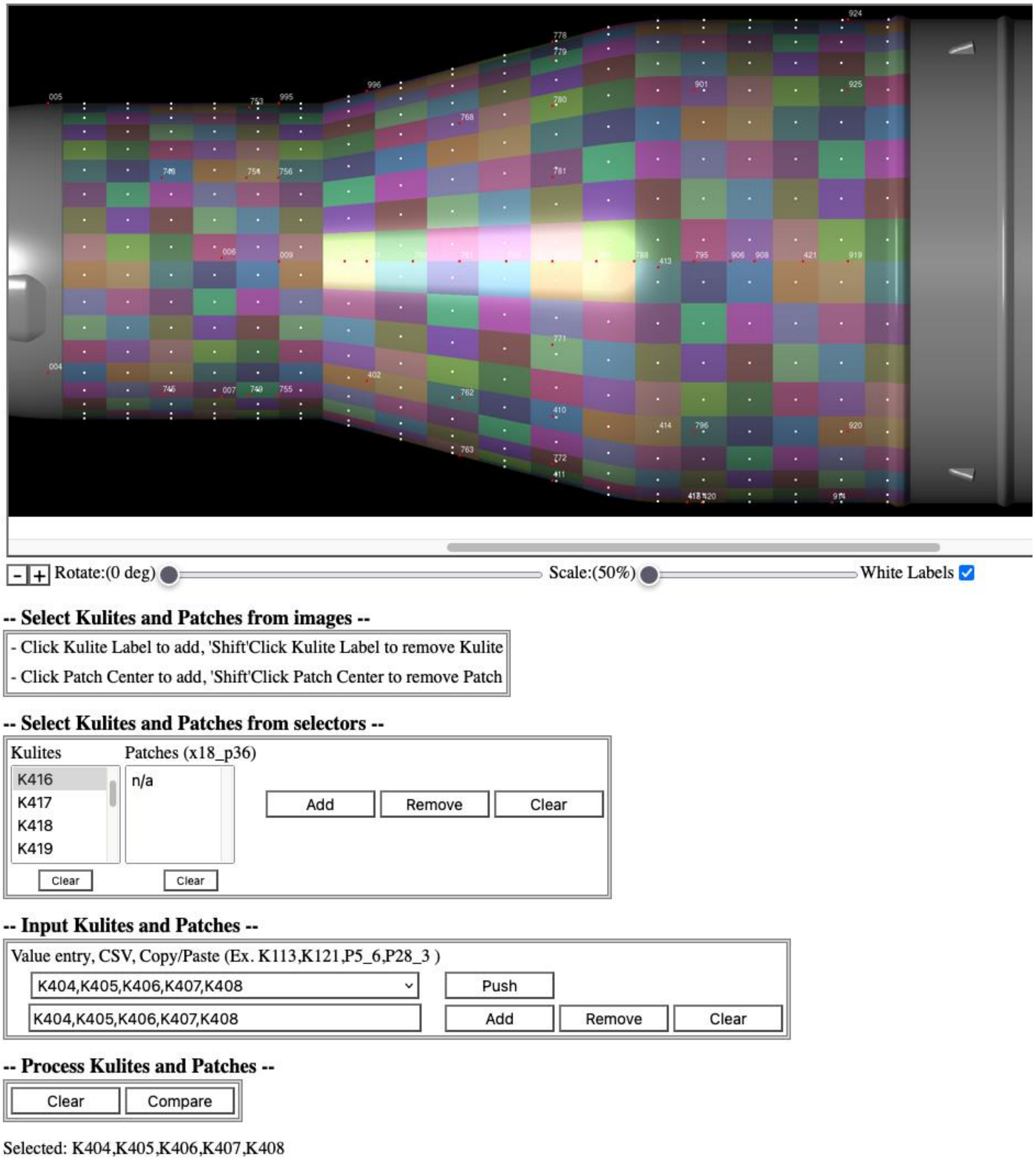


Fig. 8 MiniWall Application for uPSP and Kulite Data on a Wind Tunnel Model Patches

2) **Interactive MiniWall Application:** The Interactive MiniWall is an extension of the MiniWall application. The Interactive MiniWall incorporates a representation of the test vehicle with the user defined surface patches and Kulites integrated into the representation. The vehicle representation can be rotated, translated, and scaled to view specific portions of the vehicle surface. This allows the user to focus on the surface patch and Kulite data for vehicle locations of interest. An example of the Interactive MiniWall representation is shown in Fig. 9.



Rotate:(0 deg) Scale:(50%) White Labels ☑

-- Select Kulites and Patches from images --

- Click Kulite Label to add, 'Shift'Click Kulite Label to remove Kulite
- Click Patch Center to add, 'Shift'Click Patch Center to remove Patch

-- Select Kulites and Patches from selectors --

Kulites: K416, K417, K418, K419

Patches (x18_p36): n/a

-- Input Kulites and Patches --

Value entry, CSV, Copy/Paste (Ex. K113,K121,P5_6,P28_3)

K404,K405,K406,K407,K408

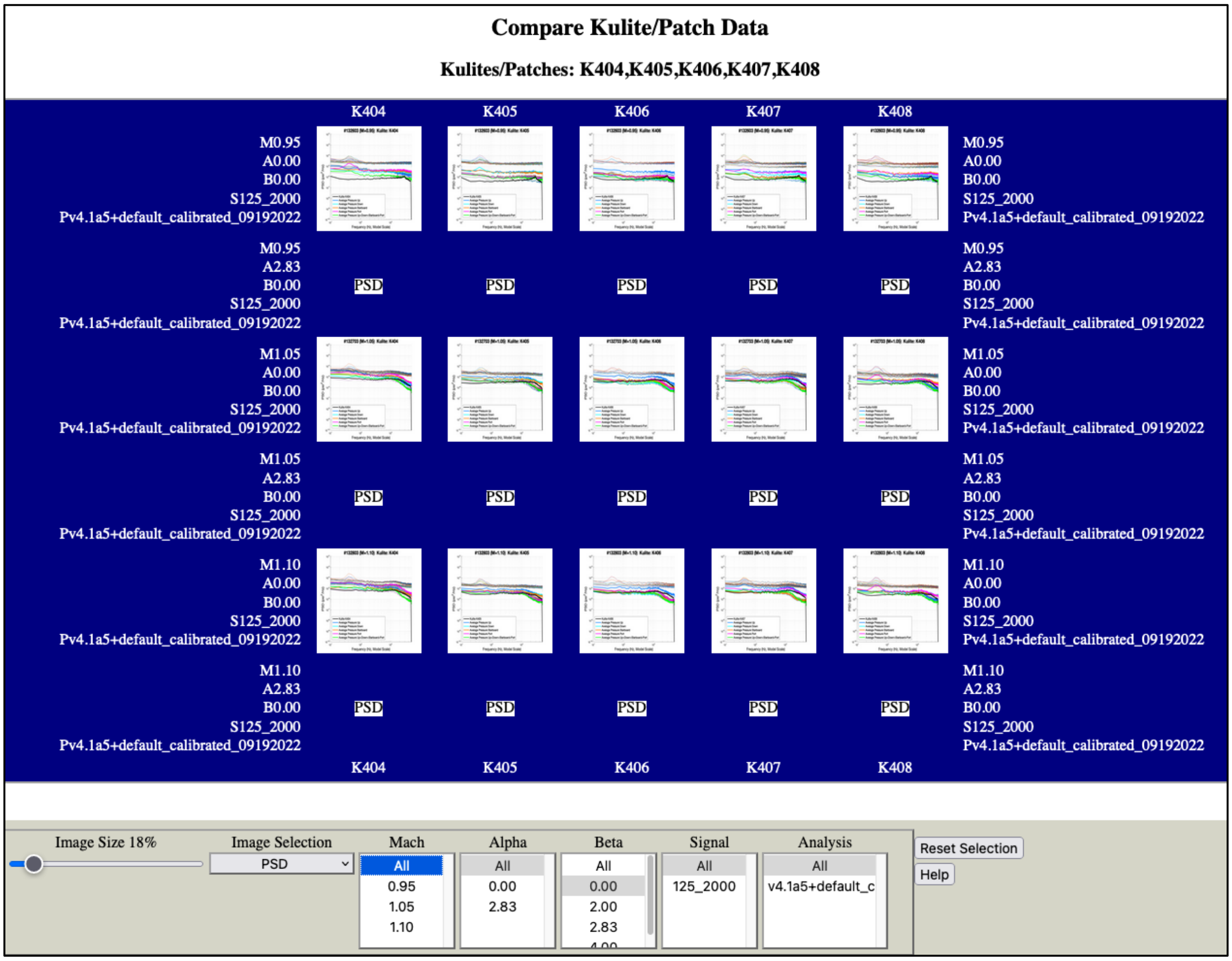
K404,K405,K406,K407,K408

-- Process Kulites and Patches --

Selected: K404,K405,K406,K407,K408

Fig. 9 Interactive MiniWall Application

In Fig. 9, the vehicle is represented with the surface patches (colored rectangles) and the Kulites (white labels) at their exact locations on the vehicle. The application allows the user to modify the vehicle representation to select patches and Kulites of interest with a mouse click on the representation. Alternately, the user can select patches and Kulites from several selection widgets in the application. Once selected, a comparison of the data for the user selection is presented. A sample comparison of patch and Kulite data is presented in Fig. 9.



Compare Kulite/Patch Data

Kulites/Patches: K404,K405,K406,K407,K408

	K404	K405	K406	K407	K408	
M0.95 A0.00 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022						M0.95 A0.00 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022
M0.95 A2.83 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022	PSD	PSD	PSD	PSD	PSD	M0.95 A2.83 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022
M1.05 A0.00 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022						M1.05 A0.00 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022
M1.05 A2.83 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022	PSD	PSD	PSD	PSD	PSD	M1.05 A2.83 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022
M1.10 A0.00 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022						M1.10 A0.00 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022
M1.10 A2.83 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022	PSD	PSD	PSD	PSD	PSD	M1.10 A2.83 B0.00 S125_2000 Pv4.1a5+default_calibrated_09192022
	K404	K405	K406	K407	K408	

Image Size 18%

Image Selection: PSD

Mach	Alpha	Beta	Signal	Analysis
All	All	All	All	All
0.95	0.00	0.00	125_2000	v4.1a5+default_c
1.05	2.83	2.00		
1.10		2.83		

Fig. 10 Interactive MiniWall Data Comparison

In Fig. 10, a MiniWall representation for the selected Kulites is presented. The behavior of this representation is identical to that of the MiniWall representation and allows the user to select data images at test conditions of interest. This provides a direct comparison of selected patch and Kulite data over the test envelope.

3) **PyVista Visualization Tool:** The PyVista visualization tool is an in-development application which provides visualizations for available scalars across processed uPSP datasets, querying NAS resources through an SSH connection to obtain and locally cache necessary data. The user of the application can skim through available datapoints, find a datapoint for analysis, and then select from available scalars for that datapoint. Selected datasets are then downloaded on an ad hoc basis. Taking place within an interactive 3D scene, scalar visualizations take the form of a colorized overlay of the grid’s 3D model, where the colorization representing the scalar value of each node on the grid is performed along a color gradient scaled to the dataset. Kulites are rendered with a corresponding 3D label that can be toggled on and off as desired. Additionally, users can select grid points to be given a 3D label. These labels display the currently

selected scalar and update automatically based on any changes to the selected datapoint or scalar selection within a datapoint. These labels allow users of the application to quickly compare scalar values between specific nodes on the model across differing datasets.

Moving forward, the application will seek to further support uPSP analysis capabilities by acting as a remote front-end for sub-grid analysis tasks leveraging NAS resources, such as processing only an interactively selected range of nodes.

IV. Conclusions

One of the goals of AETC's uPSP project is to imagine what ground testing looks like in ten to twenty years and start executing those ideas now. The uPSP project is actively pursuing this goal. The future of aerosciences will focus on solving unsteady, separated flow, especially since NASA and its stakeholders continue to develop more advanced aerospace vehicles. To solve these challenges, a variety of tools in the aerosciences "toolbox" will be required. One of these tools will be the uPSP technology. Over the past three years, the uPSP development team has taken a systematic view of what the future of ground testing looks like and has developed several data products that will enable customers to solve the challenging problems in unsteady aerodynamics as well as developed processes and build the infrastructure and software to enable real-time analysis of these challenges.

V. Future Work

The project still has some key milestones planned. One goal since 2015 was to develop a uPSP software that would be available to the public through the NASA Software Catalog. In early 2023, it is expected NASA-developed uPSP software will be available through the NASA Software Catalog. The software currently supports the two most popular input formats for high-speed cameras (*.mraw & *.cine). The goal was to enable a community of users at other NASA AETC facilities, private ground test facilities, or university labs through well-documented, robust software so others could start processing their uPSP data sooner.

Over the next year a formal data products document will be produced to be shared with future customers of the ARC UPWT. The document will highlight what data products are currently offered and the details of how these products are derived and what customization is available for the individual customer.

The uPSP technology has seen a giant leap in maturity over the past three years. The uPSP development team at ARC has worked closely with current and future customers to understand requirements and data products desired, and along the way developed a strong, technical knowledge base about the uPSP technology and its deployment in large ground testing facilities. The pandemic changed the trajectory of what was previously planned for continued development testing in large-scale facilities, like the ARC UPWT. For the latest technical achievements to be realized, at least one more demonstration of the uPSP technology at ARC UPWT, preferably on an open, non-sensitive geometry is required before offering this capability to future customers.

Lastly, the uPSP technology is not only for measuring unsteady flow phenomena on launch vehicles. The unsteady flow on aircraft is a major concern and more efficient aircraft could be produced if this phenomenon is measured at higher resolution with the uPSP technology. It is expected that there will be development needed for a model with lower intensity values and deforming wings. An open, non-sensitive model like NASA's High Lift Common Research Model (CRM) would be an ideal candidate to demonstrate to NASA's aeronautics projects and commercial aviation the value that the uPSP technology provides.

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