Launch Vehicle Loads Analysis Using Pressure-Sensitive Paint

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Challenge

- NASA and its Stakeholders are developing more advanced aerospace vehicles and require a new state-of-the-art to meet their requirements.
  - Higher spatial resolution
  - Less conservative loads estimates / compute loads directly
  - Limited facility availability
  - Lack sufficient computation tools
- New advanced aerospace vehicles have complex flow that is hard to measure and compute
  - Engines mounted in new areas
  - Active flow control
  - **Ascent launch vehicles**
- Current method to assess unsteady aerodynamics employs hundreds of pressure transducers.
- This method has long lead times, is expensive, and produces overly conservative results.

NASA ARC 11x11 TWT – SLS

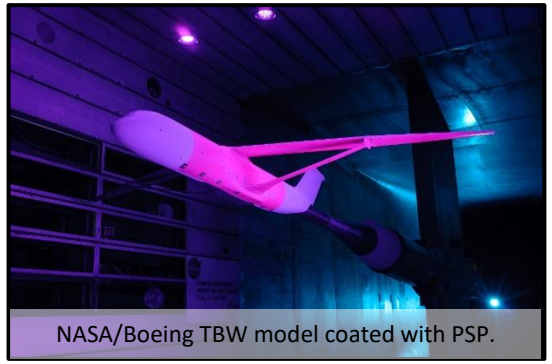
NASA GRC 8x6 SWT – Boundary Layer Ingestion

NASA NFAC 40 x 80 – Active Flow Control

Ground Tests & Their Measurements

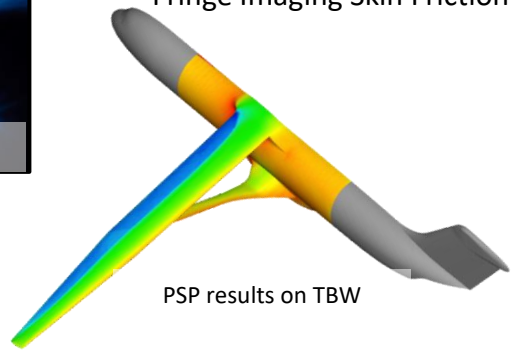
Aerodynamic Forces
Surface Pressure over some Area

Quantify Steady, Time-Averaged Forces



NASA/Boeing TBW model coated with PSP.

- Balance
- Pressure taps
  - can be expensive
  - limited in number
  - spatial limitation
- Optical Technique
  - Pressure-Sensitive Paint (PSP)
  - Shadowgraph
  - Infrared Thermography (IR)
  - Model Deformation Measurement
  - Fringe Imaging Skin Friction (FISF)



PSP results on TBW

Ground Test Toolbox
- Balances
- Strain Gages
- Thermocouples
- Pressure Transducers
- Optical Techniques

CFD Simulation Toolbox

Flight Test Toolbox

Quantify Unsteady, Time-Resolved Forces

The next major challenge for aero- and fluid dynamics is the understanding of unsteady flows. It is the performance-limiting factor for many flight vehicles and dictates the structural requirements for launch vehicles and their payloads.

\- David Schuster, NASA Aerosciences Technical Fellow

- **To understand unsteady aero-physics, must measure unsteady surface pressure.**
- The ability to ***measure*** and ***compute*** these flows remains a challenge.
- Improving the state of the art, will reduce margins

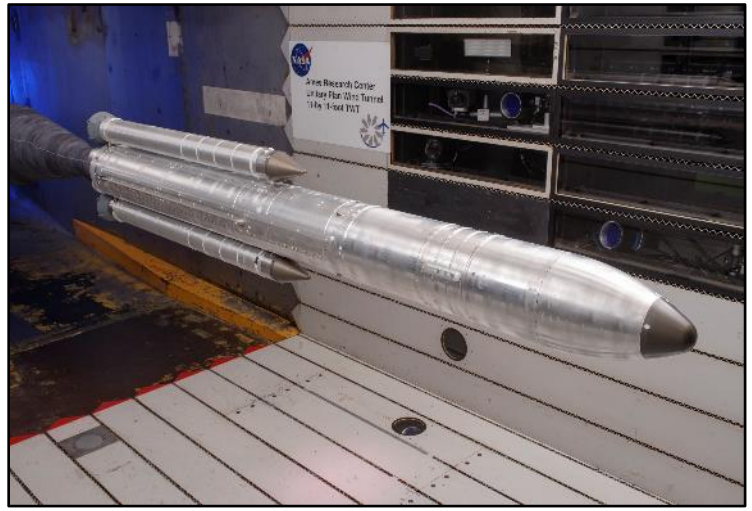
3

Current method

July 2013

- July 2013: t11-0265
  - Launch vehicle buffet forcing functions (BFF) estimated from sparse, unsteady pressure measurements (Kulites)
  - Rocket was too heavy
  - Formed a special task team to investigate why
  - Details of the pressure integration scheme are critical to getting the right answer
- Dec 2013: t11-0273
  - SLS spent significant effort refining BFF estimates
  - Improved processing to refine estimates and added instrumentation for a repeat test
  - Effort highlighted need for high spatial resolution pressure data to evaluate BFF estimation techniques
- Dec 2017: t11-0344
  - Added more instrumentation, repeated test

Dec 2013



Dec 2017

Where's the Gap

CFD Simulation

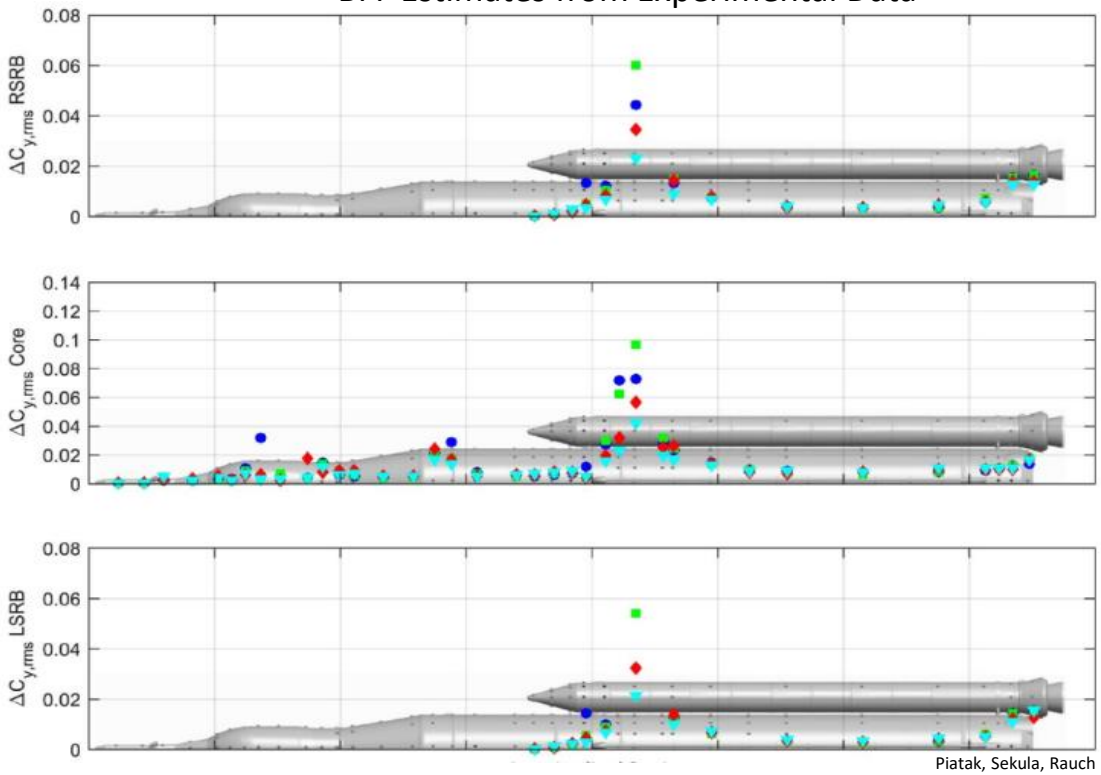
Rogers, Dalle, Chan

- **What do customers have**
  - Surface pressure measurements
  - Simulation data
  - High spatial resolution
  - Limited high temporal resolution

OR

  - Surface pressure measurements
  - Experimental data
  - Sparse spatial resolution
  - High temporal resolution

BFF Estimates from Experimental Data

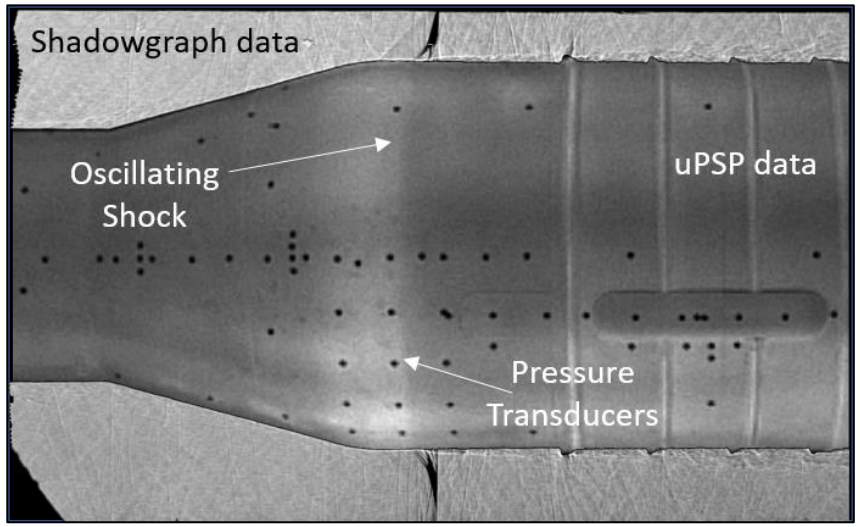


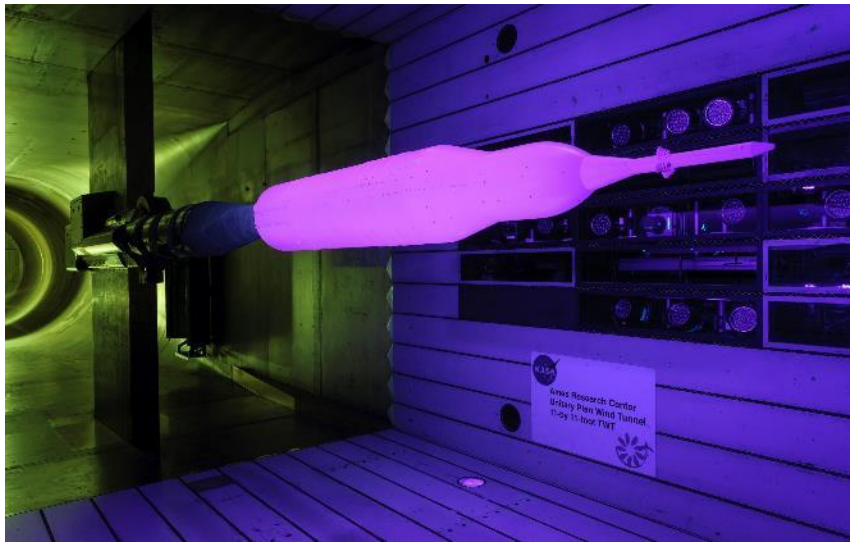
Piatak, Sekula, Rauch

- **What do customers want**
  - Surface pressure measurements
  - Experimental data
  - High spatial resolution
  - High temporal resolution

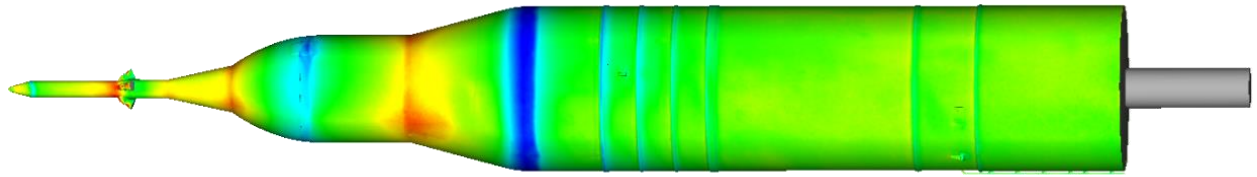
Develop new state-of-the-art to assess unsteady aerodynamics

- Fast response paint measures surface pressure fluctuations up to 25kHz
- High-powered LEDs excite the paint
- High-speed cameras record intensity of the paint's response
- Develop algorithms to convert intensity to pressure and dynamic loads data
- Develop software visualization package to address customers' needs

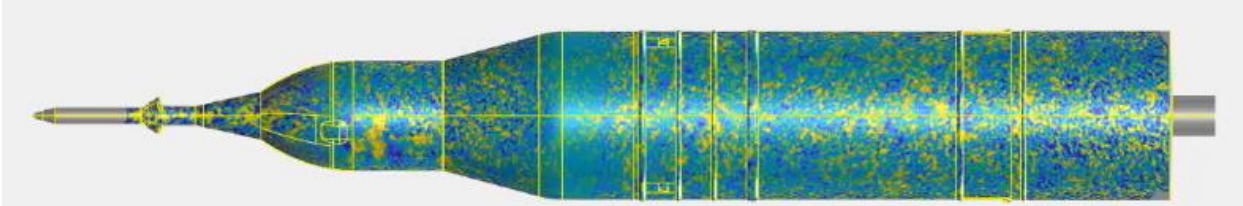




Dec 2017



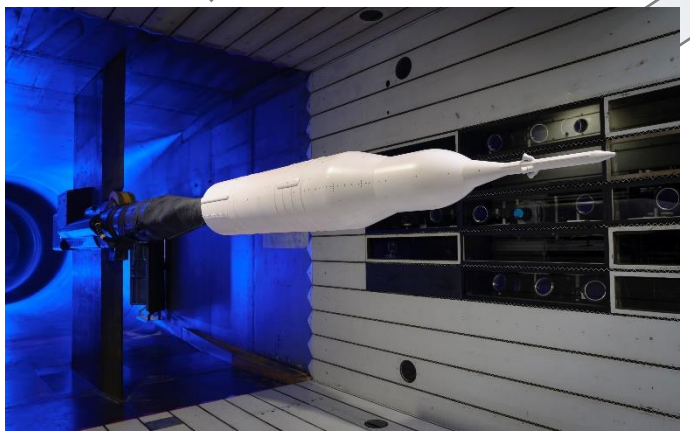
Time-averaged PSP



Time-resolved PSP

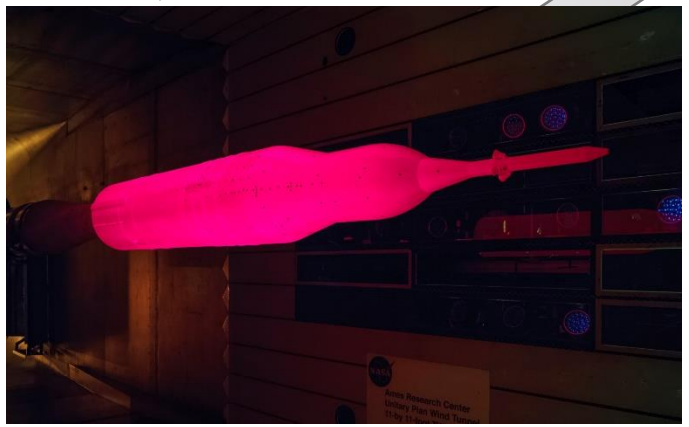
What is the uPSP System?

1. Apply porous, fast-response luminescent paint

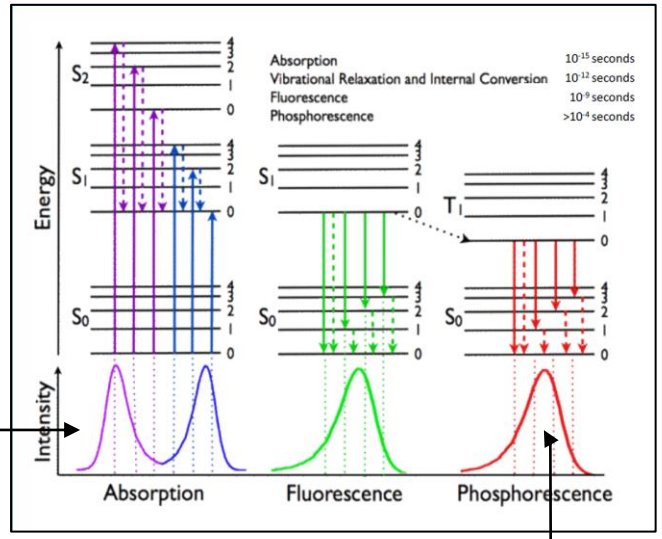


2. Excite paint with 400-nm wavelength light source

3. Photons are emitted at 650-nm wavelength as a f(pressure, temp)

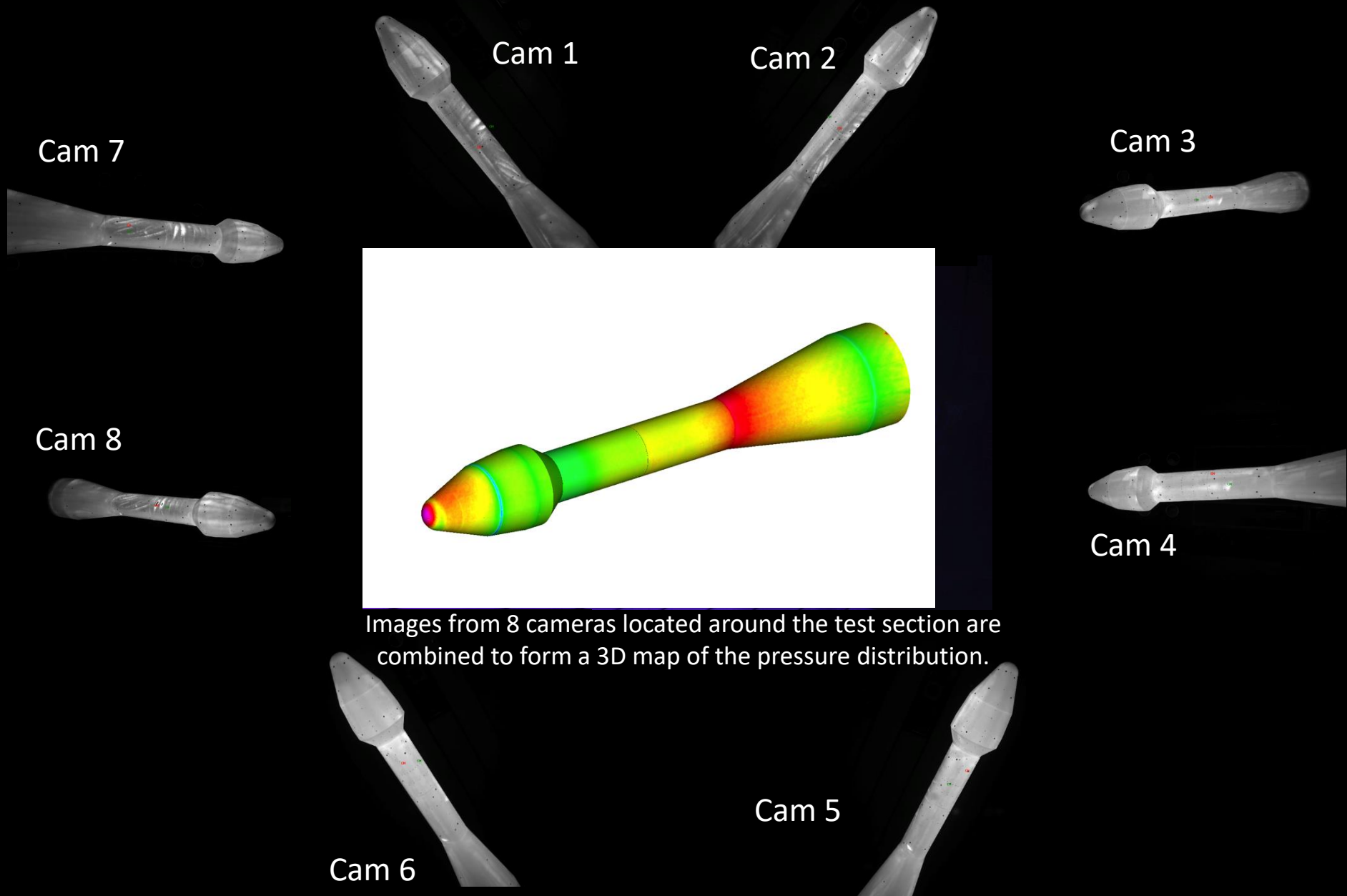


Jablonski Diagram



4. Emission is measured with high-speed cameras

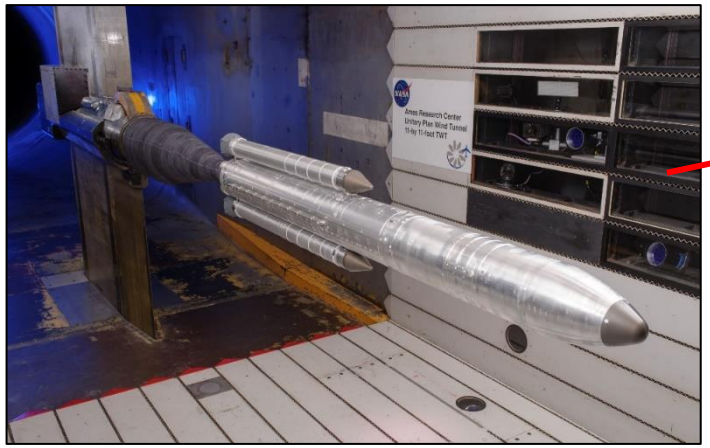
PSP Background

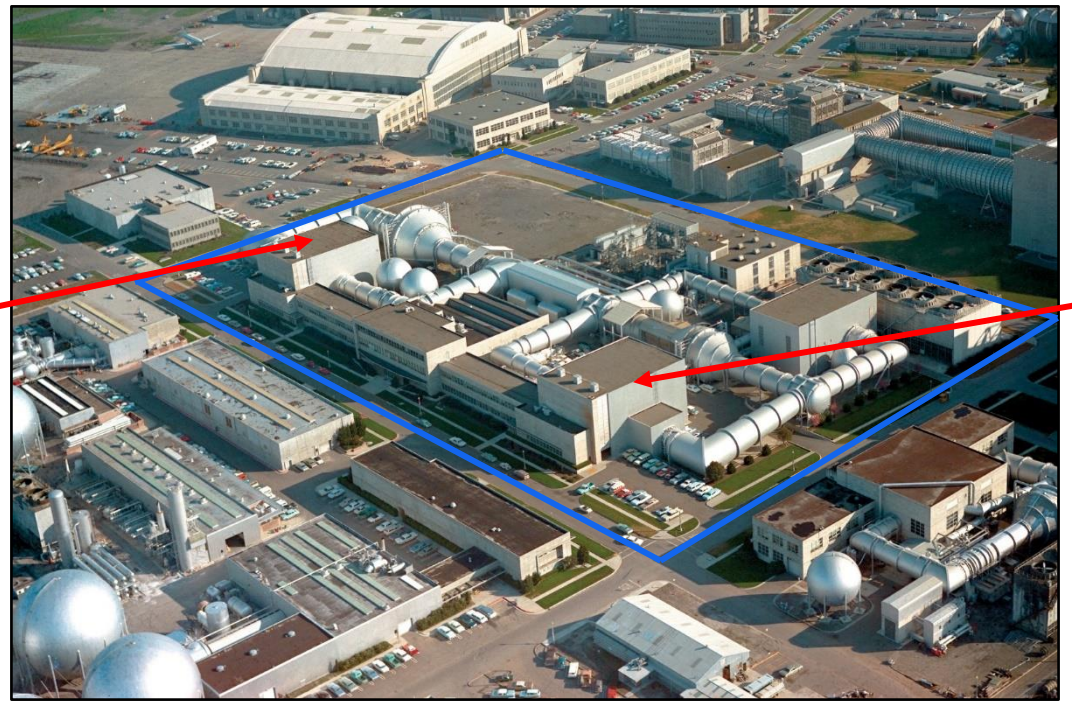


Images from 8 cameras located around the test section are combined to form a 3D map of the pressure distribution.

NASA Ames Research Center's Unitary Plan Wind Tunnel (UPWT)

NASA Space Launch System (SLS)





NASA Space Launch System (SLS)

11-by 11-foot Transonic Test Section

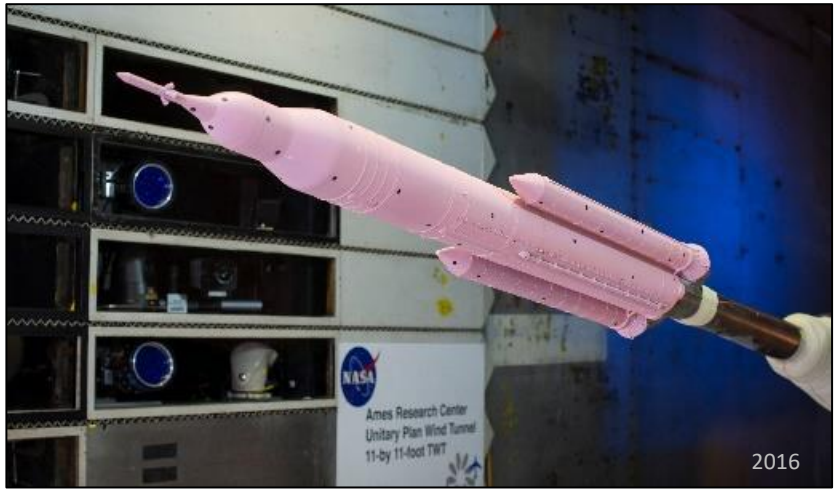
- Mach Range 0.2 – 1.4
- Reynolds Number = 0.3 – 9.6 Mil/ft
- Stagnation Pressure = 0.2 – 2.2 atm

9-by 7-foot Supersonic Test Section

- Mach Range 1.55 – 2.55
- Reynolds Number = 0.5 – 5.7 Mil/ft
- Stagnation Pressure = 0.2 – 2 atm

Past Applications of Time-averaged (Steady-State) PSP

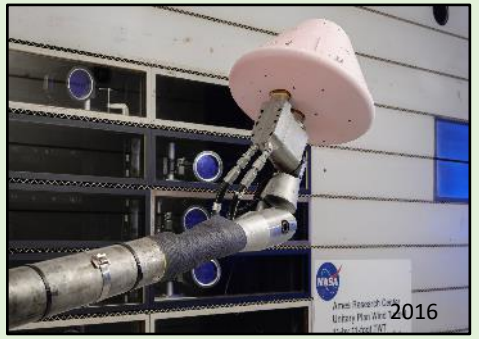
NASA SLS

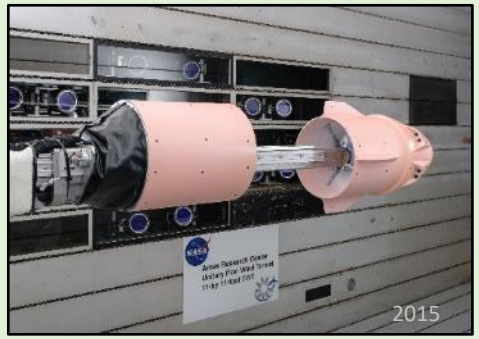


NASA X-planes

NASA NESC

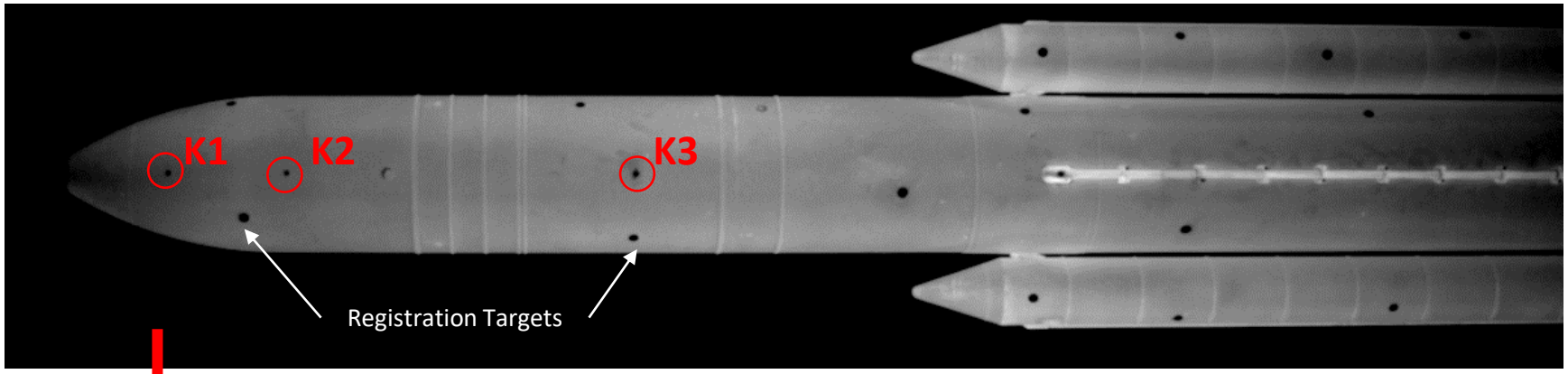
NASA MPCV





Commercial Crew

Begin Understanding Operational Deployment



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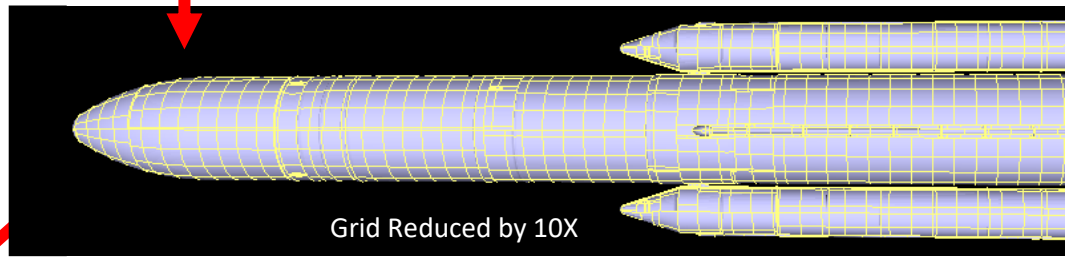
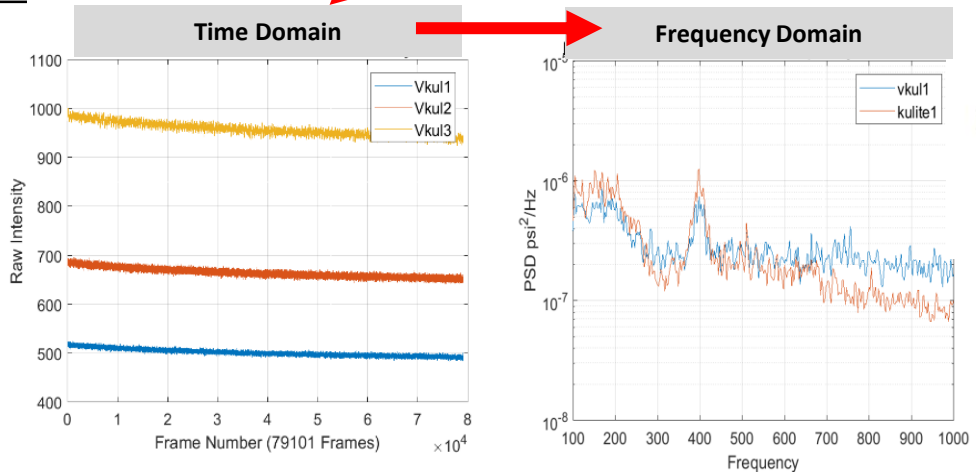
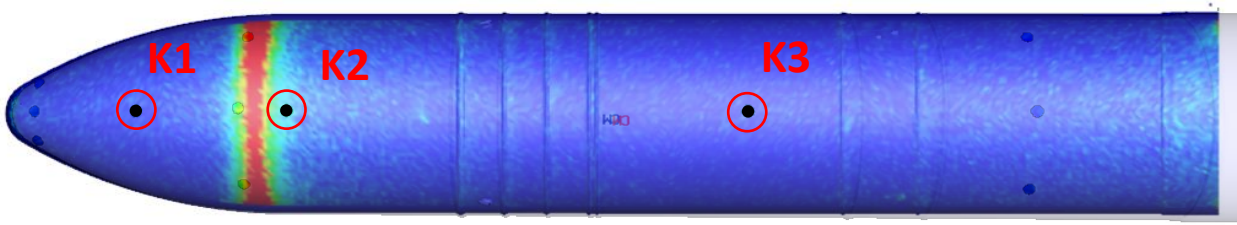


SLS Force & Moment Test

- Single camera
- 3 Kulites®
- **2 hours of testing**
- **<u>1TB of raw data</u>**



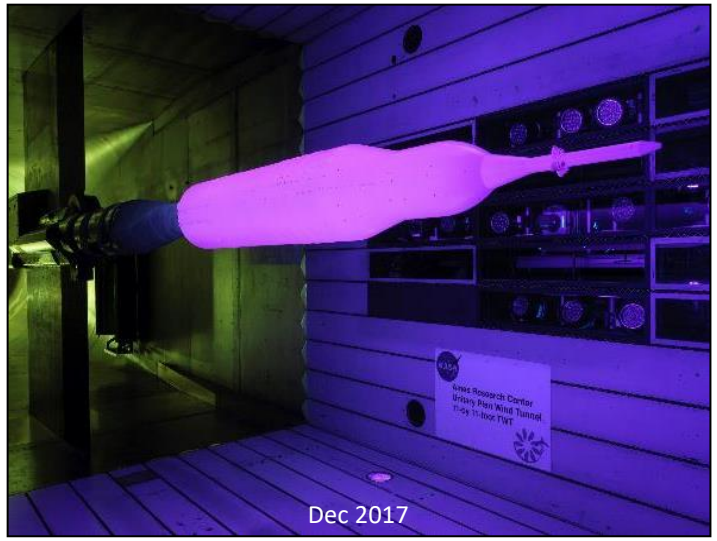
Executing this at a large number of points, provides:

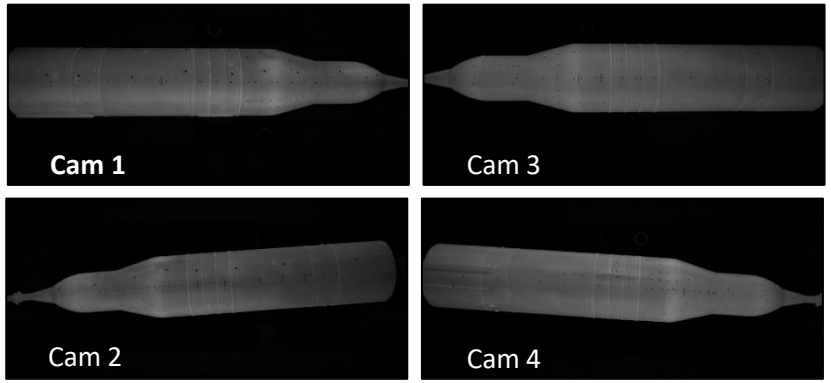


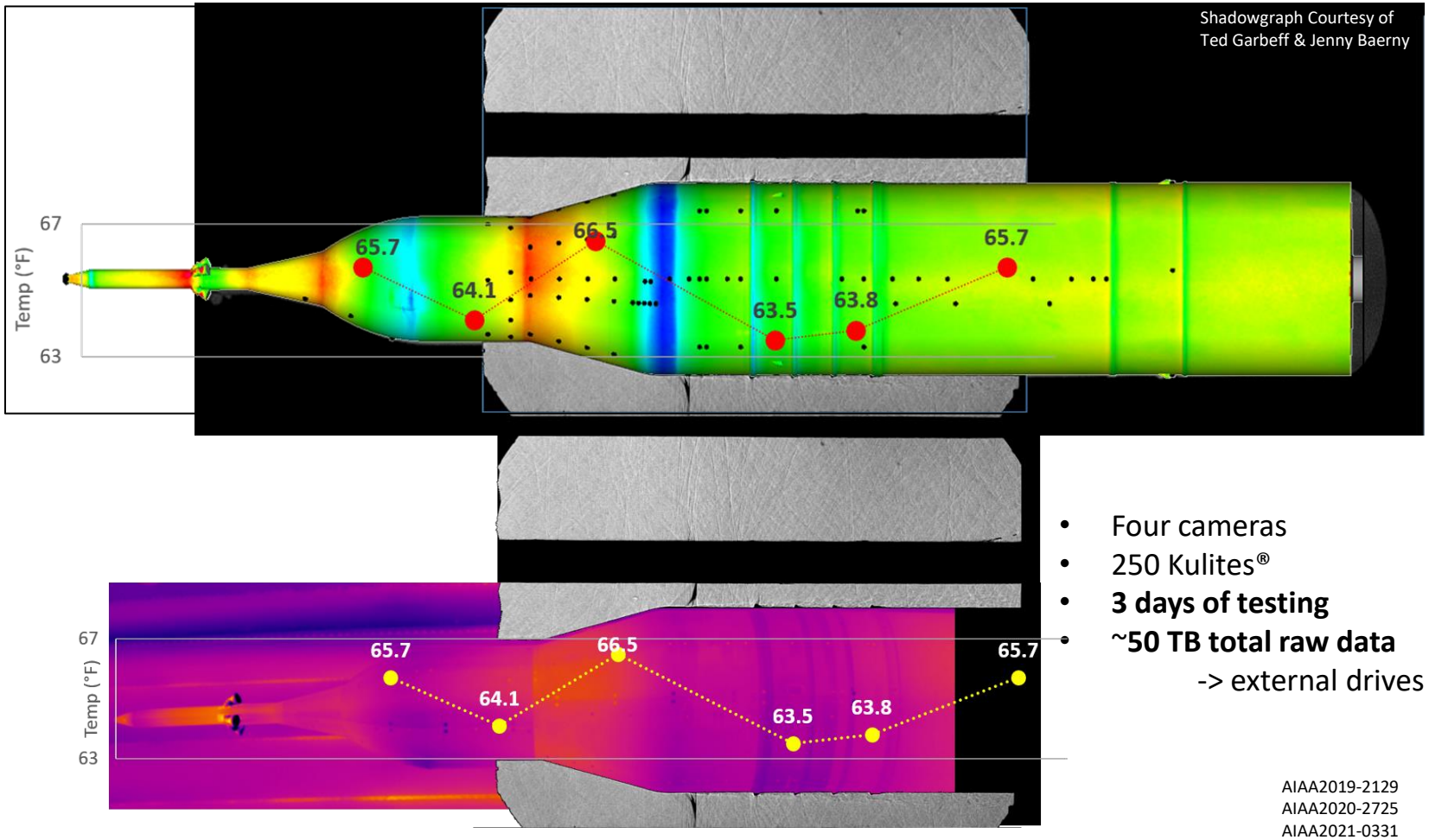
64,000 PSDs at one frequency

- **Needed more storage**
- **Needed better tools to process data**

Scale up to multi-camera, collect temperature data



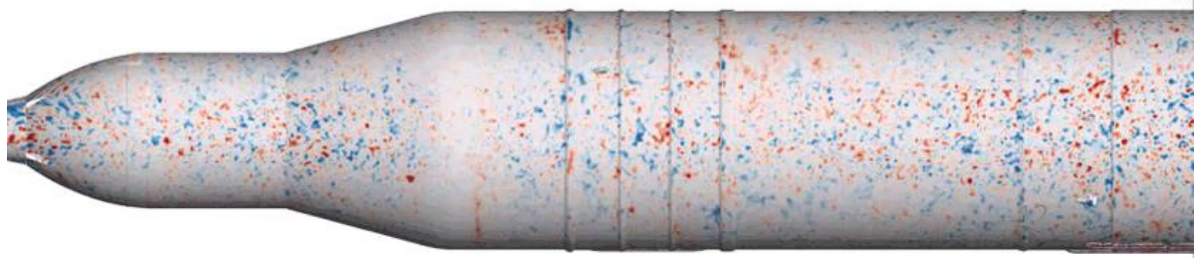




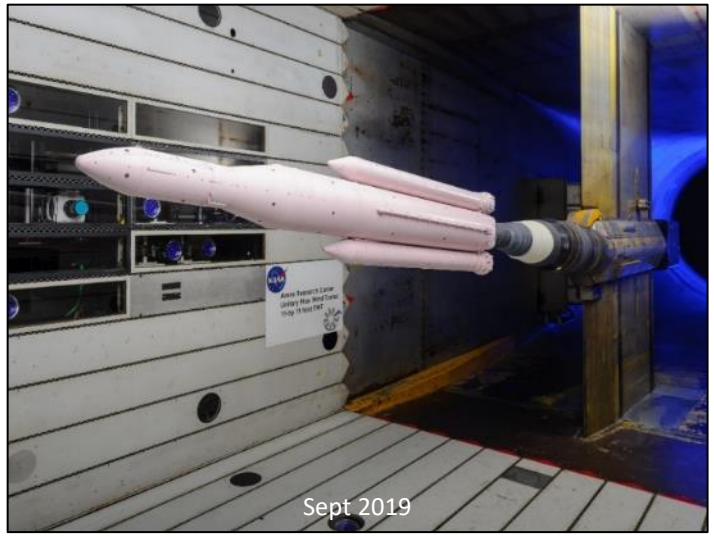
- Four cameras
- 250 Kulites®
- **3 days of testing**
- **~50 TB total raw data**
  -> external drives

AIAA2019-2129
AIAA2020-2725
AIAA2021-0331

- **Performing analysis led to look at other data sources**
- **12 External Hard Drives + 3 months later…**
  Data was processed on NASA Advanced Supercomputer (NAS)



Seasoned Idea but with New Motivation



- Identify the leverage point where efforts would make the biggest difference.
- Connect ***Communities*** and ***Facilities***
- ***Facilitates advancements in model-based engineering***

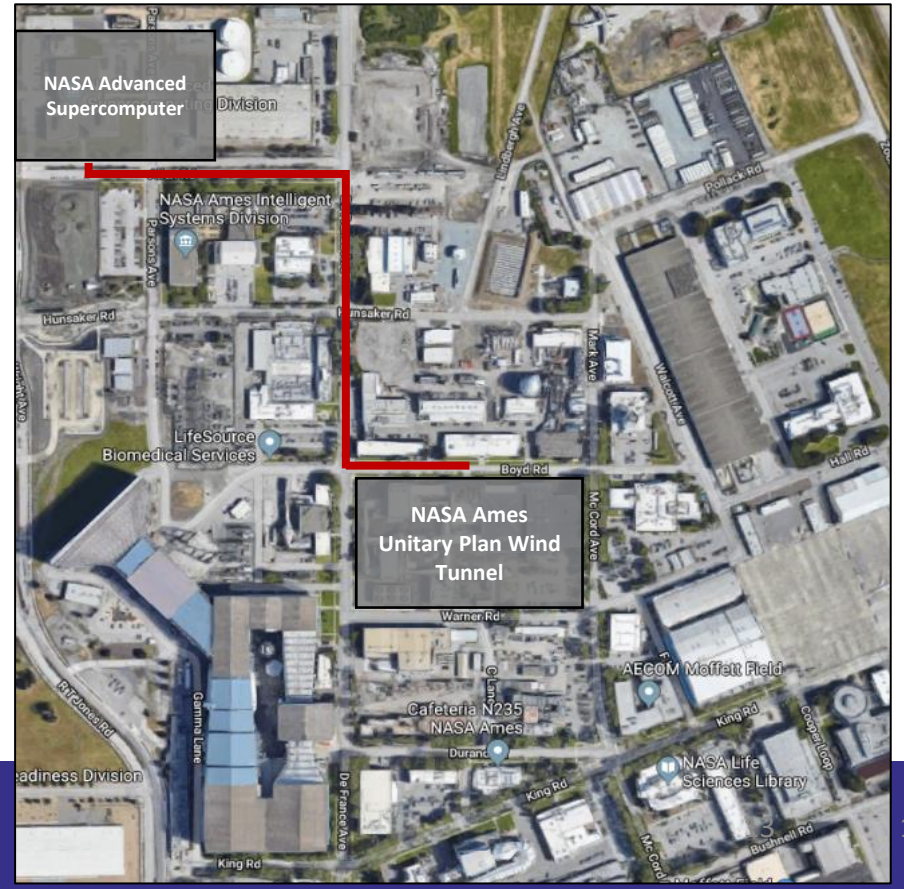
AIAA2020-0516

Project: Red Rover

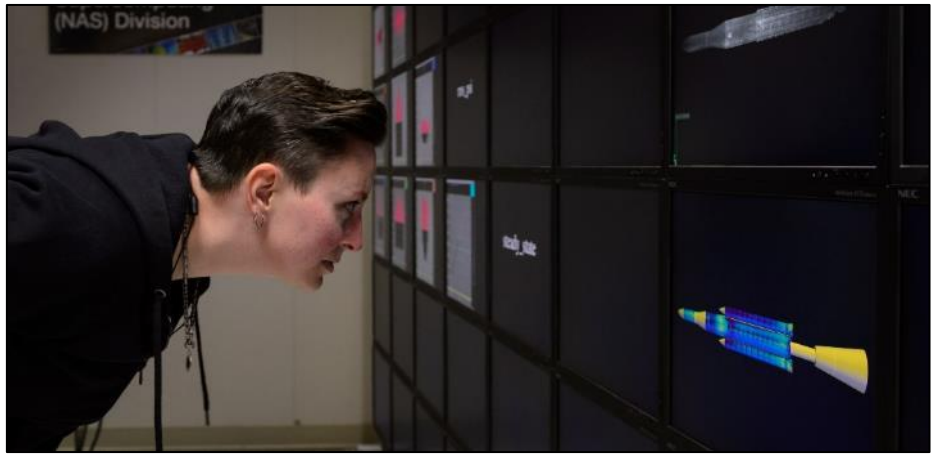
- Established Connection between UPWT to NAS
- Fast, Powerful, Secure, Reliable
- **Transferred**, **Processed**, and **Visualized** in near real-time
- **150 TB of data in 5 days.**

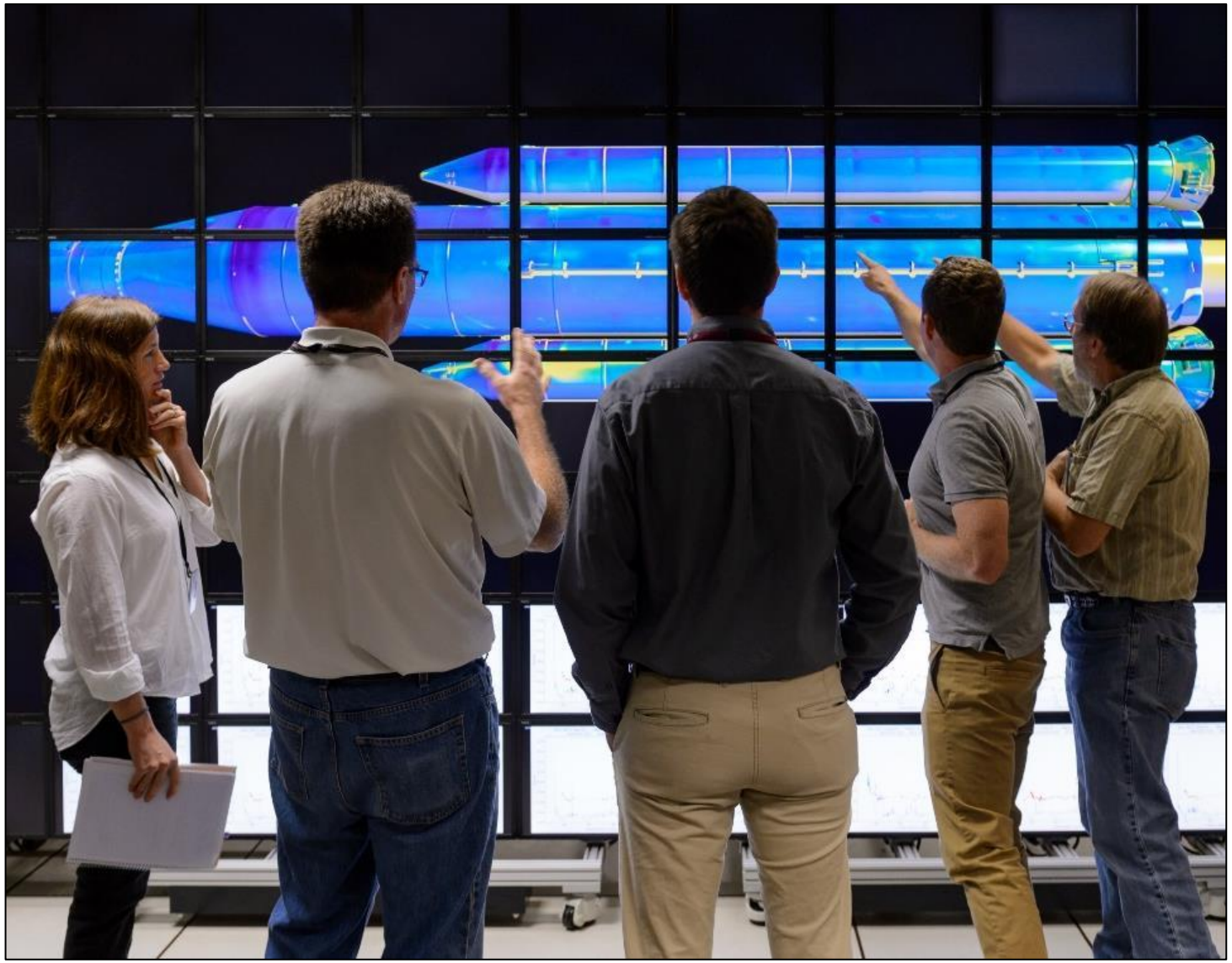
NASA's HECC Goals:

- **Infuse HEC** into NASA's scientific and **engineering communities**.
- Assure preparedness to meet NASA's future modeling, simulation, and **analysis** needs.



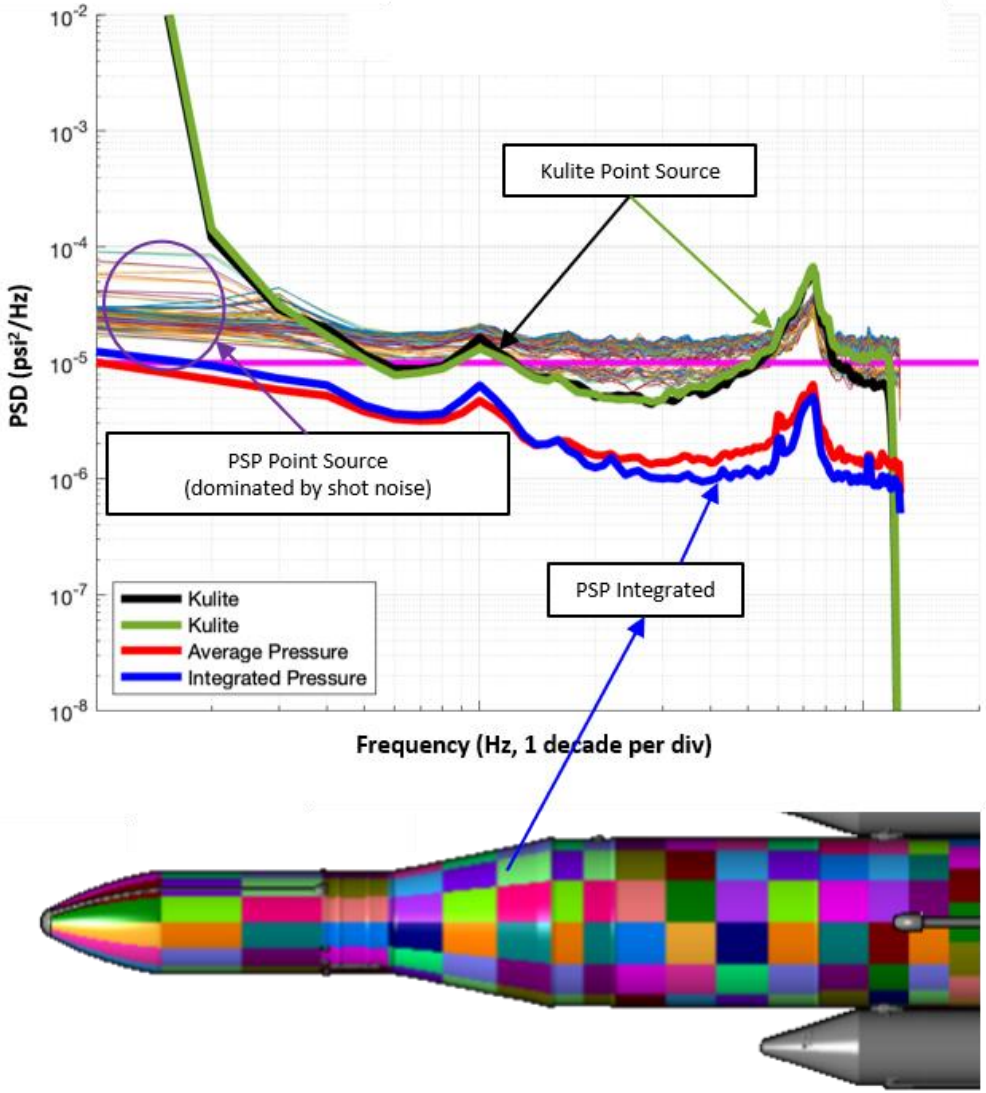
Demonstration Creates Conversation





Unitary Plan Wind Tunnel → NASA Advanced Supercomputer ⇢ Remote User

Data Products Produced by uPSP



From Months to Hours:

- Processed 120 Test Conditions x 300 patches
- Transferred via NAS to SLS NASA/Boeing
- SLS NASA/Boeing ran FEM process (~16 hours)

What's the value:

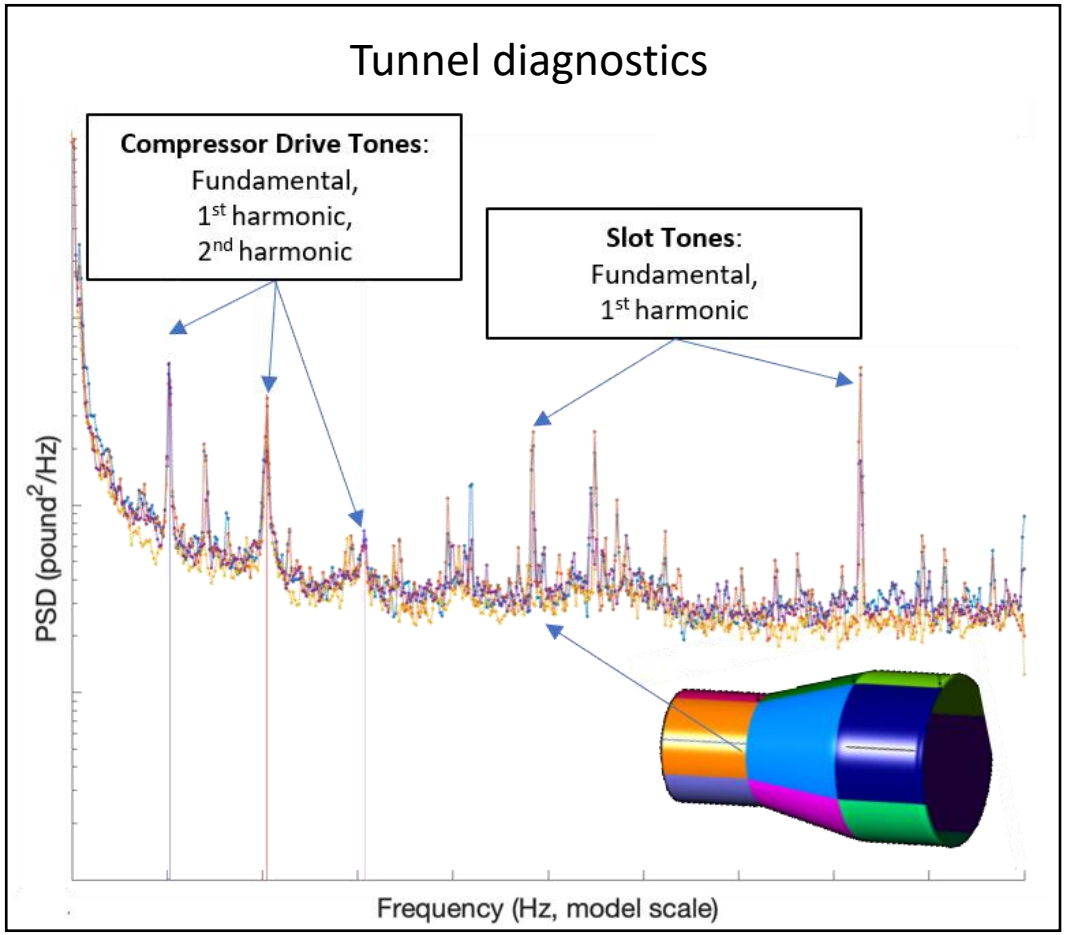
- Benefit was ability to run a wide range of test conditions.
- Data showed:
  - good variation in levels and frequency in high-noise regions.
  - *Area with noise floor concerns*.

Collaboration with SLS program and Boeing has helped the team understand applications and requirements for spacecraft and aircraft wind tunnel models and how the data is used for acoustic analysis.

DISCLAIMER: More development here presented in next presentation by Bremner, Shaw-Lecerf, Li, & Roozeboom.

Data Products Produced by uPSP

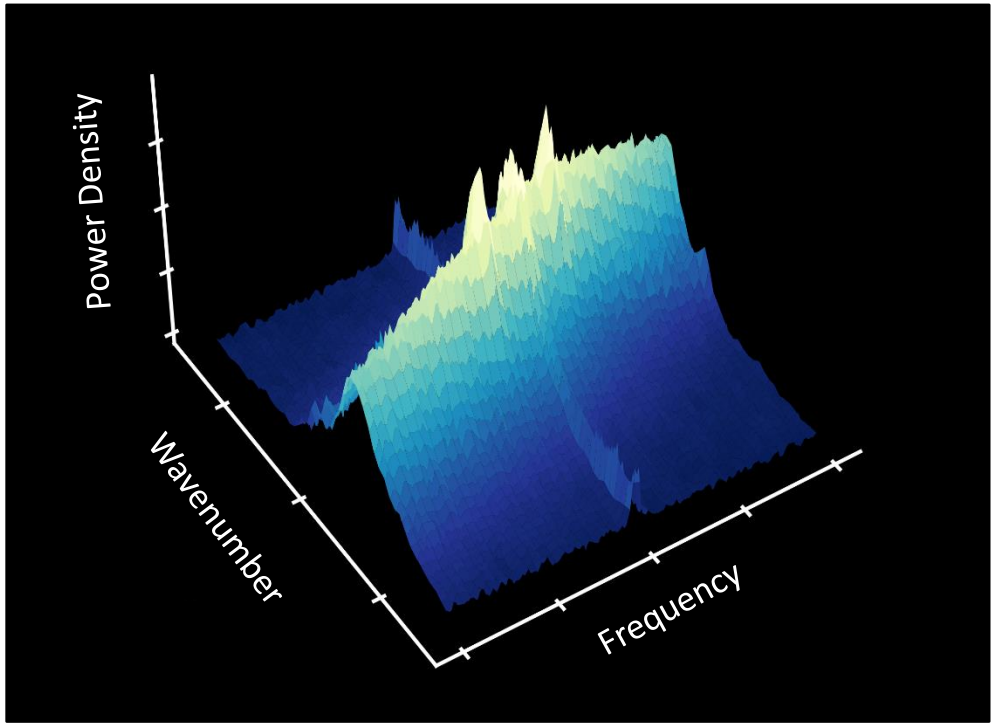
Tunnel diagnostics



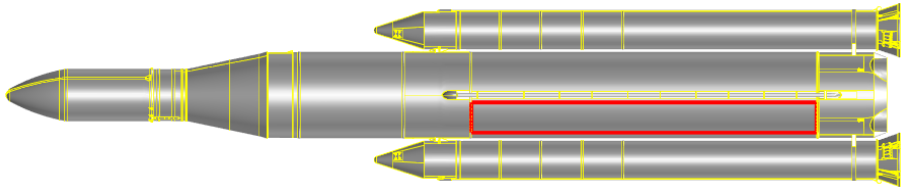
- The uPSP data over large area was integrated.
- Aerodynamic flow features and shot noise are removed.
- Remaining spectral peaks are tunnel tones.

Turbulent Boundary Layer Convective Speeds

Wavenumber-Frequency Pressure Spectrum

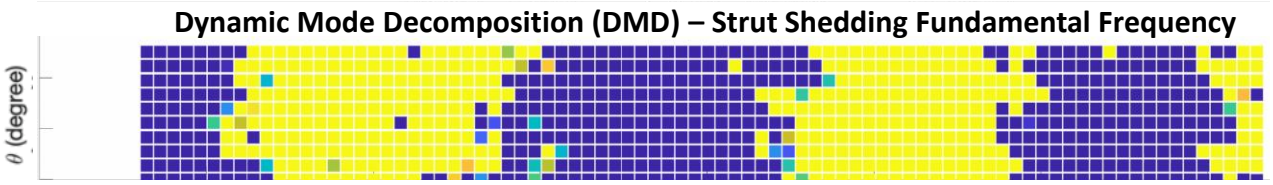


Wavenumber-Frequency Analysis: Strut Shedding and 1st Harmonic

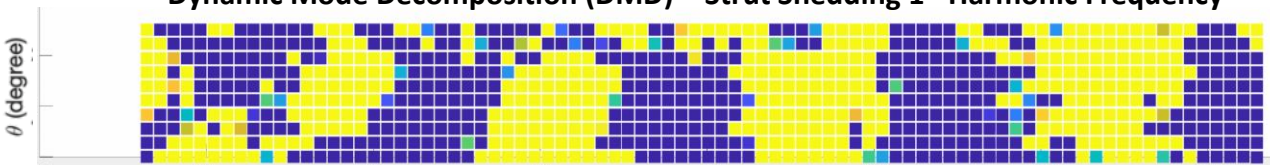


Data is from a portion of SLS Core from Sept 2019 uPSP demonstration.

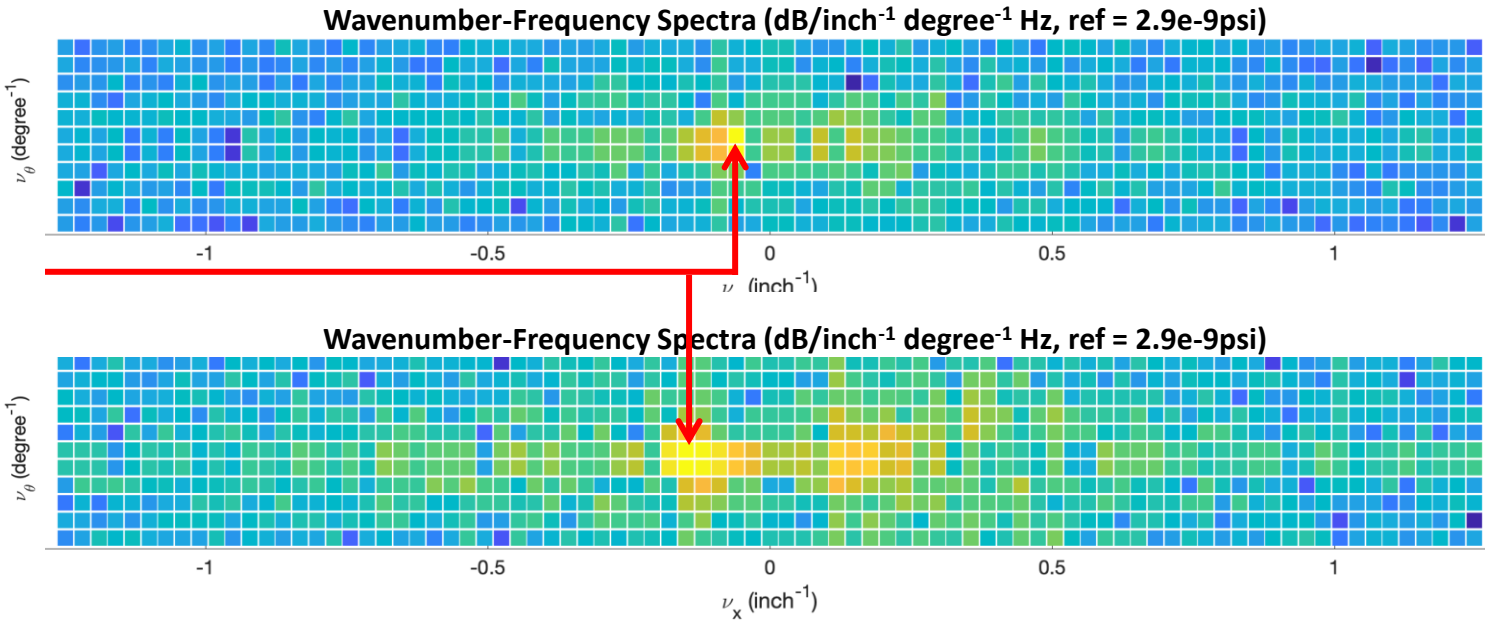
AIAA 2020-0141



DMD demonstrates the flow from strut is moving upstream.



Wavenumber-Frequency Analysis confirms flow is traveling upstream in the Boundary Layer with a value <0.

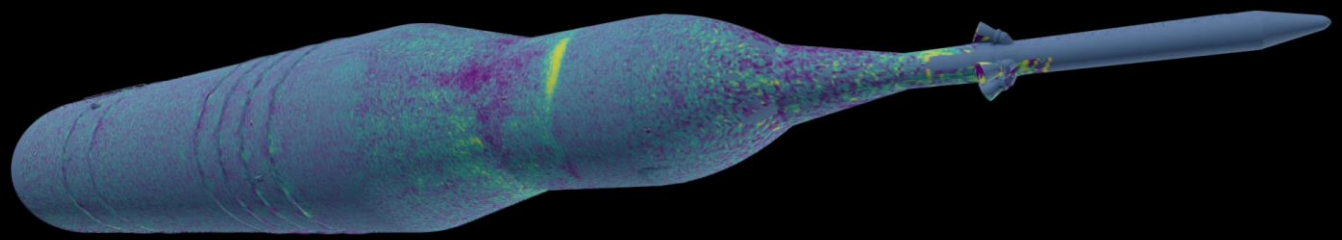


Summary

- Measurement of Unsteady Surface Pressures is **critical** to design aerospace vehicle
  - Improving the state of the art, will reduce margins
  - Develop uPSP technology - from research lab to a production wind tunnel **capability**
- **Must** connect *Experimental* and *Computation* Facilities and Communities
  - People + Facilities + Tools
  - Facilitate advancements in model-based engineering, data-driven modeling,
  - 'Get the data in the right environment'
- AETC uPSP Capability Challenge Project - Demonstration Creates Conversation
  - Advance the state of the art in …
  - Real-time steering of wind tunnel experiment

Interested in collaboration?
Nettie.Roozeboom@nasa.gov

Acknowledgments



NASA uPSP Capability Challenge Team
NASA Ames Research Center's Unitary Plan Wind Tunnel
NASA ARMD Aerosciences Evaluations and Test Capabilities (AETC) Portfolio Office
NASA Space Launch System (SLS) Program
NASA High-End Compute Capability (HECC)
NASA Engineering and Safety Center (NESC), Aerosciences and Structural Dynamics Technical Discipline Teams