Real-Time NASA Wind Tunnel Data Analysis with HPC

Connecting the Ames Unitary Plan Wind Tunnel to NASA Advanced Supercomputing

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Smart Labs of the Future

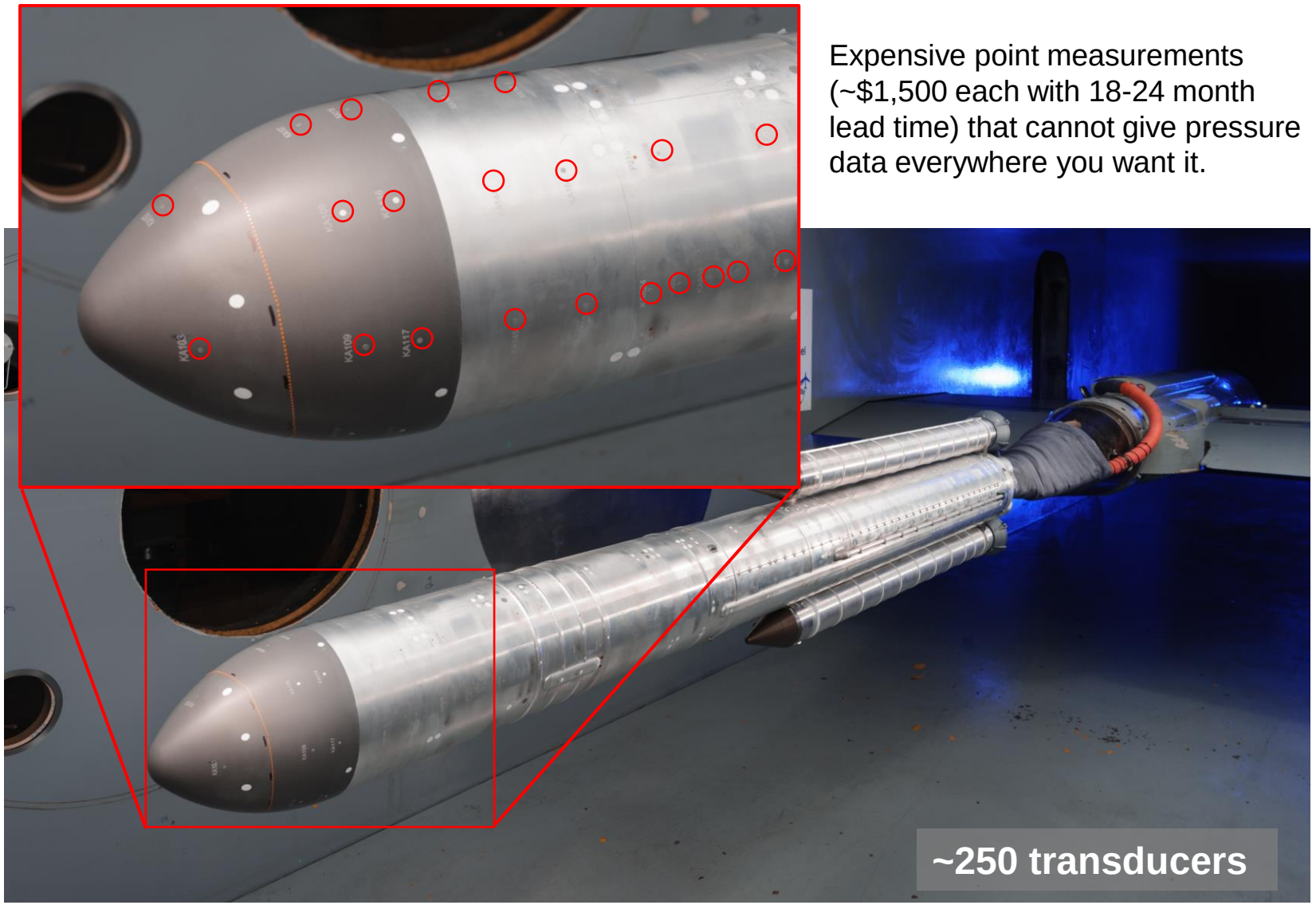
Exascale Computing Roundtable

28 May 2025

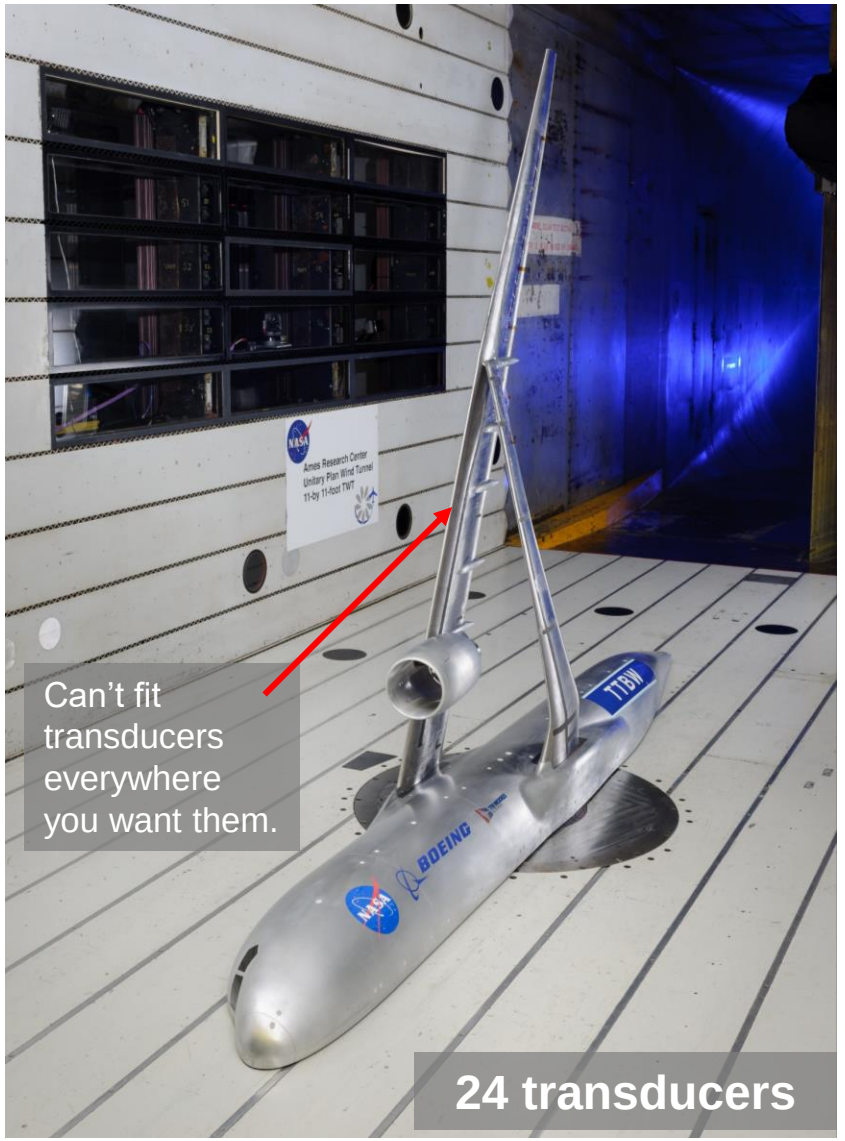


A Need for Innovation

Expensive point measurements (~$1,500 each with 18-24 month lead time) that cannot give pressure data everywhere you want it.

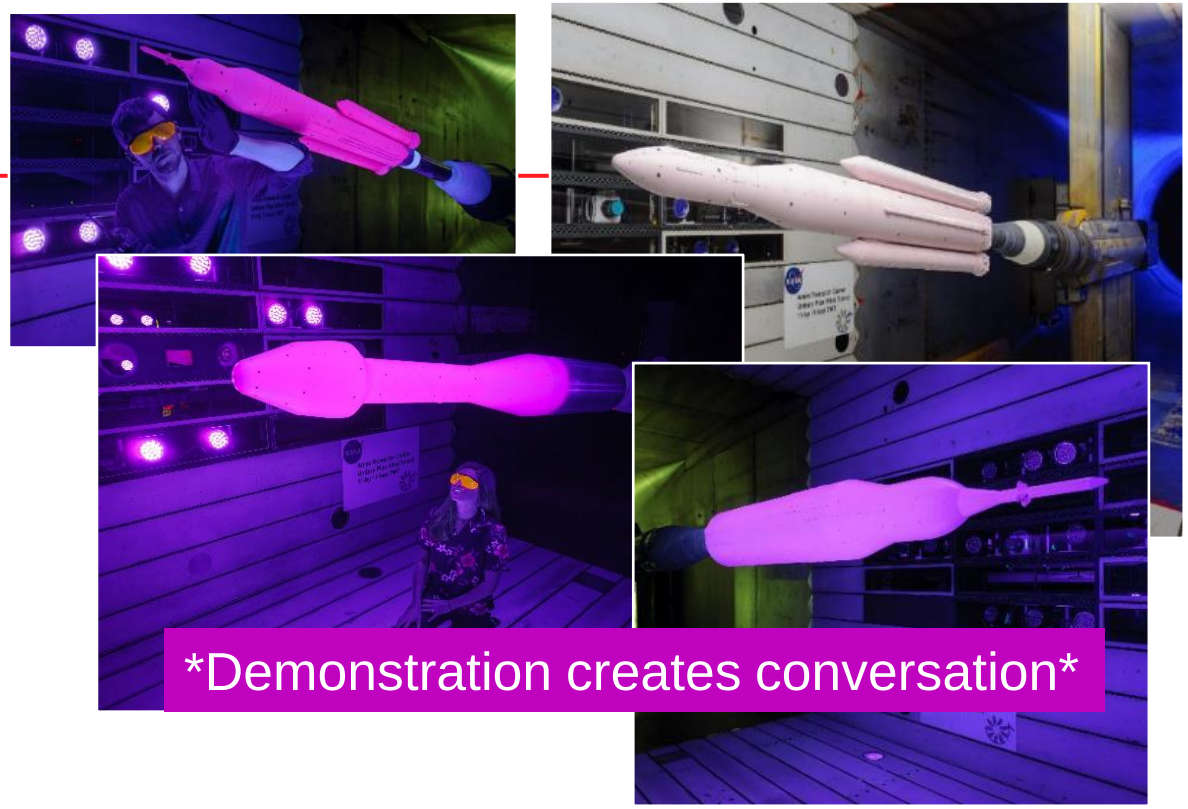


NASA ARC Unitary Plan Wind Tunnel (UPWT)
Supersonic 9-by 7-Ft



NASA ARC Unitary Plan Wind Tunnel
(UPWT) Transonic 11-by 11-Ft

What is uPSP?

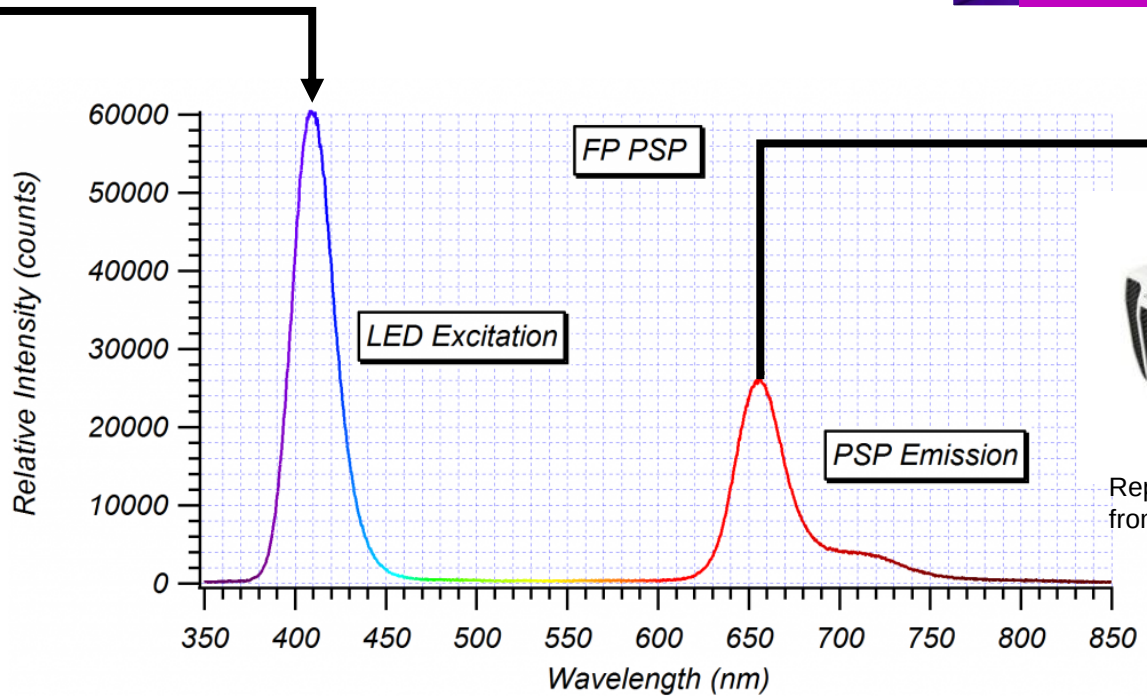


Unsteady Pressure-Sensitive Paint

1. Apply porous, fast-response PSP to model
2. Illuminate paint with 400 nm light source
3. Paint emission intensity is a function of pressure
4. Measure emission with high-speed cameras



Reproduced with permission from ISSI





Reproduced with permission from Vision Research, Inc.

-8 high-speed cameras
-1.5MP
-10k fps
-40 lamps

Paradigm Shift: New State-of-the-Art **System**

World-Class Transonic Wind Tunnel Leveraging World-Class High-Performance Computing

NASA Ames UPWT - 11 x 11-ft Test Section (Transonic)







NASA Advanced Supercomputing Division (NAS)



Single-mode fiber

"This is a **paradigm shift** from how ground testing has historically been executed."
–Dr. Ron Colantonio, NASA Director of AETC

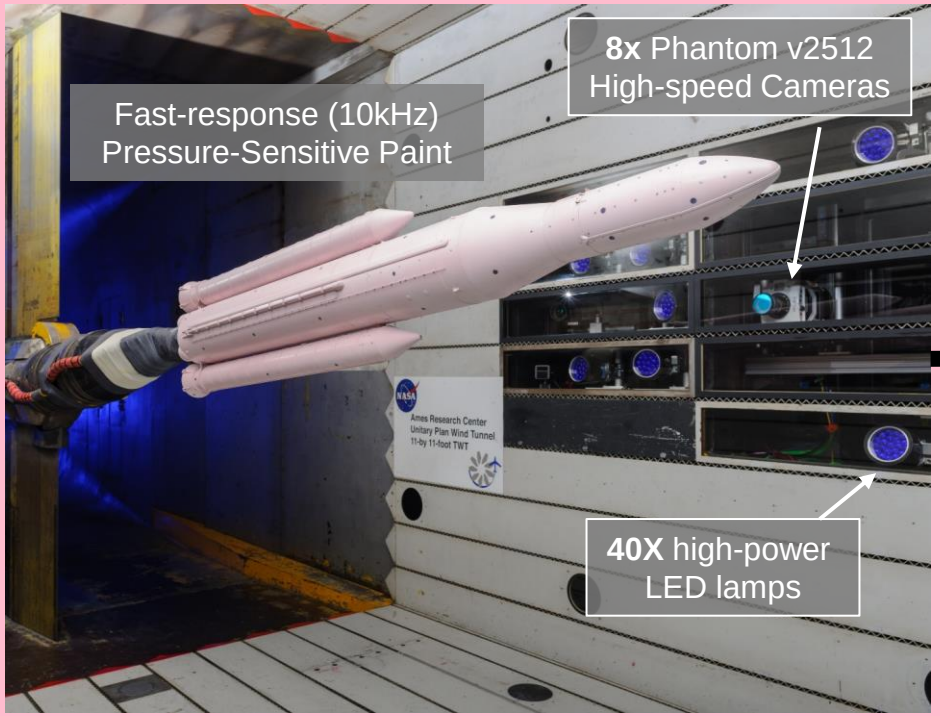
DARWIN Project, 1990s

Koga, D., Korsmeyer, D., and Schreiner, J., "DARWIN Information System of NASA – An Introduction", AIAA Advanced Measurement and Ground Testing Conference, New Orleans, LA, June 1996. https://doi.org/10.2514/6.1996-2249

Paradigm Shift: New State-of-the-Art **System**

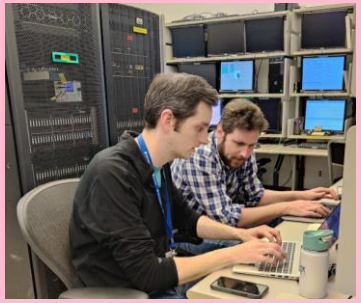
World-Class Transonic Wind Tunnel Leveraging World-Class High-Performance Computing

NASA Ames UPWT - 11 x 11-ft Test Section (Transonic)



Data Acquisition





NASA Advanced Supercomputing Division (NAS)



uPSP Data Processing Software + long-term data storage

Single-mode fiber

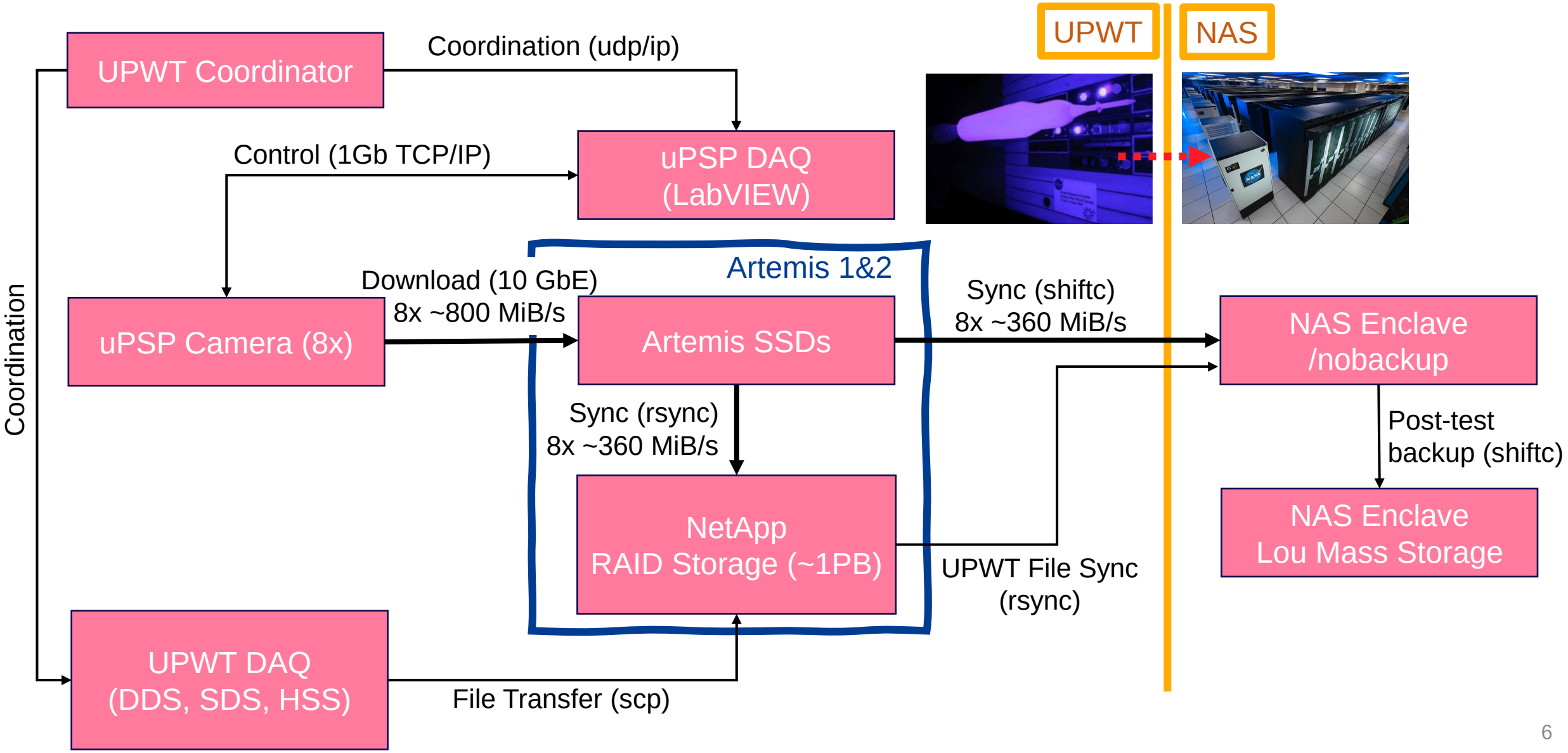
https://github.com/nasa/upsp-processing

"This is a **paradigm shift** from how ground testing has historically been executed."
–Dr. Ron Colantonio, NASA Director of AETC

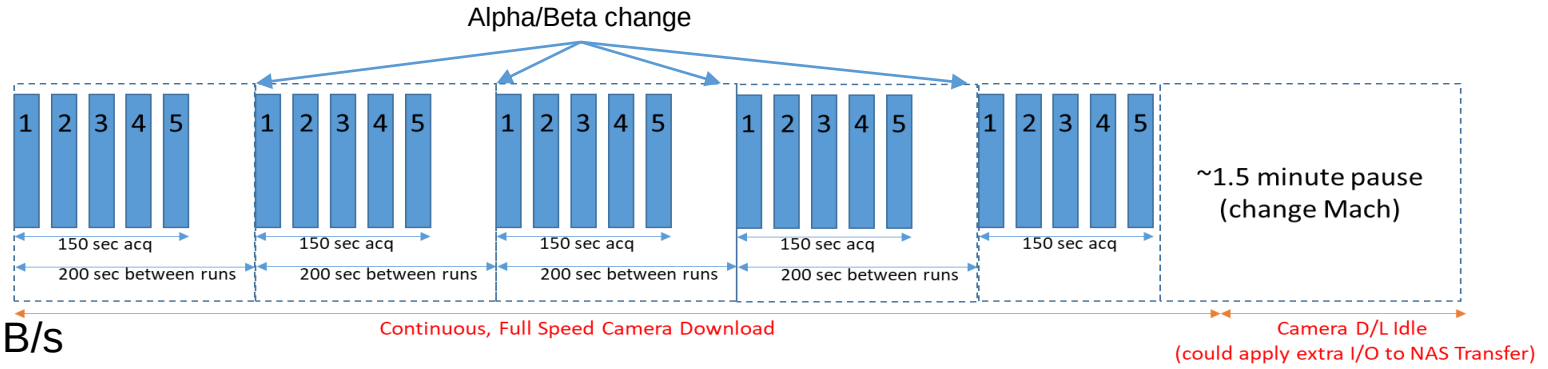
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Project: Red Rover 2.0



PSP Time Per Data Point



"Reference Acquisition use case" from Red Rover Requirements document

- 7 partitions, (~30,000 frames, ~40 GB)
- 10K framerate
  - 3 seconds to acquire, 51-40 seconds to download
- Full res 1.5 MB/frame, download rate 0.8-1.0 GB/s
- Will require tunnel to wait for data offload before moving to next run

Nominal file sizes:

- Lifetime video 1 s @ 20 kHz → 29 GB
- Intensity video 5 s @ 10 kHz → 72 GB

Transfer time: 100 GB / 0.36 = ~5 minutes per complete datapoint

Processing times: using 38 nodes for 6 cameras

- Camera-to-model registration (lifetime): ~3 minutes
- Lifetime processing (20,000 frames): ~2 minutes
- Intensity processing (40,000 frames): ~4 minutes
- SPOD: ~30 seconds

End-to-end time: 2 min download + 5 min transfer + 10 min processing ≈ 15 minutes

uPSP Processing Software

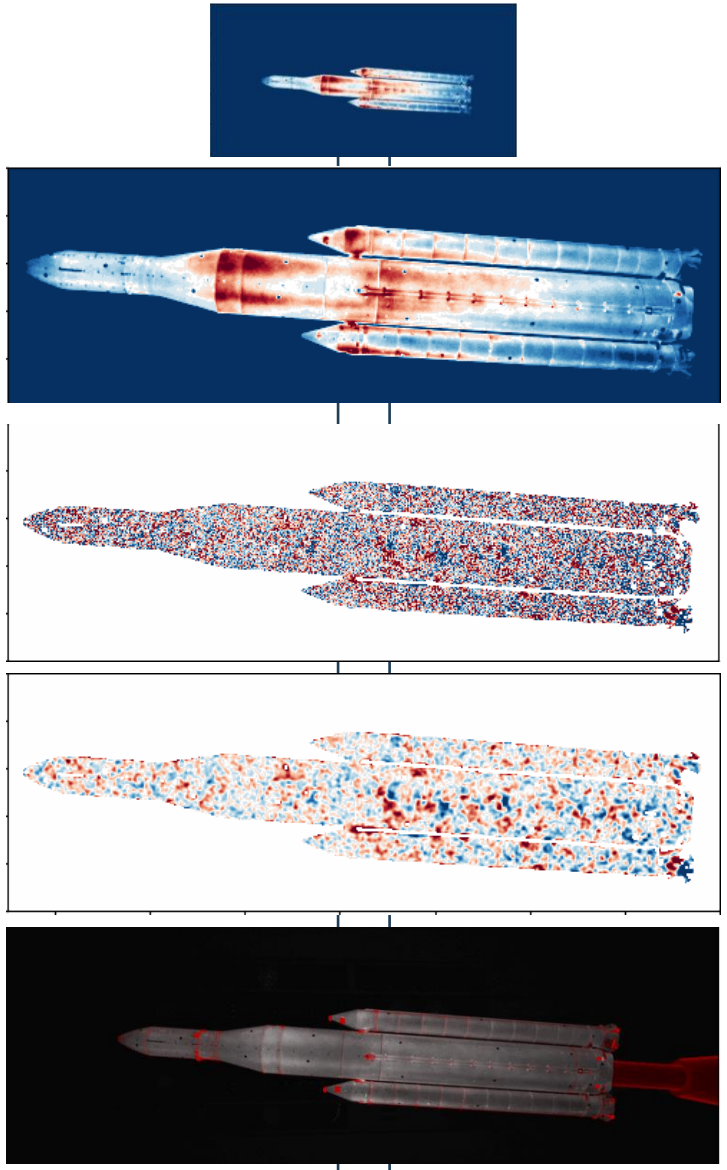
Raw video frames

Registration
Mitigate frame-to-frame vibration

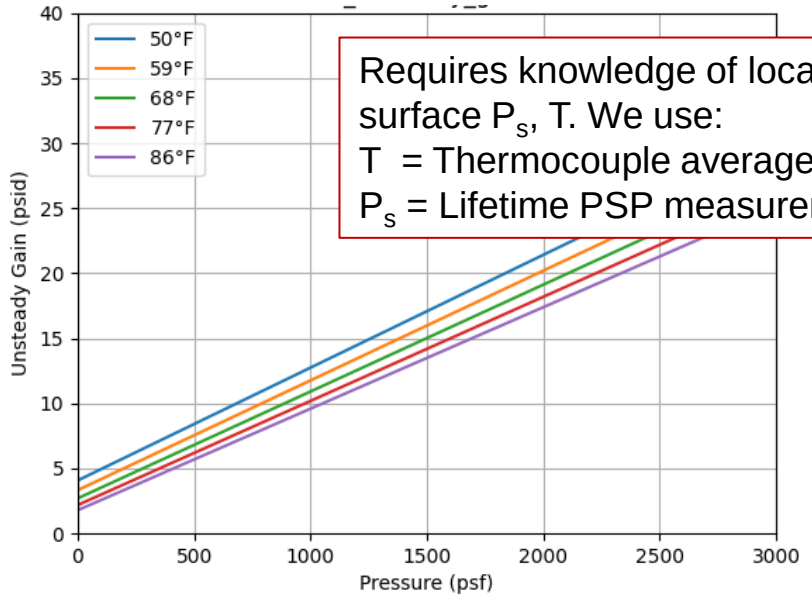
Intensity Ratio
$R[k] = Counts_{mean} / Counts[k]$
($R \propto$ Surface Pressure)

Denoising
Image filtering

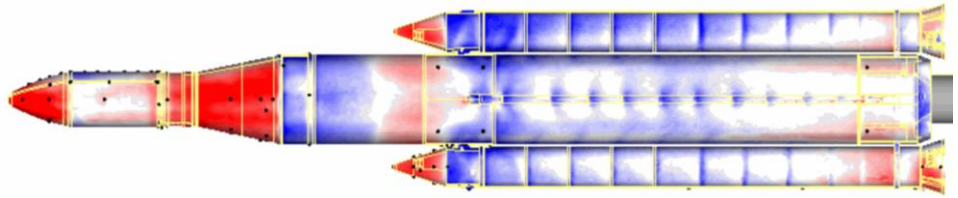
3D Projection
2D-3D correspondances



3D Surface Pressure
$P[k] = Gain(P_s, T) \times R[k]$



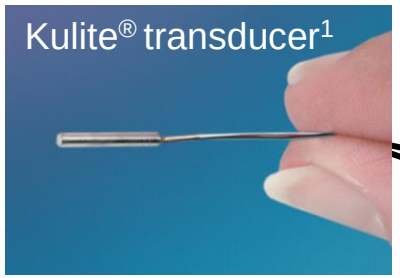
Requires knowledge of local surface P_s, T. We use:
T = Thermocouple average
P_s = Lifetime PSP measurement



Open-Source processing code:
https://github.com/nasa/upsp-processing

What's Better About uPSP?

Transducer-based dB level (**measured + interpolated)**
(courtesy T. Steva, NASA Marshall)



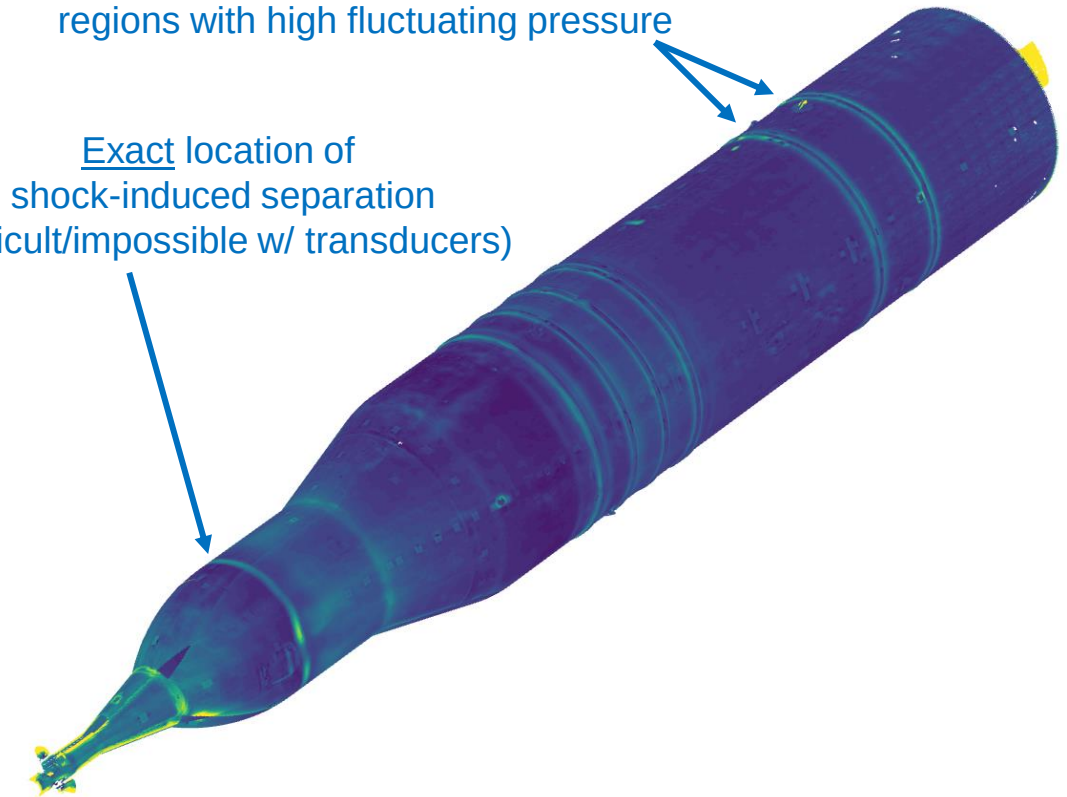
Interpolation of transducers can yield unrealistically large areas of high fluctuating pressure

Current State-of-the-art
("100's of measurements")

Unsteady PSP dB level (**measured)**

Quickly identify narrow spatial regions with high fluctuating pressure

Exact location of shock-induced separation (difficult/impossible w/ transducers)



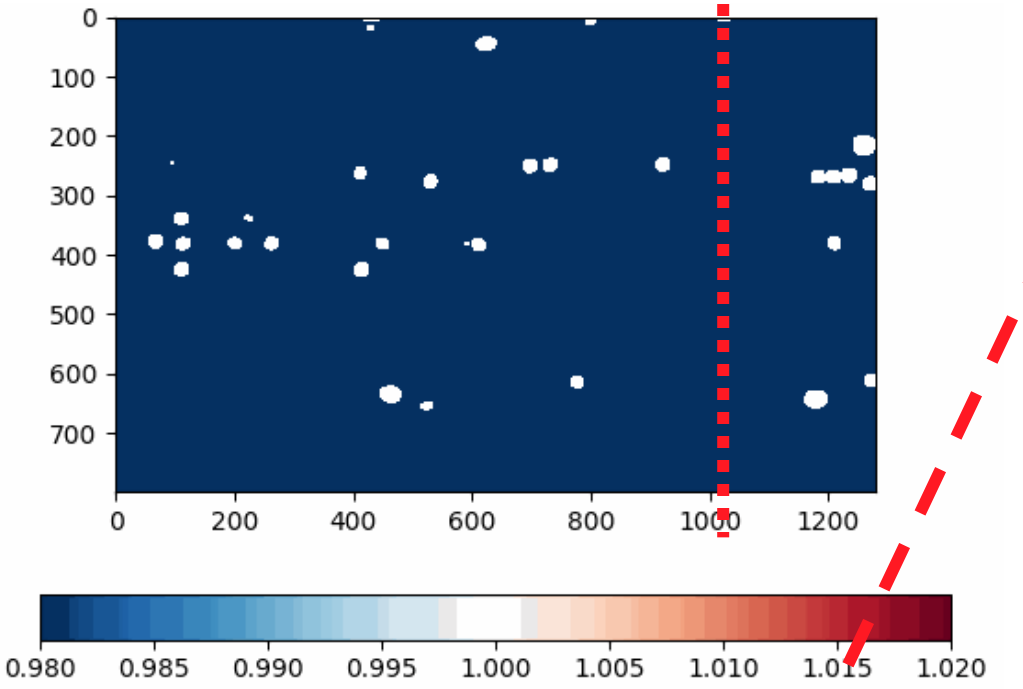
Future State-of-the-art
("1 million measurements")
Spatial Resolution Increased 10,000 X

[1]*Reproduced with permission from Kulite Semiconductor Products, Inc.*

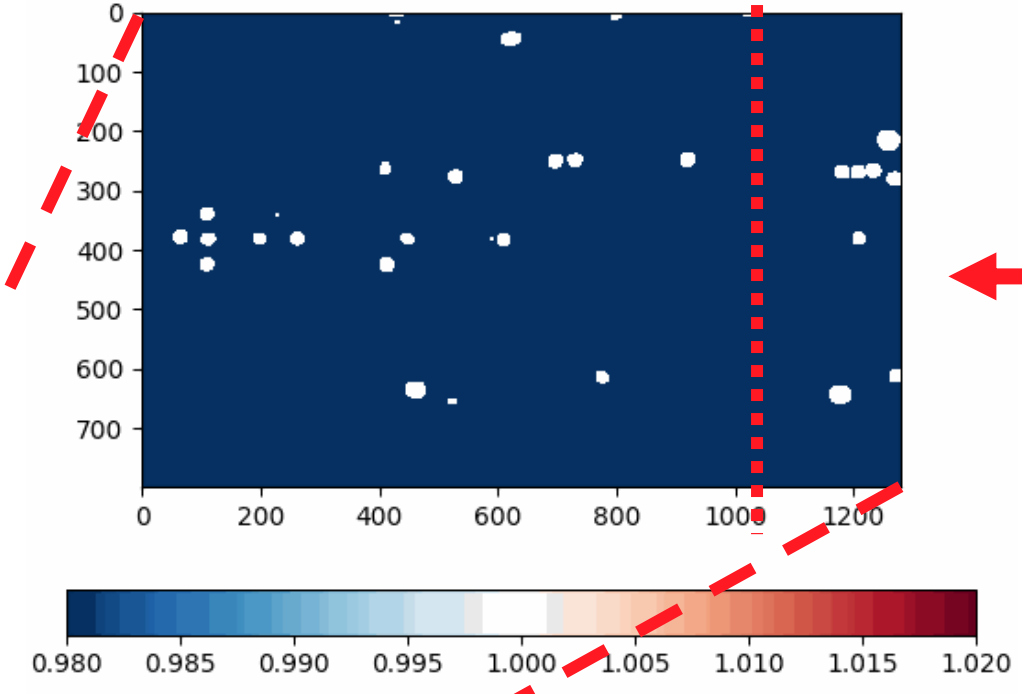
uPSP Data: Intensity Mode

"Raw" intensity ratios in 2D image plane
Frame-to-frame vibration removed

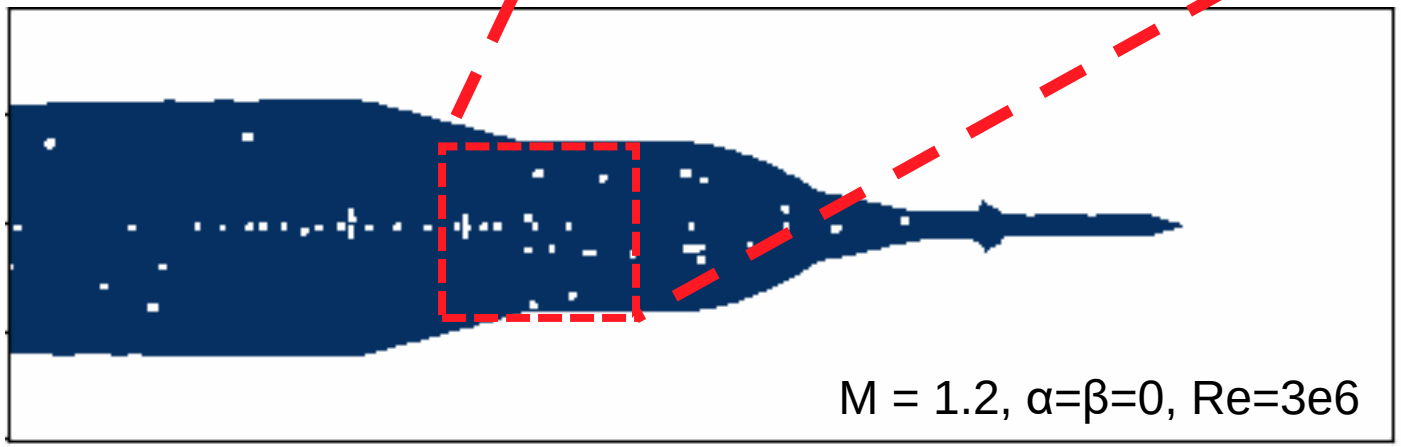
M = 0.95, α=β=0, Re=3e6



M = 1.2, α=β=0, Re=3e6



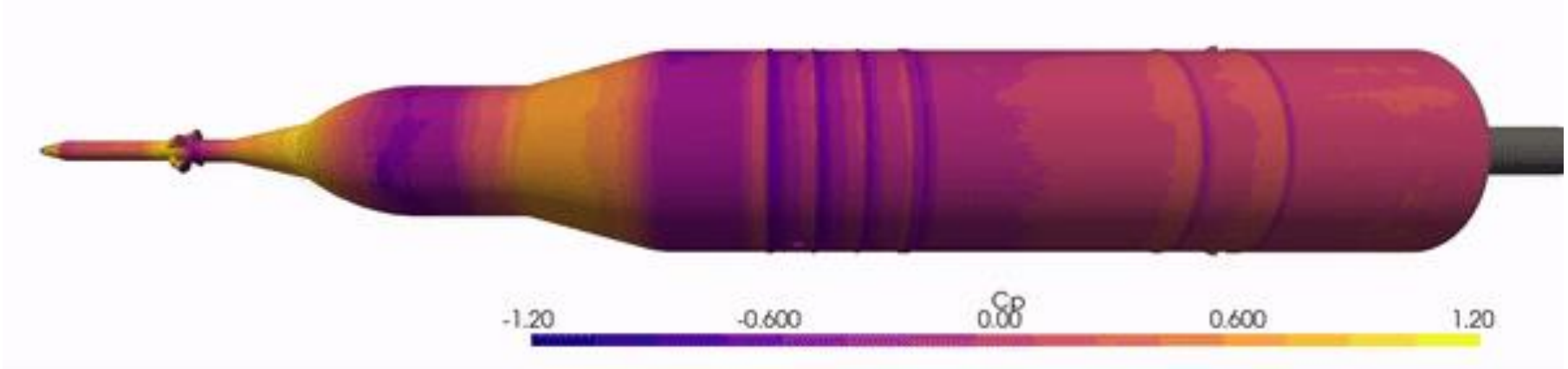
Flow



M = 1.2, α=β=0, Re=3e6

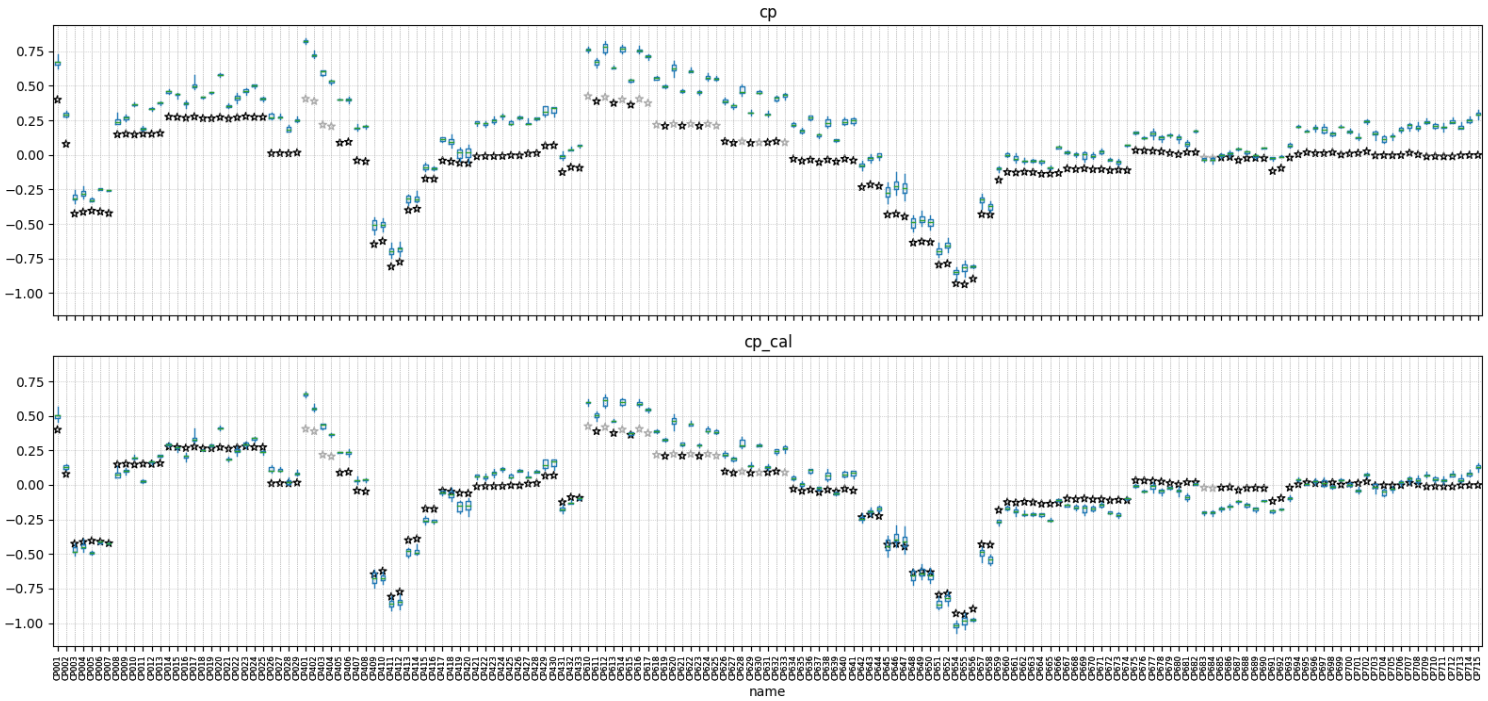
uPSP Data: High-Speed Lifetime

Mach 1.2
$\alpha = \beta = 0$



Flow

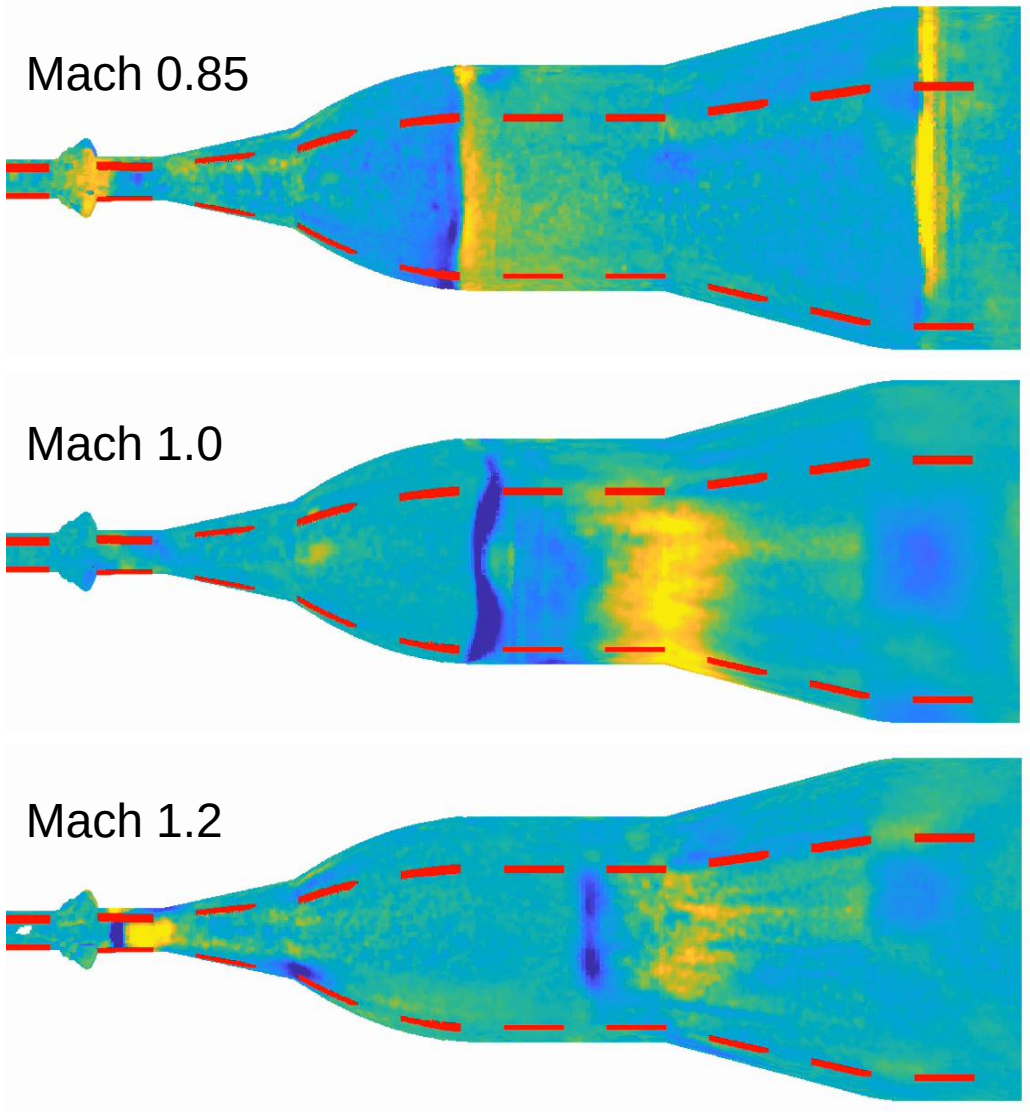
Mach 0.8
$\alpha = \beta = 0$



Data Products

- High spatio-temporal resolution
- Easily evaluate both dominant and non-dominant features
- Isolate frequencies
- Evolution in phase and time

- 1st SPOD mode at the same frequency
  - Animated in phase
  - Wake from the launch abort nozzles
  - Unsteady shock footprint
  - Pockets of turbulent separation





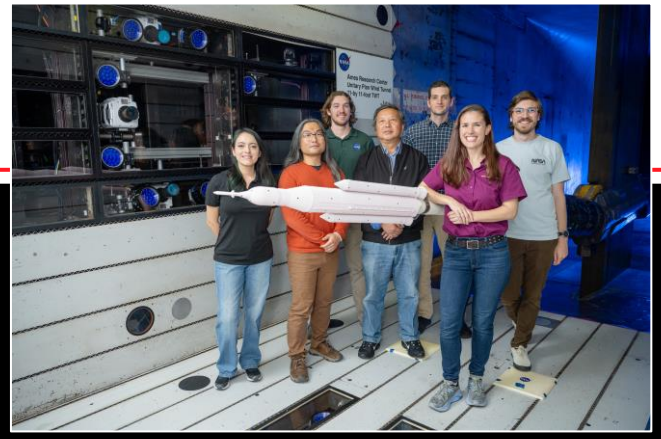




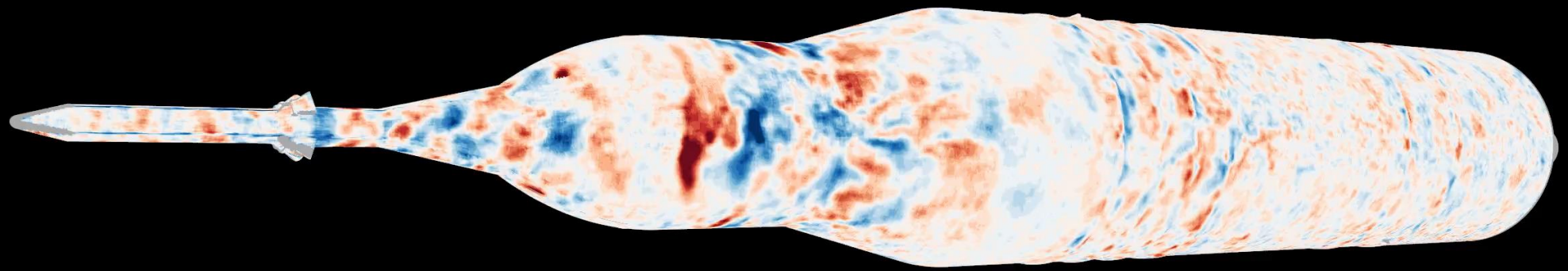


Any Questions?

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M=0.95, α= 2, β=0

It's not CFD, it's PSP!

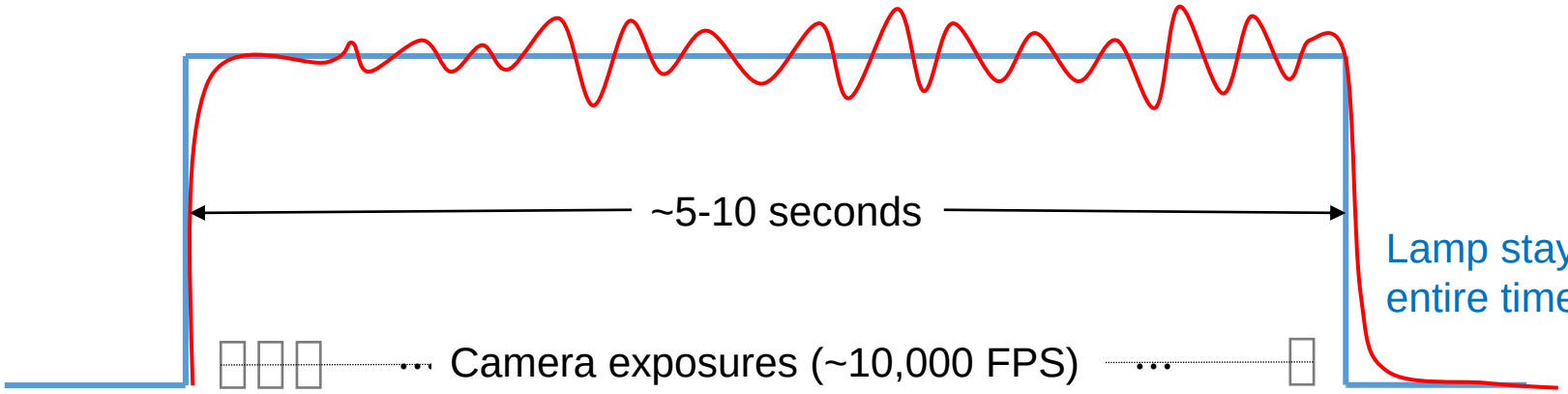
"All in all, for someone who was immersed in, fascinated by, and dedicated to flight, I was disappointed by the wrinkle in history that had brought me along one generation late. I had missed all the great times and adventures in flight."
~ Neil Armstrong (1947)

How Do We Use the Paint?

There are (2) common methods to use PSP to measure pressure.

Technique #1: "Intensity" Mode

PSP luminescence fluctuates based on instantaneous local pressure
(Lower pressure = more light from paint)



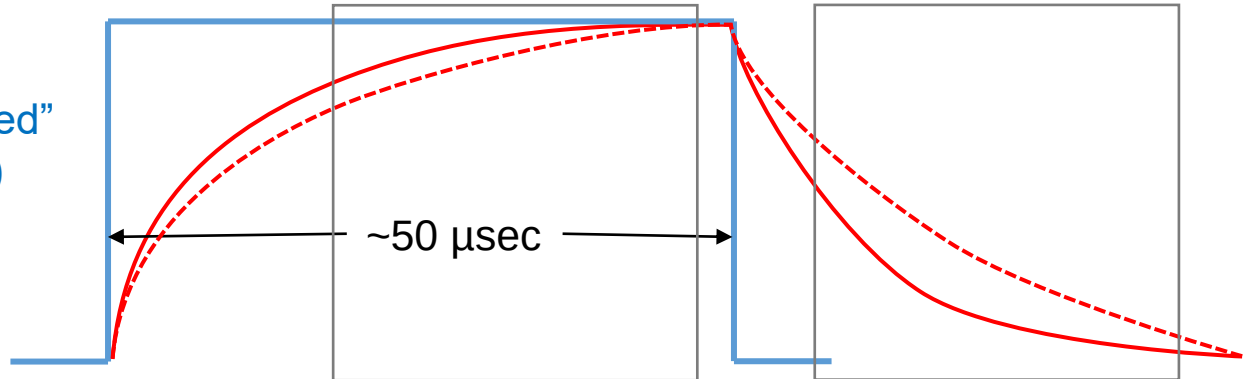
Challenge: How do we know what measured light intensity corresponds to what pressure?

- Common solution: ratios relative to a known "wind off" condition.
- But paint degrades over time!

Technique #2: "Lifetime" Mode

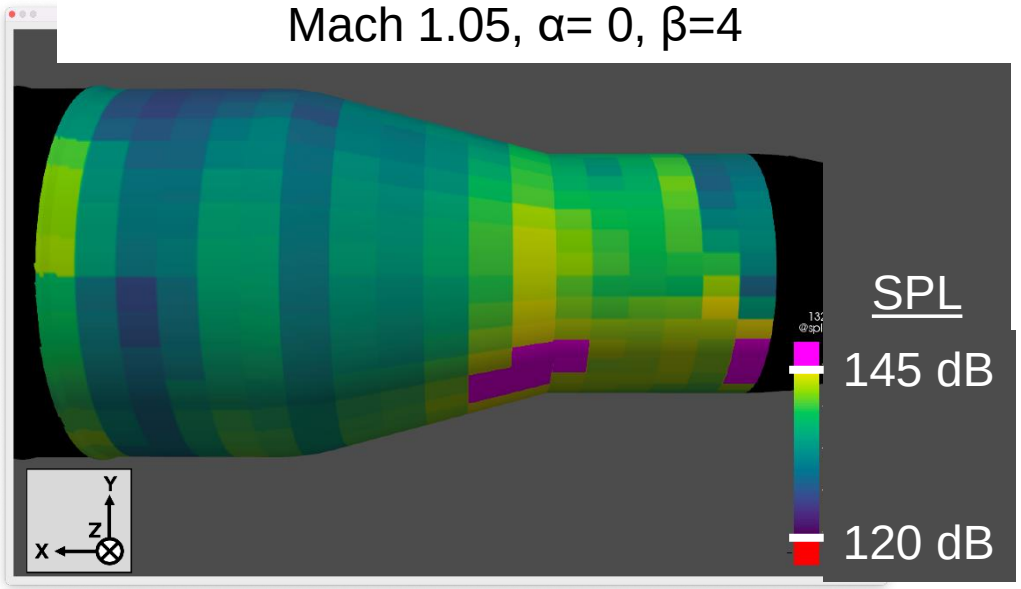
PSP luminescence decay **time constant** changes based on instantaneous pressure

Lamps are "pulsed" (step impulse)



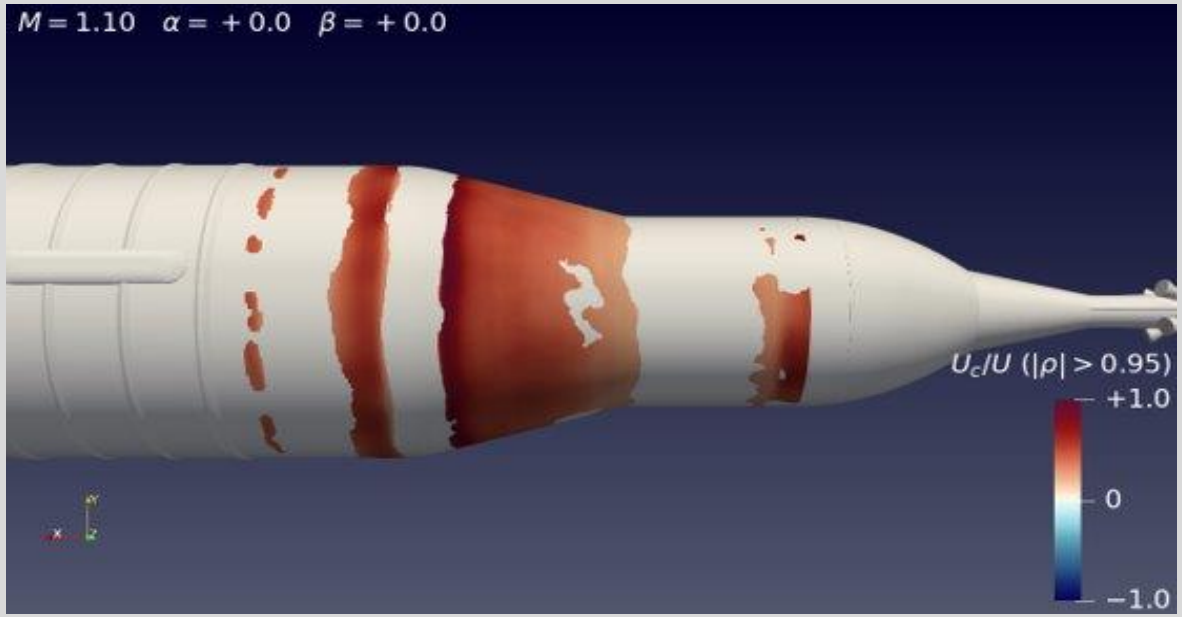
- More robust to paint degradation (+ less degradation)
- Downside: "Gate 2" is really dark → low SNR
- Workaround: average many G1/G2 's to get good data → useful for **average** surface pressure

Data Products

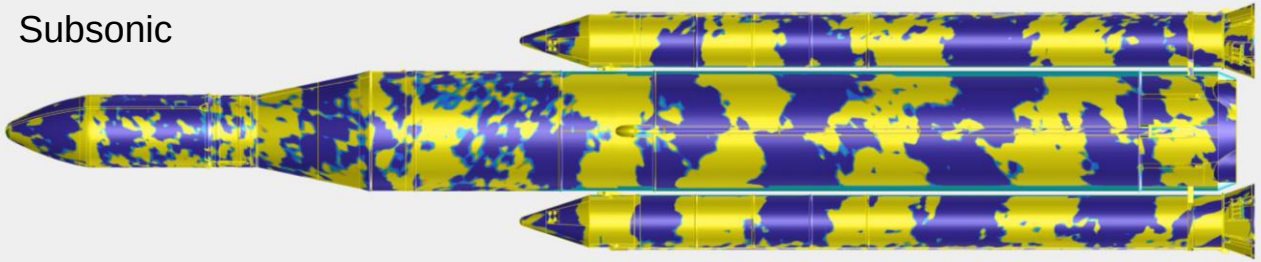


Patch-Integrated force vs. time for input into structural models.

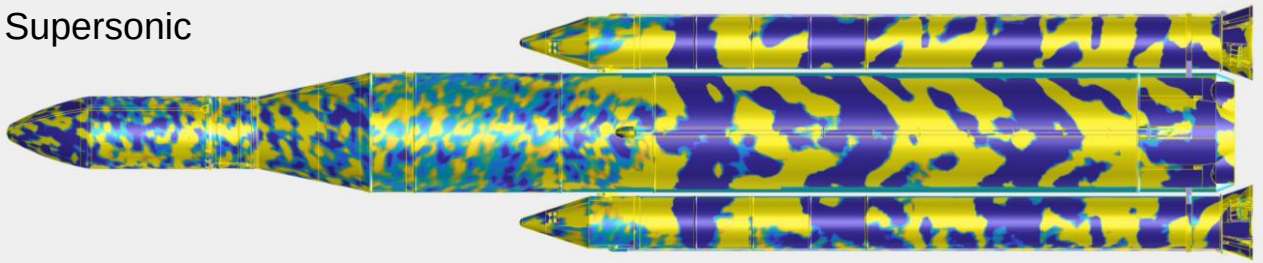
Surface map of TBL convective speed
Does not rely on amplitude cal (uses CSD)
(normally requires a transducer pair @ each location)



Subsonic



Supersonic



DMD mode visualizations across entire model.