



Unsteady PSP in the NASA Transonic Dynamics Tunnel

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Who Made This Work Possible?



- Researchers:
 - Daniel Reese, Neal Watkins, Sarah Peak, Kyle Goodman.
- Collaborators:
 - Wind tunnel personnel at TDT.
 - Aeroelasticity Branch — Bill Stevens, Bret Stanford, Francesco Sorrana, Mike Ramey, Pat Heaney, Ian Giles, Pawel Chwalowski, Dave Piatak.
 - NASA Ames — Nettie Roozeboom, Lara Lash, Marc Shaw-Lecerf, Kenny Lyons, Nick Califano.
- Funding for this work provided by the following programs in NASA:
 - Transformational Tools and Technologies (TTT) Innovative Measurements (IM) subtask
 - TTT Revolutionary Computational Aerosciences (RCA) subtask
 - Aerosciences Evaluation and Test Capabilities (AETC)
 - Revolutionary Vertical Lift Technology (RVLT) Project
 - NASA Langley Advanced Measurements and Data Systems Branch (D304)



➤ Background

- uPSP (measurement technique)
- TDT (wind tunnel facility)

➤ Measurements

- Hardware (enclosures, cam, lights)
- Software (processing — 2D intensity → 3D mapped P)
- Datamine (postprocessing — P time hist, PSDs, DMD, etc.)

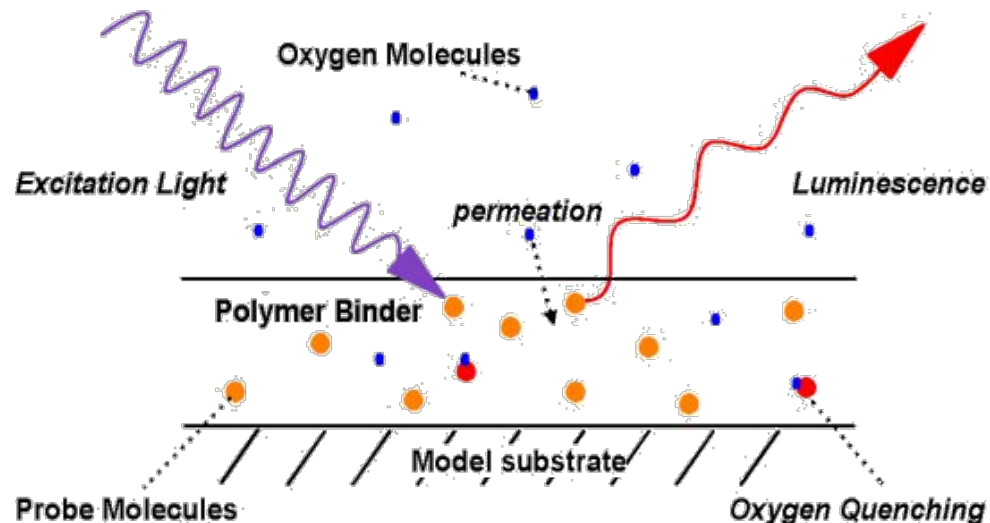
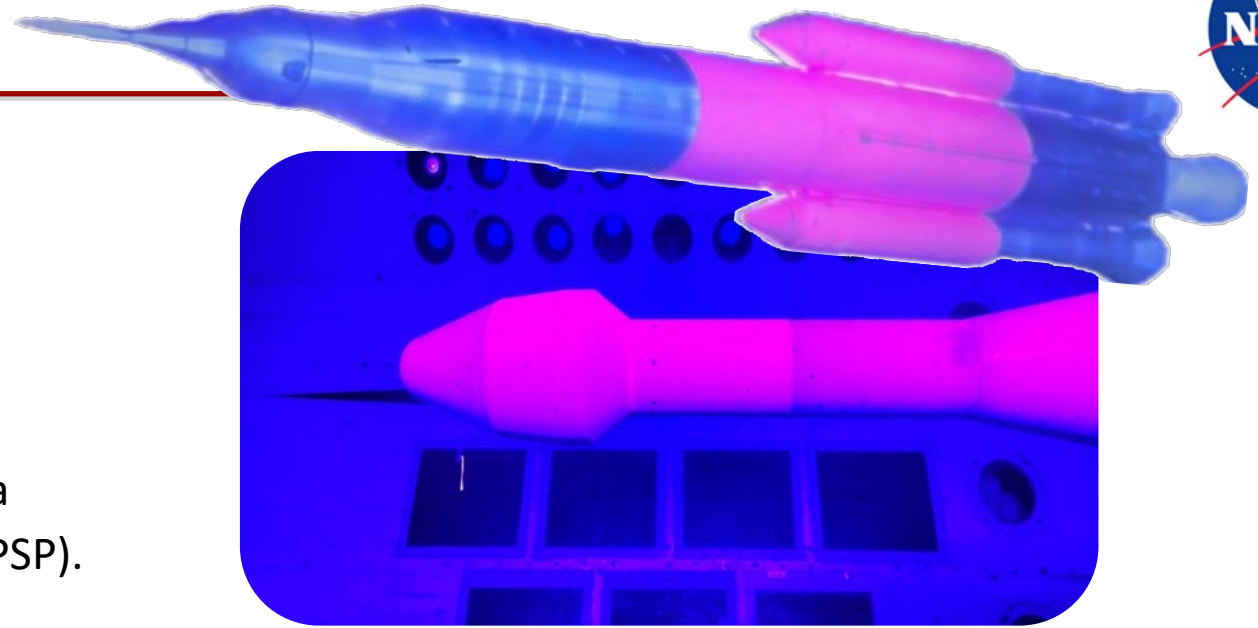
➤ Summary & Conclusions

PSP Technique



Pressure sensitive paint (PSP)

- Powerful optical method providing global measurements of surface pressure.
- Well suited for application in a variety of NASA Langley wind tunnels.
- Can provide time-resolved measurements using a variant of the process known as unsteady PSP (uPSP).



Photophysical Process

1. UV light **excites** luminescent probe molecules suspended in a permeable polymer binder.
2. Excited molecules return to ground state, releasing photons in the process. (i.e. paint **fluoresces**)
3. Emission is **quenched** by oxygen molecules. Higher pressure equates to more O₂, resulting in more quenching.
4. Emission is **captured** by a camera such that darker regions = higher pressure.

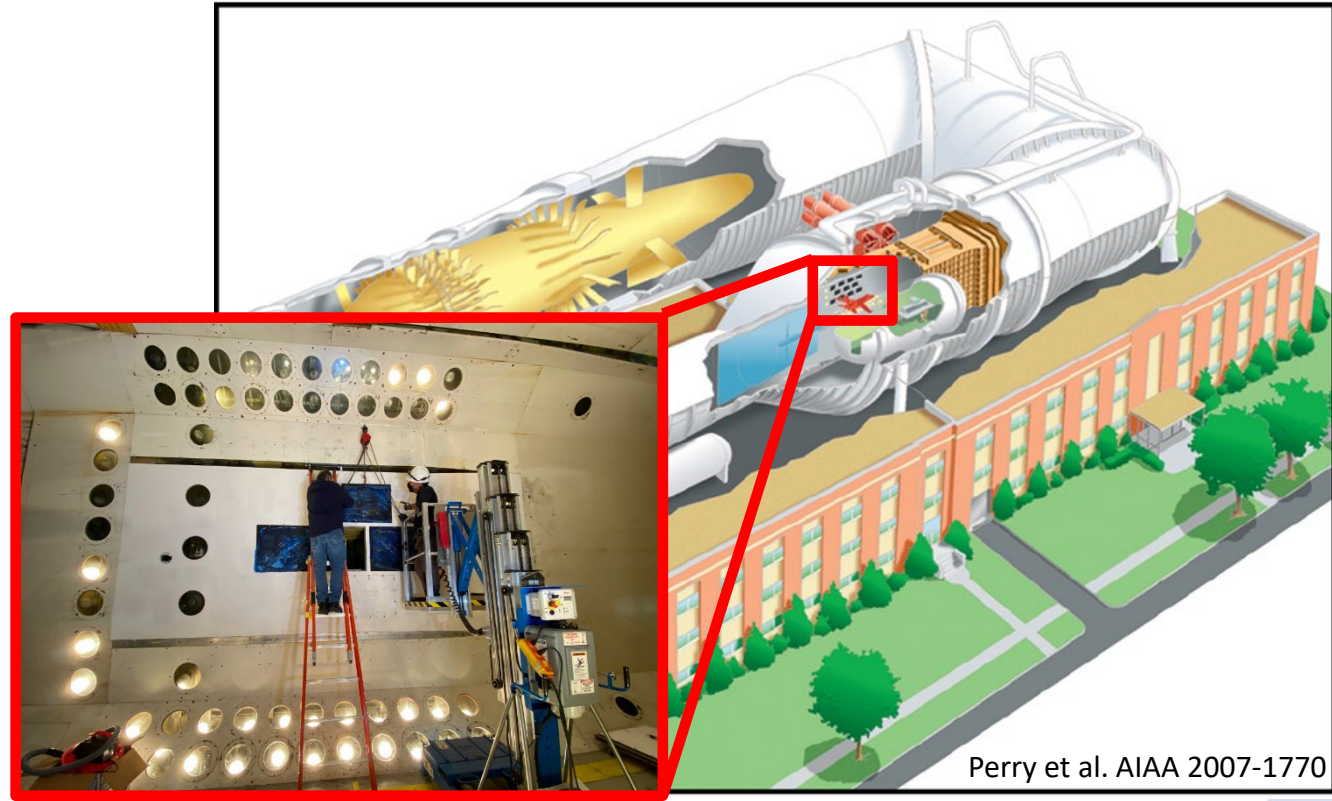
TDT: Wind tunnel facility



Transonic Dynamics Tunnel (TDT)

- Continuous-flow, closed-circuit
- $0 < \text{Mach} < 1.2$
- 16'×16' slotted test section
- $0.01 \text{ atm} < P < 1 \text{ atm}$
- Max Reynolds number of:
 - $9.6 \times 10^6/\text{ft}$ (in R-143a)
 - $3 \times 10^6/\text{ft}$ (in air)
- Max Q: 26 kPa (550 psf) in R-134a
- Optimized for aeroelastic and dynamic testing

TDT is a low pressure, high temperature environment



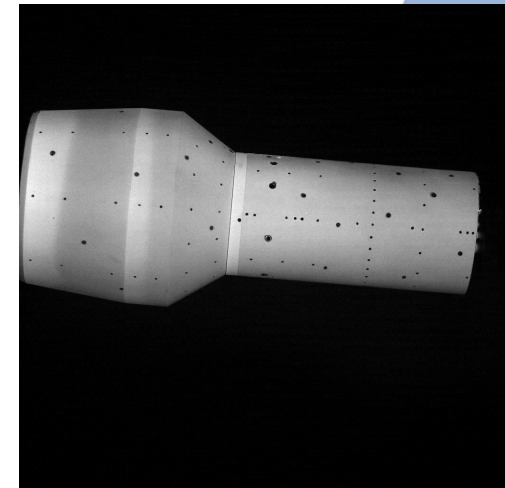
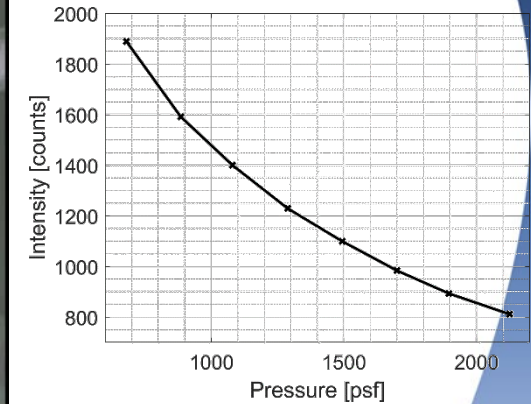
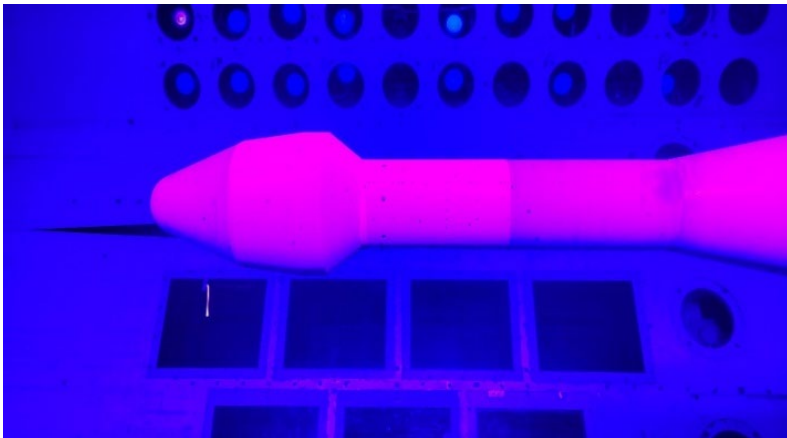
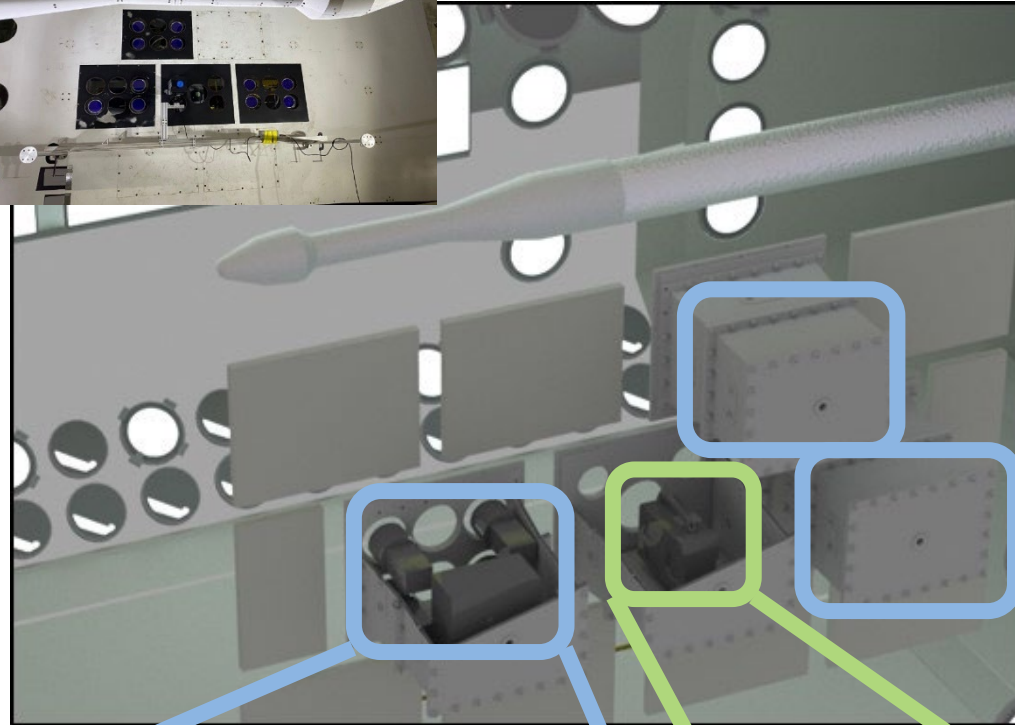
Only facility in the world capable of testing dynamic aeroelastically-scaled models at matched Mach number

TDT: Recent upgrades — Environmental Enclosures



Enclosures allow for uPSP in TDT

- Modular design to house high-speed camera & high-power UV LED lights
- Maintain atmospheric pressure as facility P is reduced
- Provide constant supply of cooling air for internal components
- Allow for remote-operation from control room of all equipment housed within (and P/T monitoring)

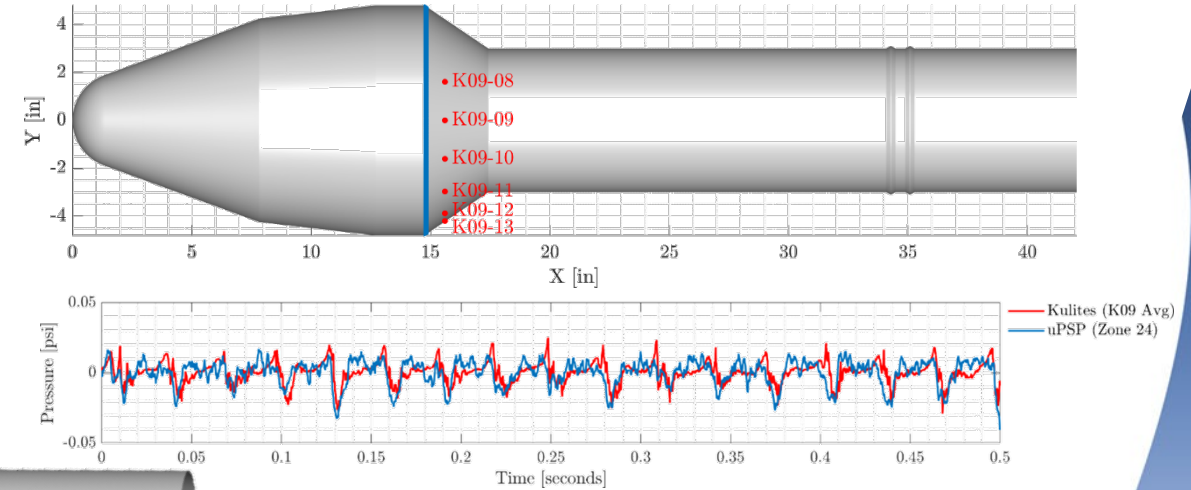
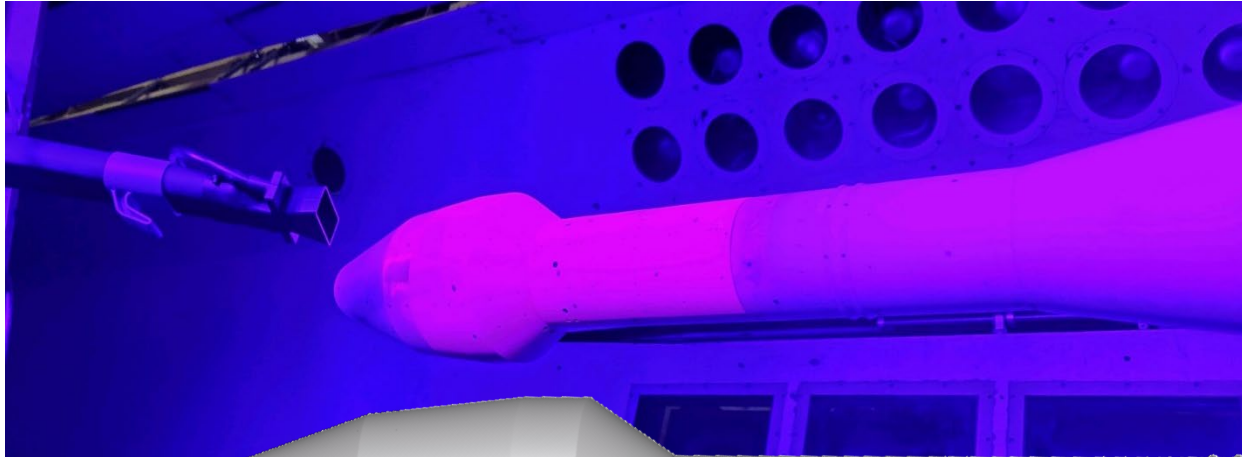
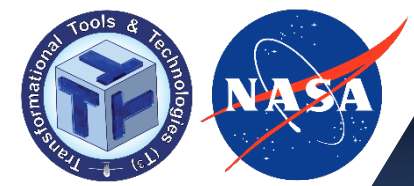


High-Powered UV Lights

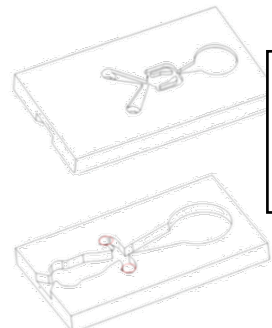


High-Speed Camera

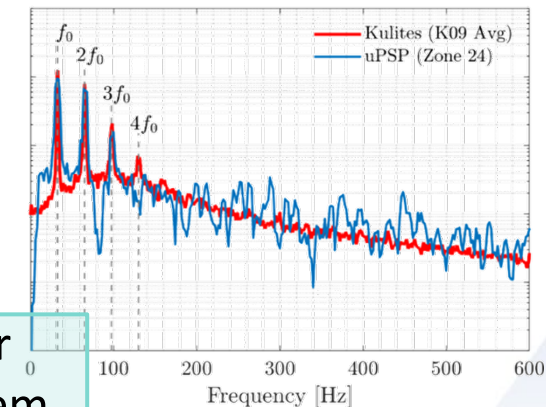
Unsteady Flow System



Small unsteady pressure disturbance resolved by uPSP system



Impinging jet with fluidic oscillator creates sweeping flow with known frequency independent of amplitude



Fundamental frequency (and higher harmonics) measured by uPSP system

<https://doi.org/10.1103/APS.DFD.2015.GFM.V0015>
<https://technology.nasa.gov/patent/LAR-TOPS-36>

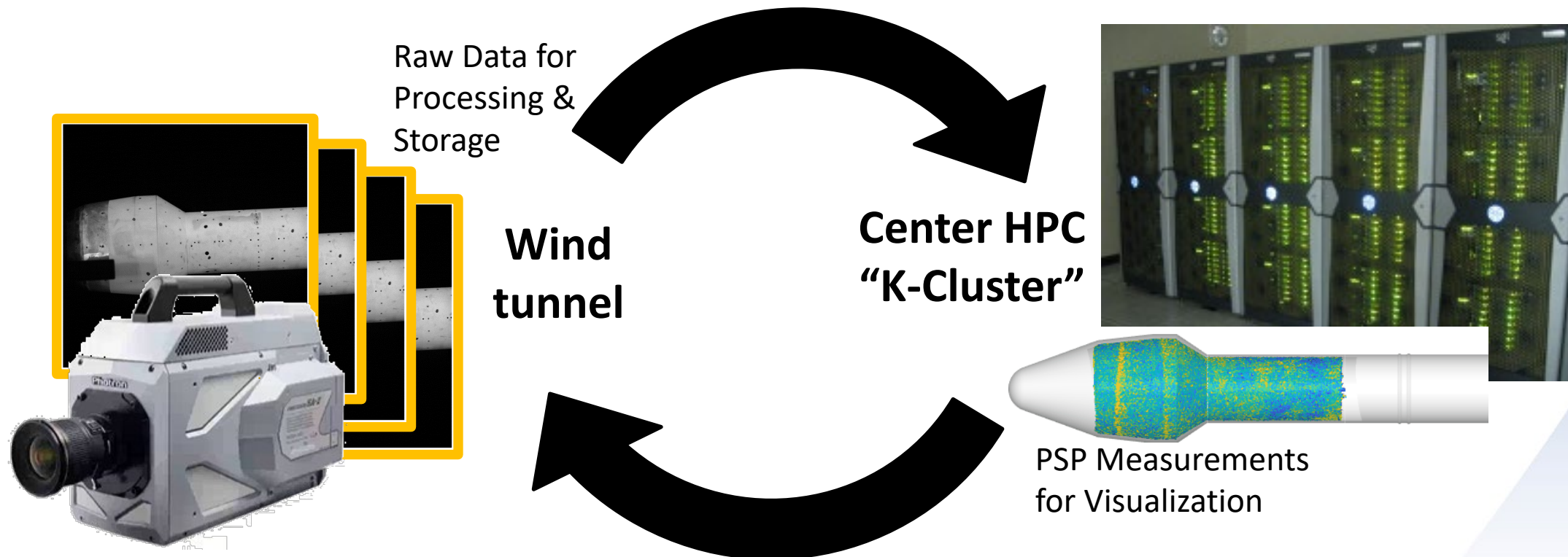
[D. Reese, *et al.*, AIAA-2022-3784]

TDT: Recent upgrades — high speed datalink

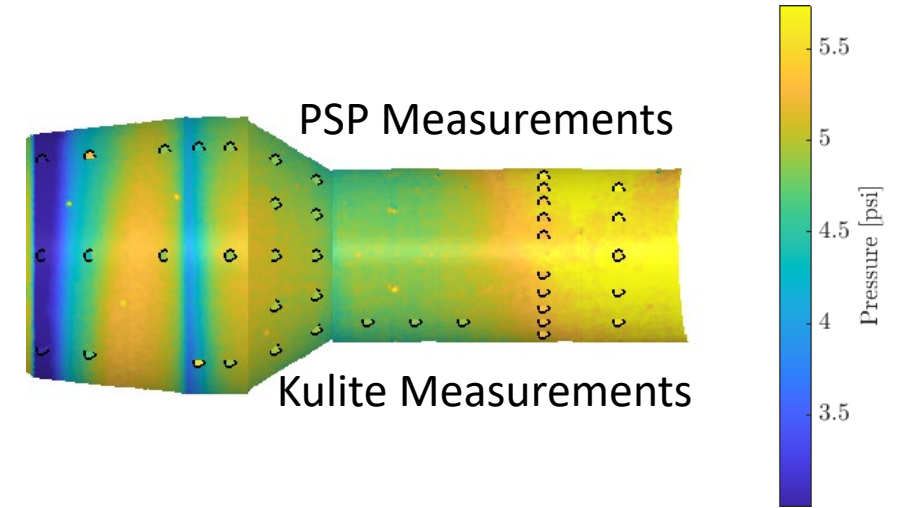
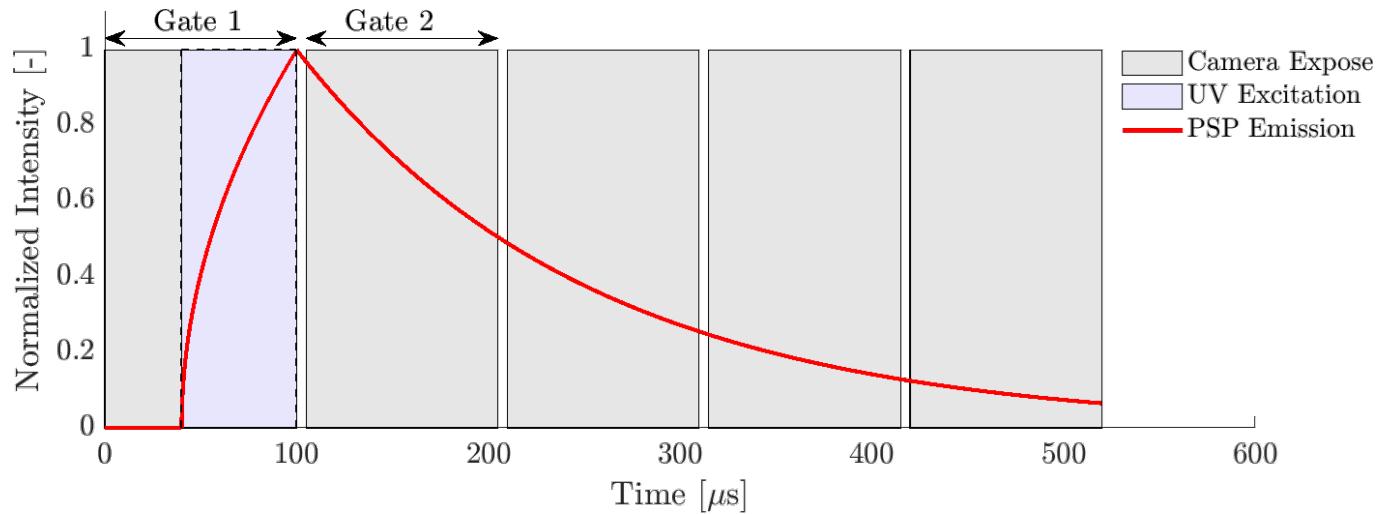


Capturing TB of data per camera each day needing processing and storage

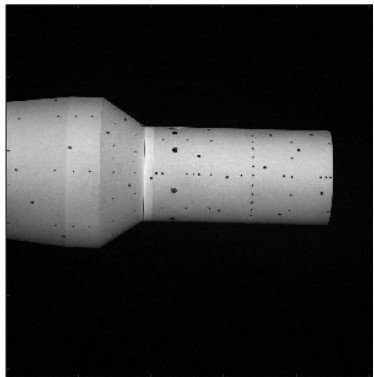
- High speed datalink between wind tunnel and LaRC's high performance compute resource
 - Need way to process/store large datasets quickly → "10 Gbps" line between TDT and K-Cluster
 - Quick turnaround opens the door for "near real time" uPSP results during testing



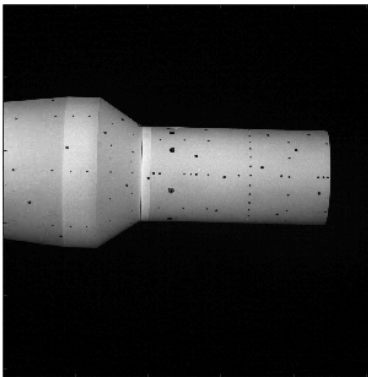
Lifetime Measurements (Steady State Solution)



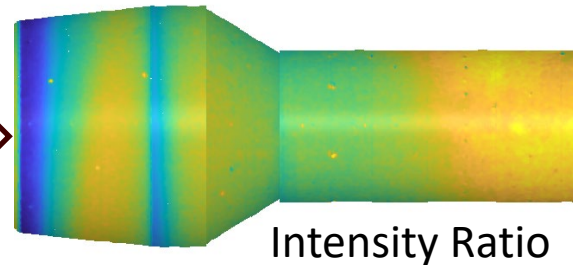
Gate 1



Gate 2

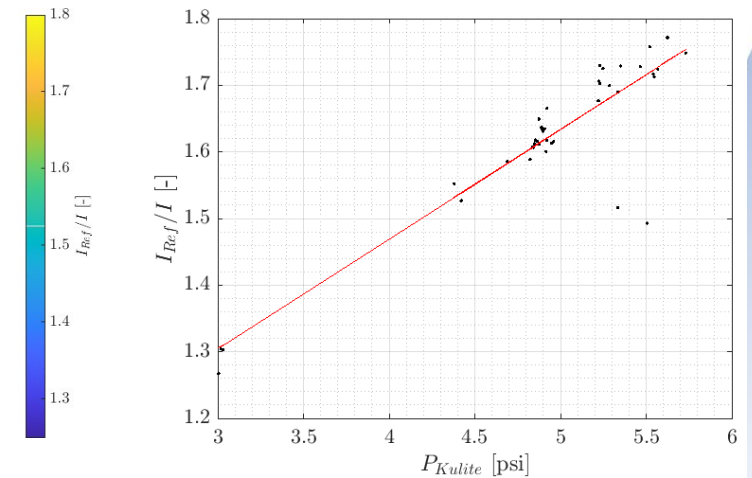


RATIO

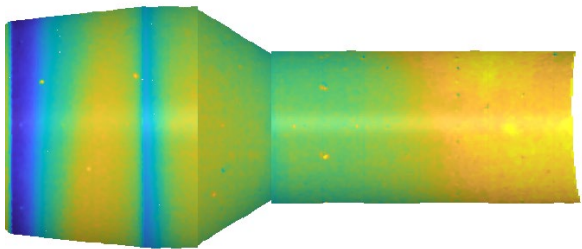


Intensity Ratio

(Average 250 Images)



Preliminary uPSP Measurements



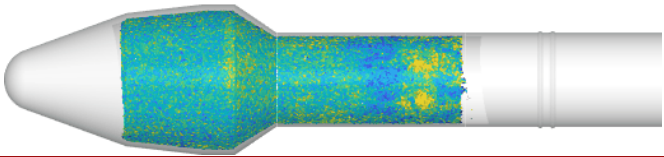
Steady State Solution
(from lifetime measurements)

Coe in TDT
Mach Sweep
($\alpha=3.5^\circ$)

Tested up to $Re = 8.8 \times 10^6 / ft$

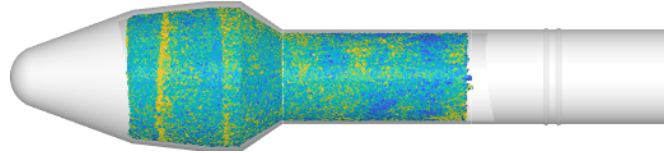


M=0.92

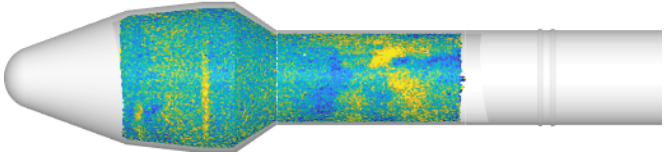


Time = 0 ms

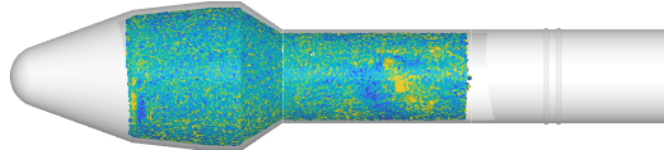
M=0.85



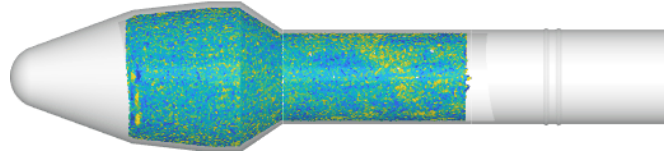
M=0.8



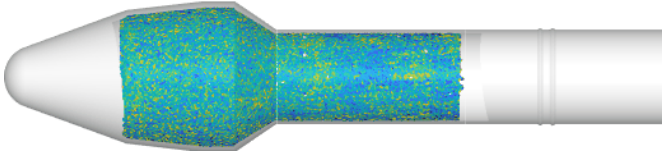
M=0.75



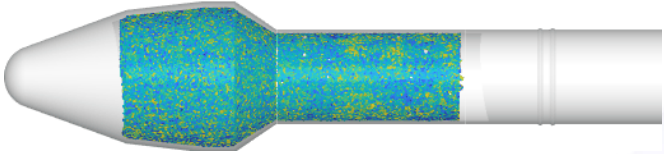
M=0.7



M=0.65



M=0.6



Playback Info
1000 frames
100 ms data
20 fps

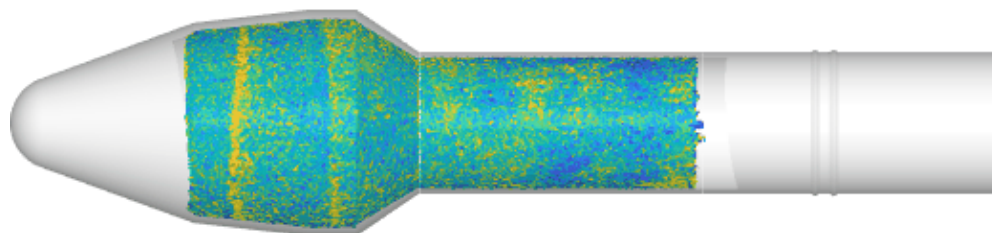
uPSP Measurements: $M=0.85$



Run 20 Point 53

Time = 0 ms

Δ Pressure



Aero Info

$\alpha=3.5^\circ$

$M=0.85$

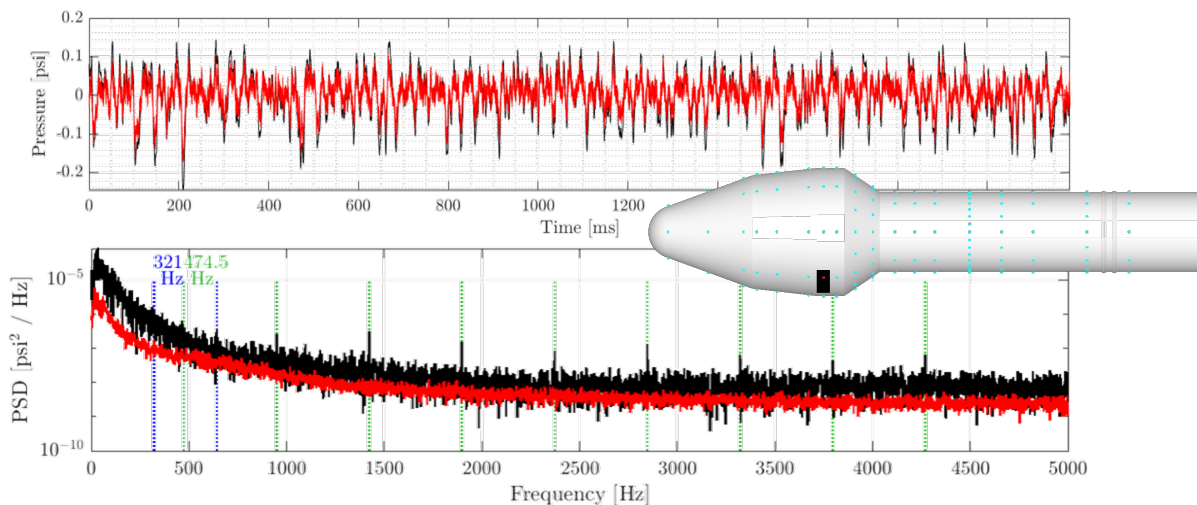
$P=326$ psf

Playback Info

1000 frames

100 ms data

20 fps



uPSP Kulite Comparison

Time histories and PSDs

Spectral/Spatial Analysis (DMD Motivation)

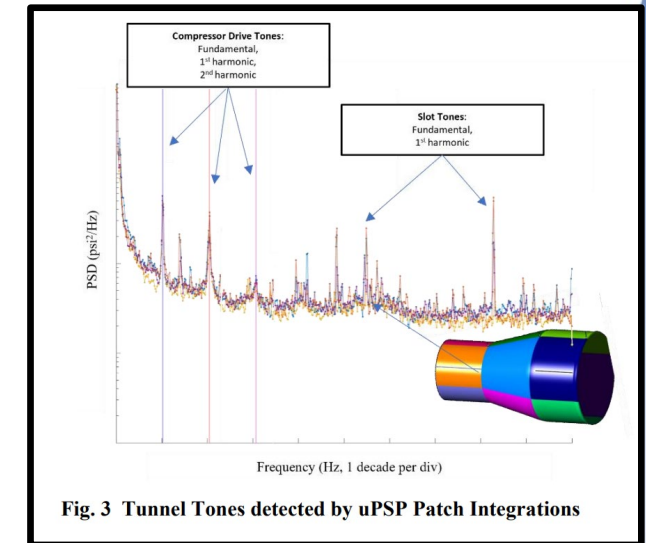
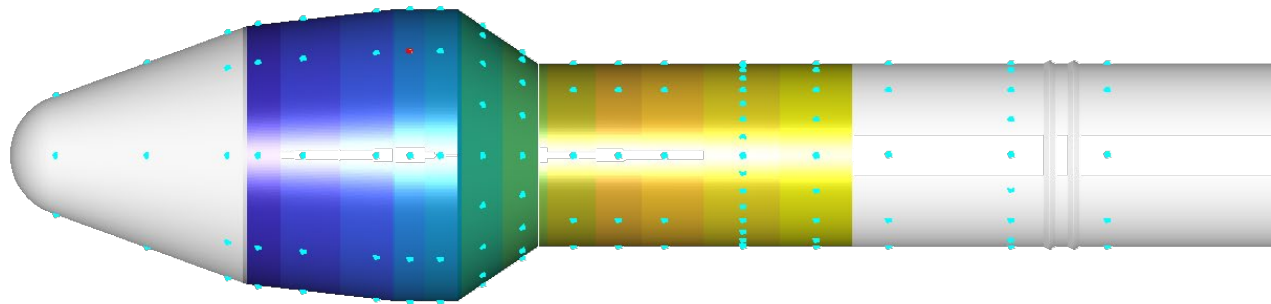
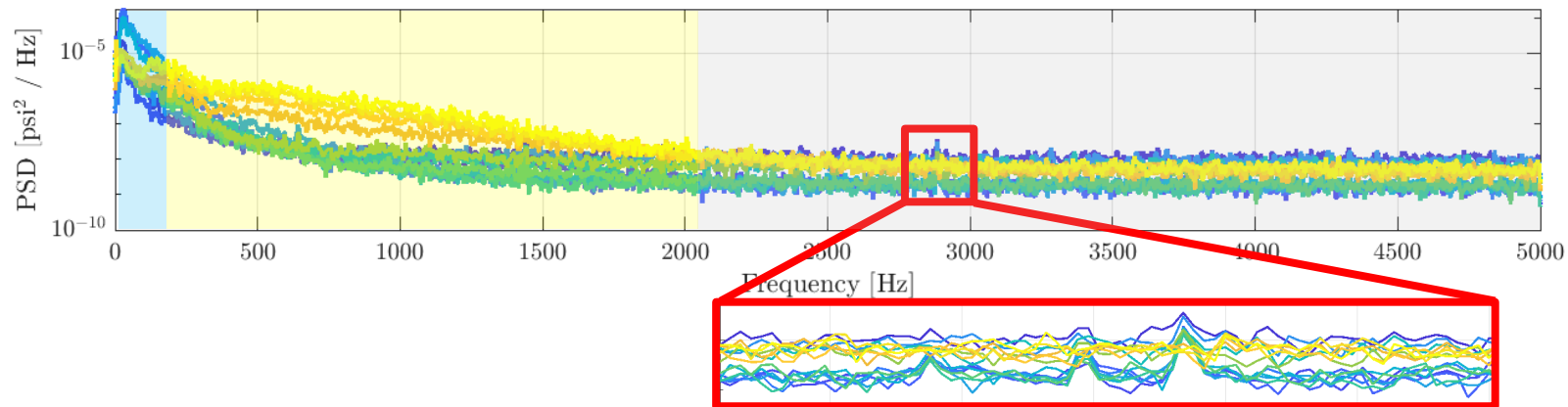
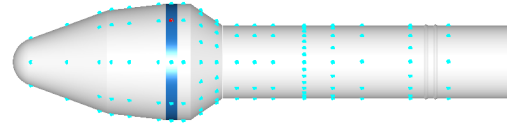
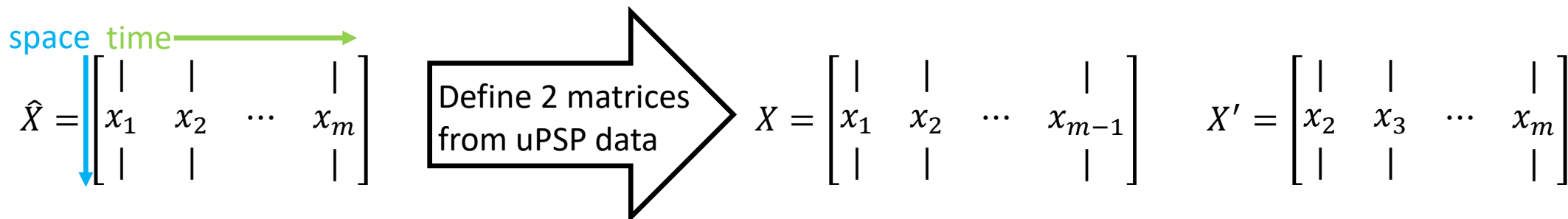


Fig. 3 Tunnel Tones detected by uPSP Patch Integrations

DMD: Background



DMD is a dynamical system of coupled **spatial** **temporal** modes

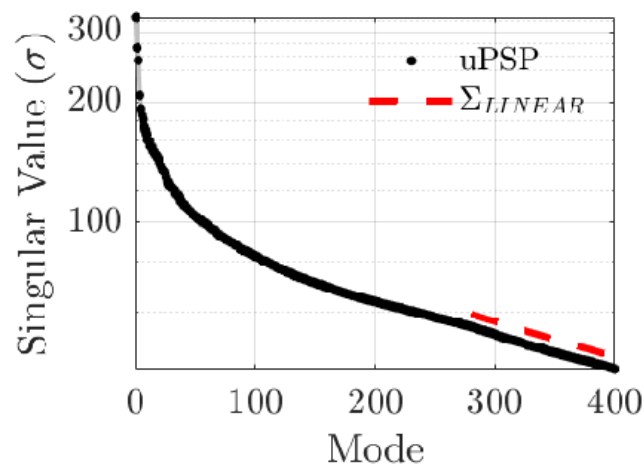


Full matrix is ~370k×45k

DMD tries to find a best fit linear operator A that advances X into X'

$$X' \approx AX \quad \text{In our case, } A \text{ is } \sim 370k \times 370k \rightarrow 137B \text{ entries}$$

Singular value decomposition (SVD) of X : $X = U\Sigma V^* \rightarrow X' = AU\Sigma V^*$



Project A onto leading modes:

$$U^* X' V \Sigma^{-1} = U^* A U = \tilde{A}$$

Eigenvalue decomposition of $\tilde{A}$:

$$\tilde{A} W = W \Lambda$$

$$\Phi = X' V \Sigma^{-1} W$$

Decouple space and time

Continue analysis using only the r “most important” modes.
 $r=400$, so $\tilde{A}$ is only 400×400

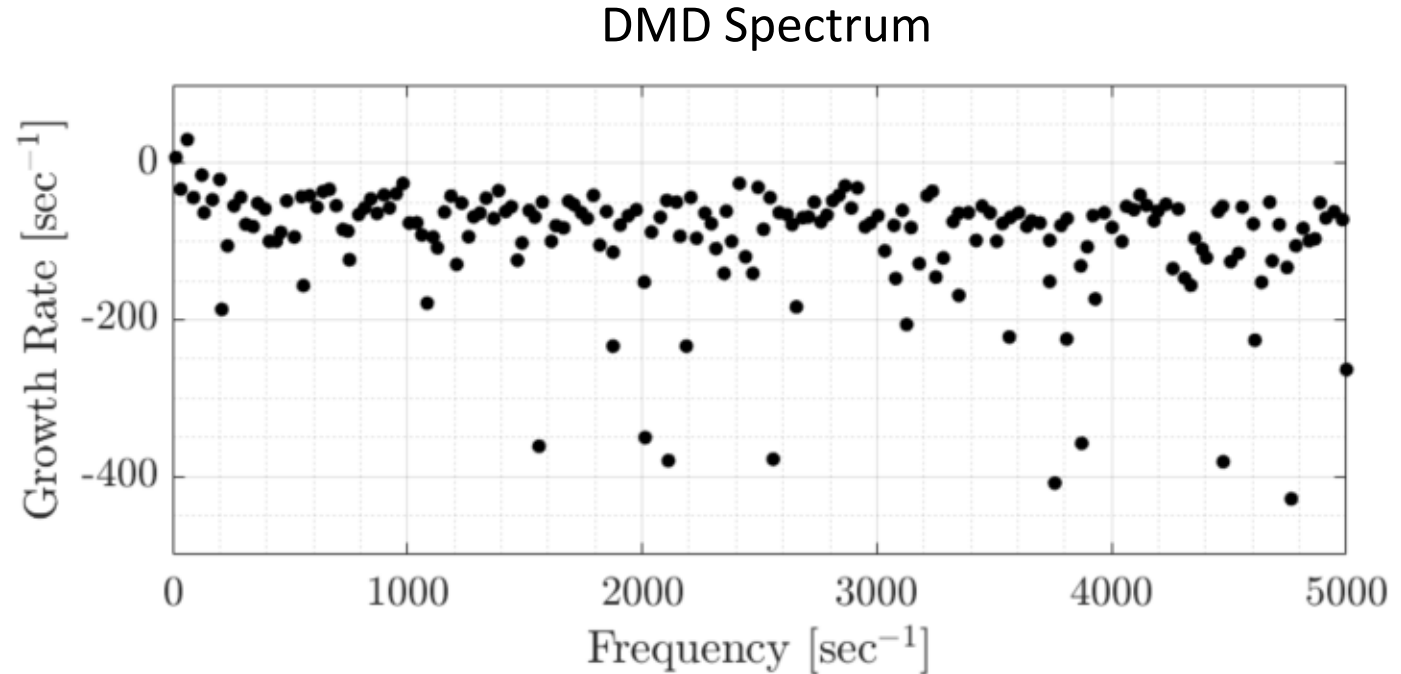
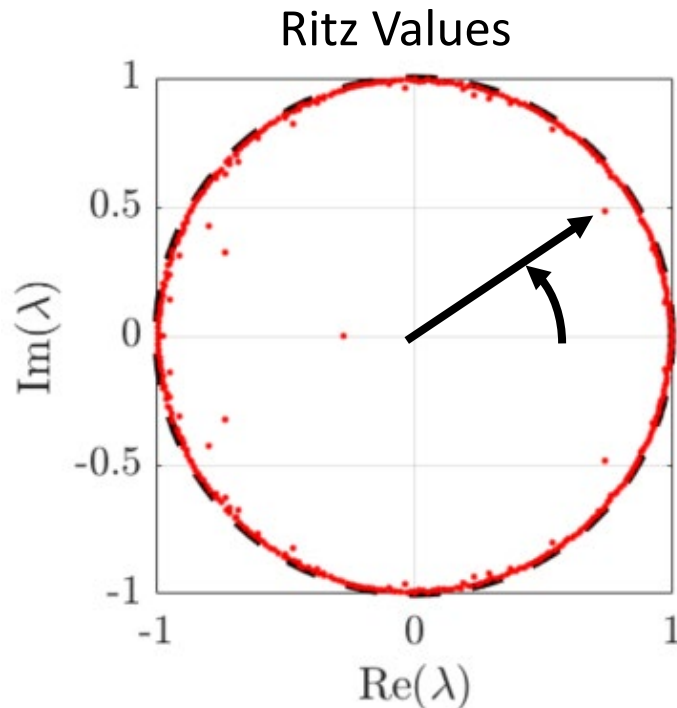
We have leading eigenvalues and eigenvectors of A without ever having to compute A

Reconstruct data using only dominant modes: $\hat{Y}(t) = \Phi \Lambda^t z_0$

DMD: Temporal Modes



DMD eigenvalues (λ) relate to temporal characteristics



Radial distance gives growth rate

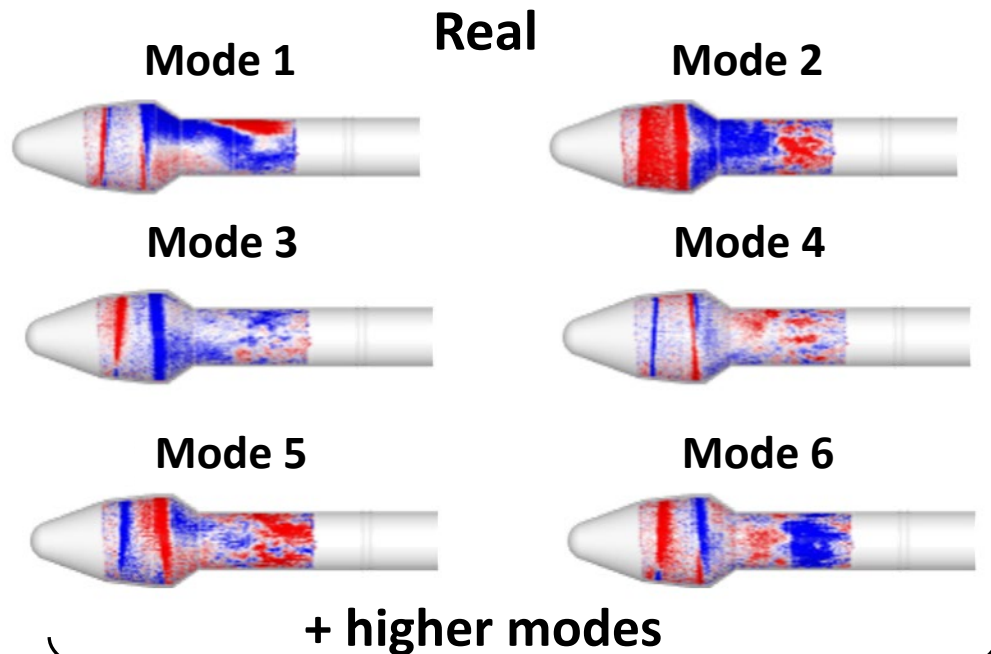
- Inside unit circle = decay
- Outside unit circle = growth
- On unit circle = oscillation

Angle determines frequency of associated mode

DMD: Spatial Modes



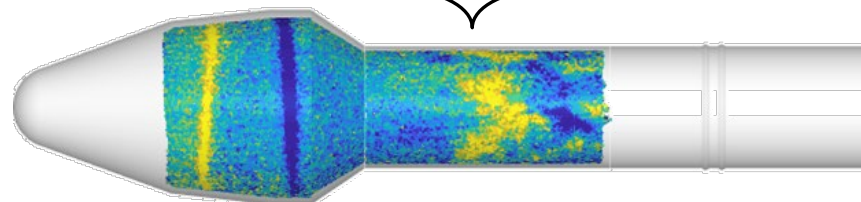
“Eigen pressure distributions” show dominant spatial coherent modes



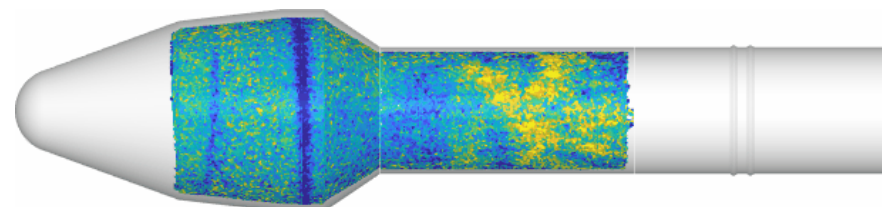
DMD eigenvectors (Φ) relate to spatial structures involved in the modal dynamics

Each Φ related to associated Λ so frequency of each mode is known

Now combine **space** (Φ) and **time** (Λ) to reconstruct uPSP data...

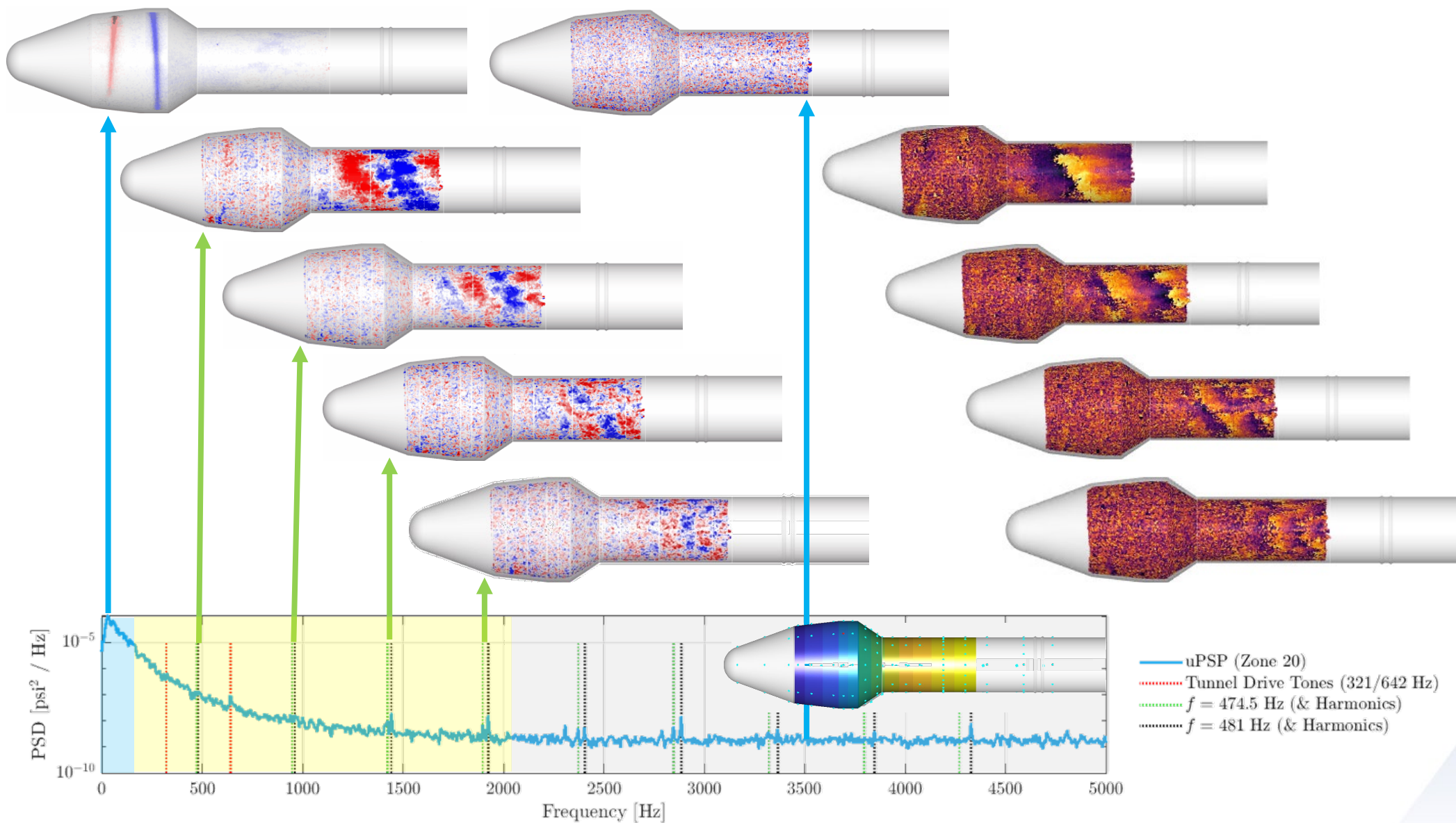


Reconstruction of uPSP data
considering only first 100 modes



uPSP measurements

DMD: PSD Insight



Summary & Conclusions



- PSP showed dynamic features spanning a wide range of frequencies on a launch vehicle in TDT
- Capable of resolving flow phenomena within the full test envelope of the wind tunnel
- High-speed datalink enabled near real time processing of data
- Lifetime technique allowed measurement of steady state pressure using the same equipment used for unsteady measurements
- Sufficiently sensitive to allow for calculation of important data products
- Next Steps:
 - Explore AI/ML for datamining large datasets
 - Moving rigid models
 - Aeroelastic models
- Funding for this work provided by the following programs in NASA:
 - Transformational Tools and Technologies (TTT) Innovative Measurements (IM) subtask
 - TTT Revolutionary Computational Aerosciences (RCA) subtask
 - Aerosciences Evaluation and Test Capabilities (AETC)
 - Revolutionary Vertical Lift Technology (RVLT) Project



BACKUP SLIDES

Lifetime Measurements (Steady State Solution)

