Data Processing Tools for Dynamic Pressure-Sensitive Paint

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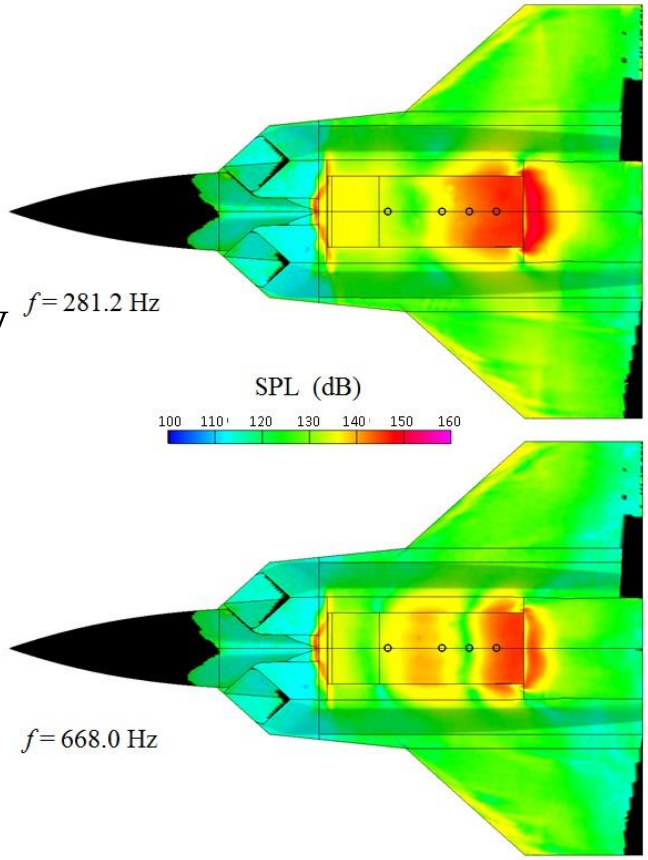
Euclidian Optics



Acknowledge

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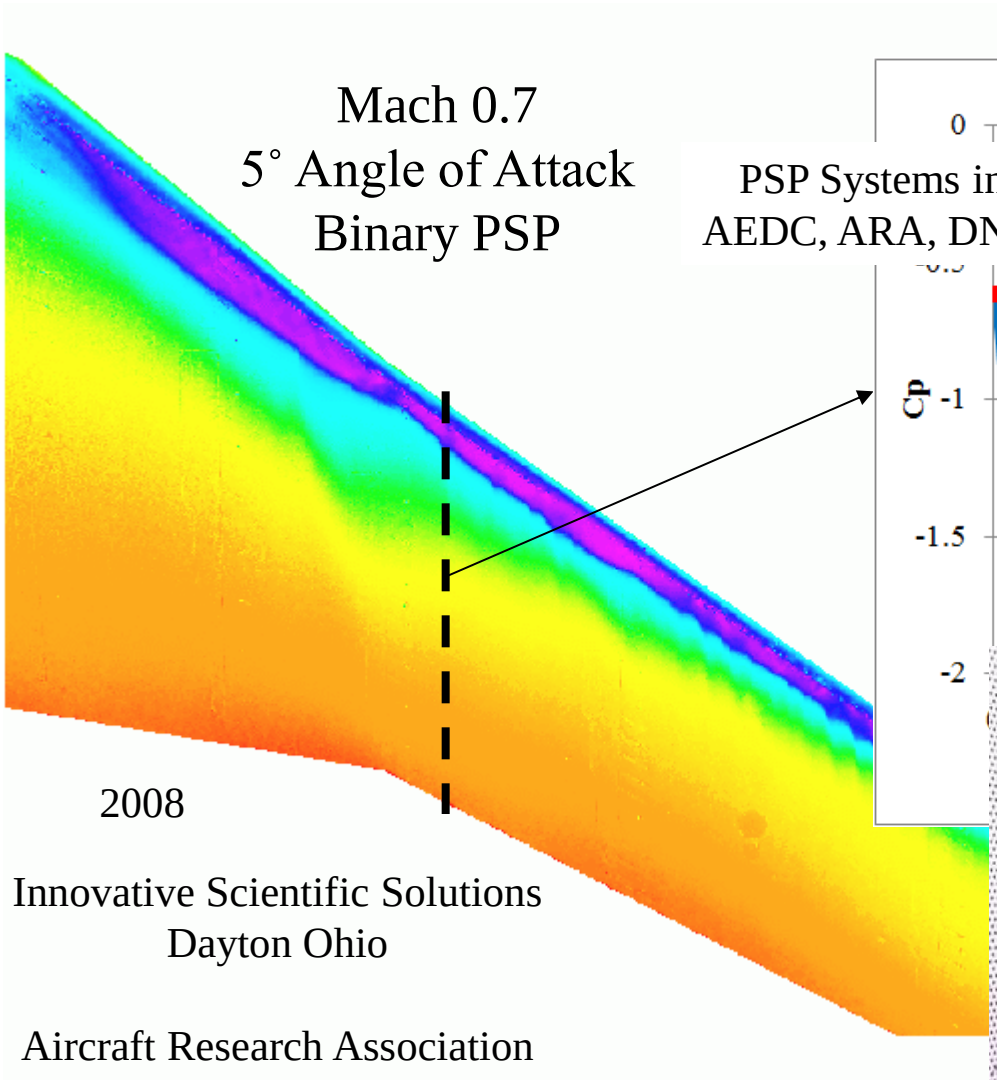
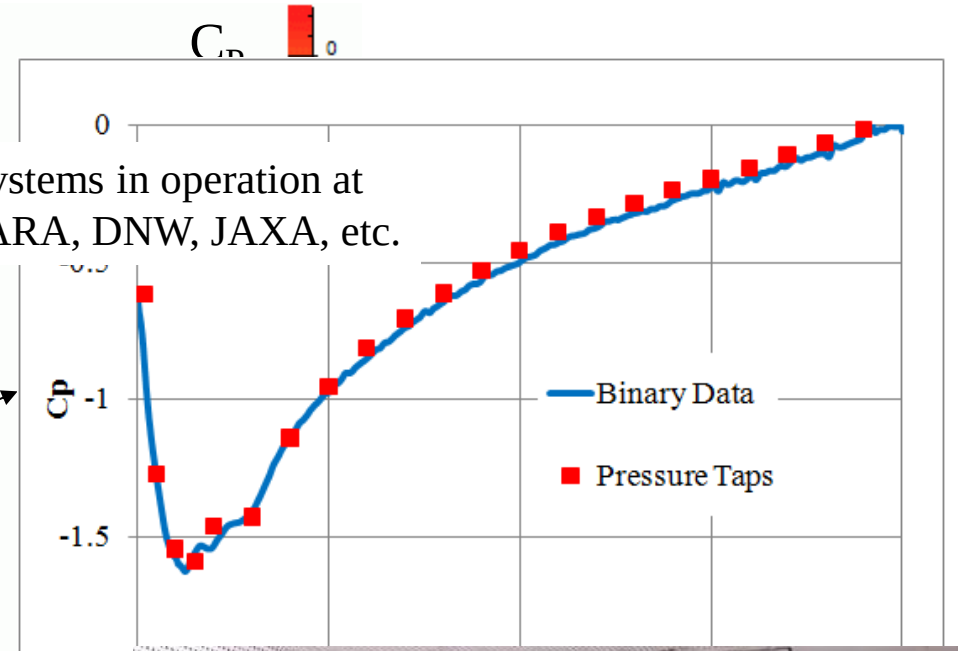
Neil Watkins, Luther Jenkins, Nettie Roozeboom, James Bell, Mark Wokie

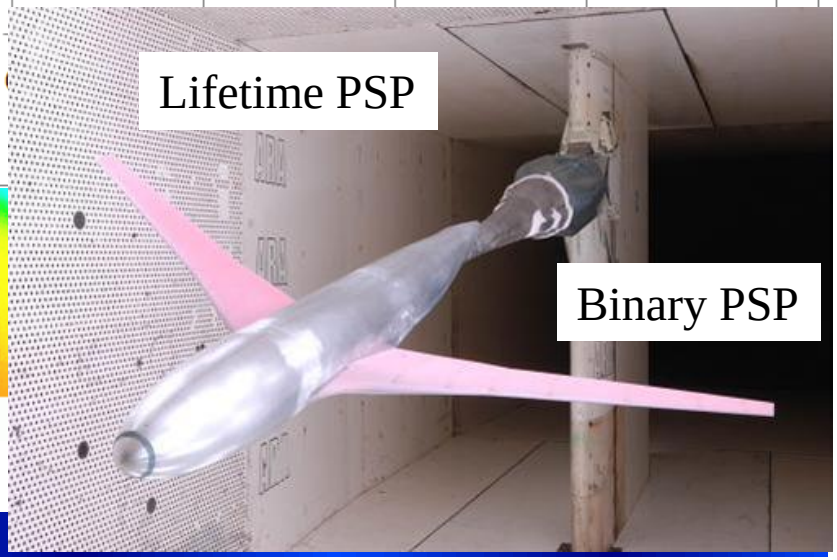
Greg Elliott

Standard PSP in Production Wind Tunnels



PSP Systems in operation at
AEDC, ARA, DNW, JAXA, etc.





Frequency Response of PSP

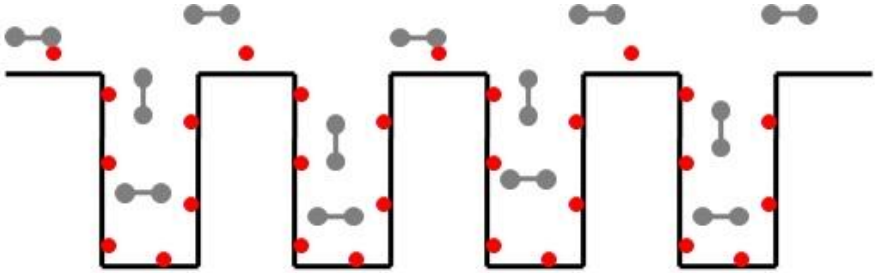
- Traditional PSP has a slow response time
  - Works well during steady testing
  - Does not respond to unsteady pressure fluctuations
- Response time is governed by gas diffusion in the paint binder:

$$\frac{\partial [O_2]}{\partial t} = D_m \frac{\partial^2 [O_2]}{\partial z^2}$$

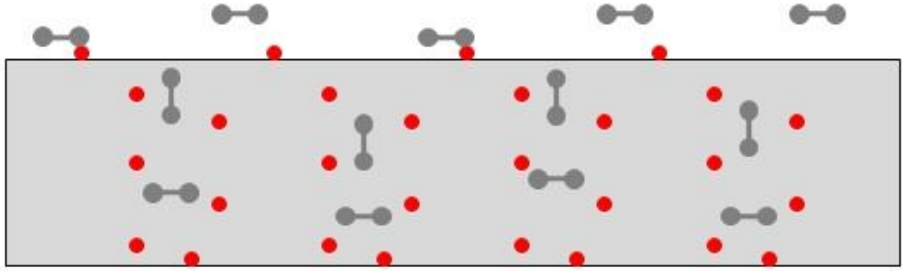
$$\tau \propto h^2 / D_m$$

  - Decrease paint layer thickness (h^2)
    - Thin paint limits Signal-to-Noise
  - Increase gas diffusivity within the paint binder (D_m)
    - Open system is fully quenched at low pressure, limits Signal-to-Noise

Porous PSP for Fast Response



Fast PSP has open pores that increase surface area. Active probe sits on the surface and Oxygen has direct access to the probe.

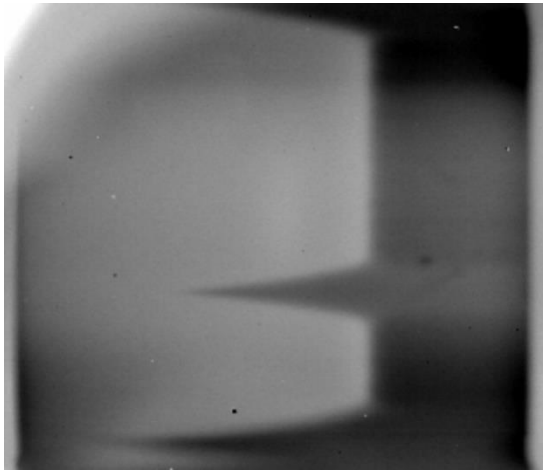


Regular PSP requires that the Oxygen diffuse through the binder to the active probe. The diffusion process is much slower.

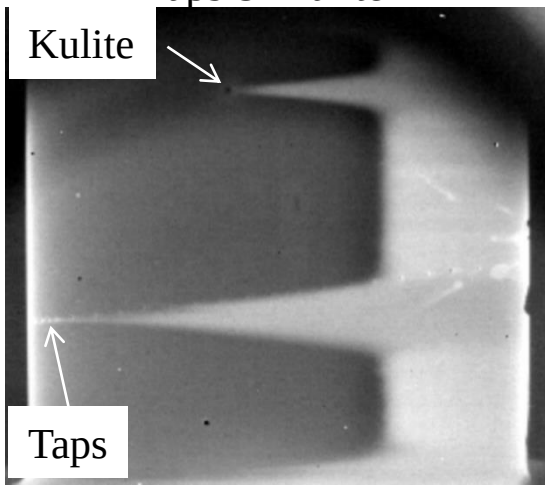
- Anodized Aluminum
  - 100+ kHz
  - High temperature sensitivity
  - Application not always practical
  - Quenched at low static pressure
- PtTFPP-PP
  - ~20 kHz response
  - High temperature sensitivity
  - Spray on surface with airbrush
  - Operation to 2+ atm.
- Turbo-Fib
  - ~2 kHz response
  - Lower temperature sensitivity
  - Spray on surface with airbrush
  - Operation to 1+ atm.

How Intrusive is PSP?

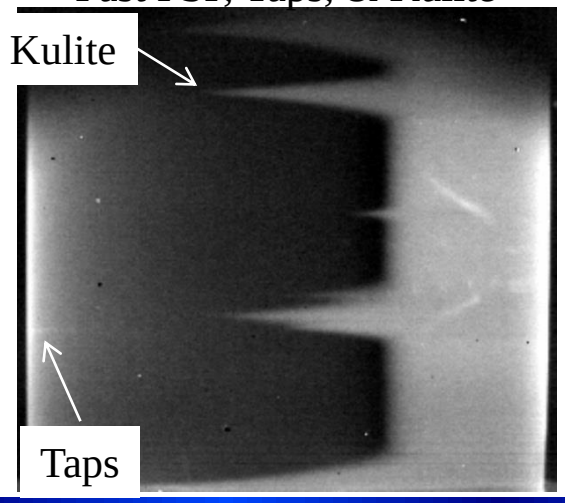
No PSP or Kulite



Taps & Kulite



Fast PSP, Taps, & Kulite



IR on a natural laminar flow airfoil

$\alpha = -6°$
$M = 0.28$
$Re_c = 1.8$ million

Fast PSP does not transition the flow

Jim Gregory ~ 2010

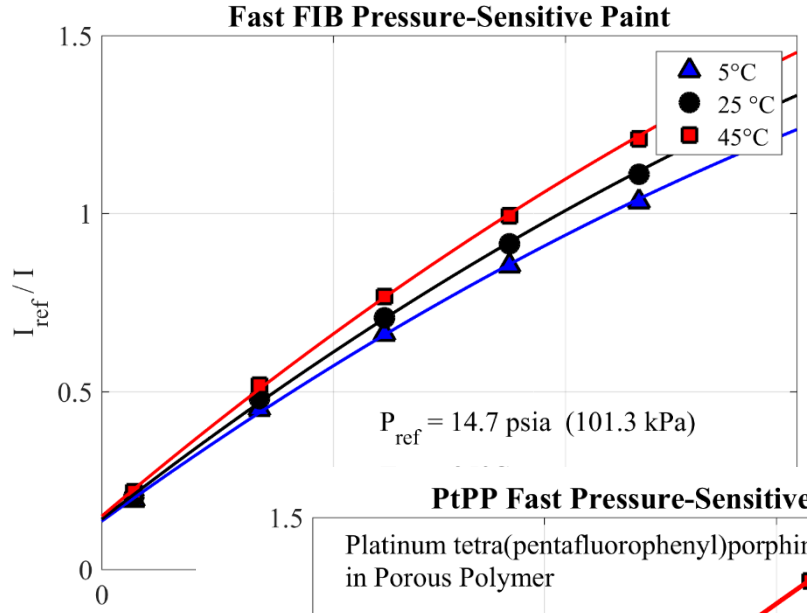
Apply fast PSP to laminar flow airfoil to study fast PSP impact on laminar flow

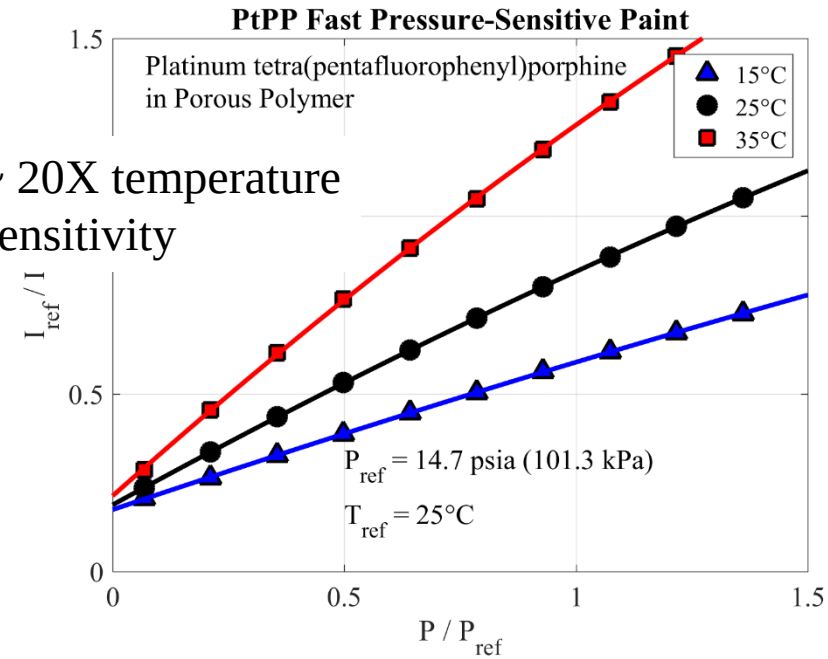
Surface finish of Fast PSP is smooth, does not trip boundary layer . Does better than traditional taps, or fast transducer.

Everything is intrusive. PSP is no worse than a pressure tap. (might be better)

Fast Paint Calibrations

- Porous Polymer
  - ~20-kHz Response
  - 1% - kPa
  - High Temp. Sens.
- Turbo-Fib
  - ~2-kHz Response
  - 1% - kPa
  - Low Temp. Sens.
- Which is the "best" choice



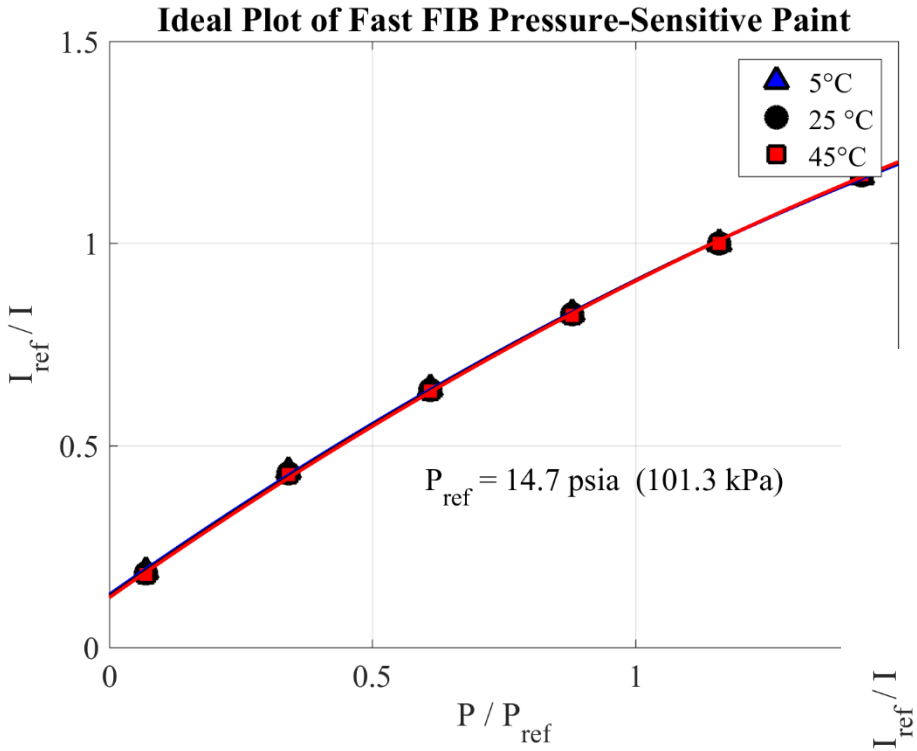


~ 20X temperature sensitivity

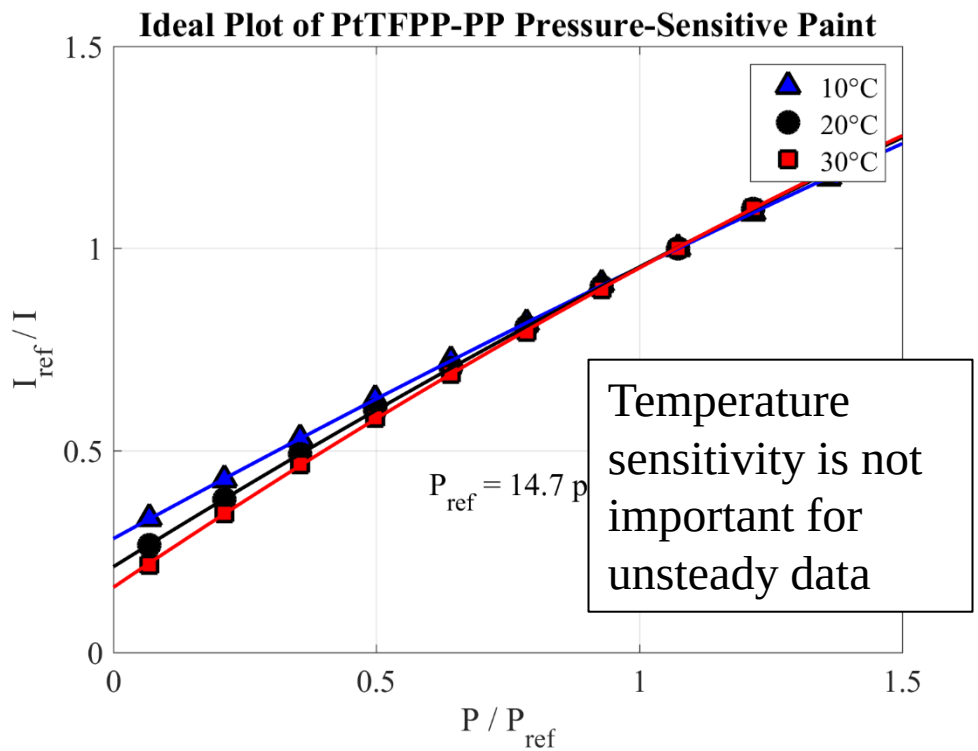
A Few Keys to Fast PSP Data Processing

- Recognize where PSP errors originate
  - Model motion, illumination, temperature, sedimentation, photodegradation
  - Low frequency content >> Wind-off to Wind-on
  - Separate mean and rms data, process independently
- AC couple the measurement
  - Average wind-on is the wind-off
  - Thermal gradients built in to the running wind-off
  - Minimal motion, temperature variation, etc.
  - Ratio and multiply by slope of PSP
- Fast PSP acquired in 2 sec.
  - Only concerned with errors that occur on this time scale

Ideal PSP for Pressure Fluctuations



Ideal PSP Plot
Normalize each isotherm at reference pressure
PSP slope at each temperature

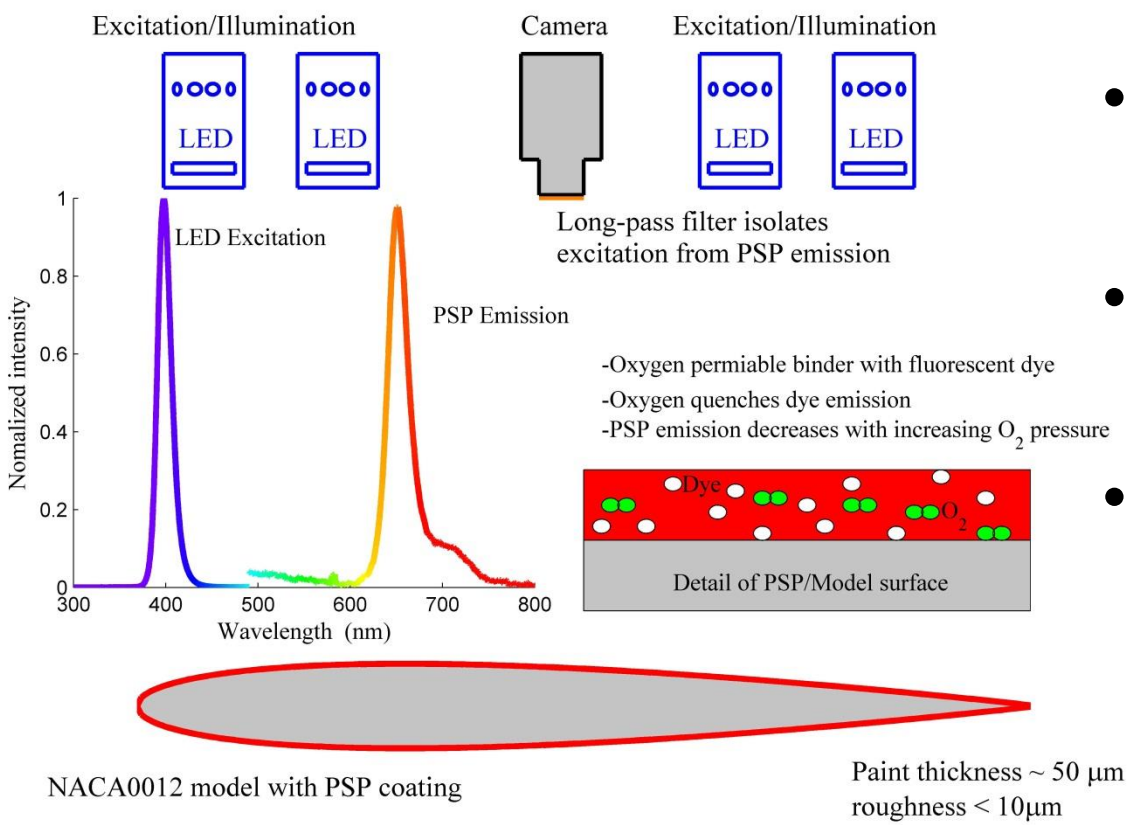


Temperature sensitivity is not important for unsteady data

Ideal PSP for AC coupled processing
- average wind-on is wind-off
- temperature gradients are not relevant
- local slope of calibration curve is key

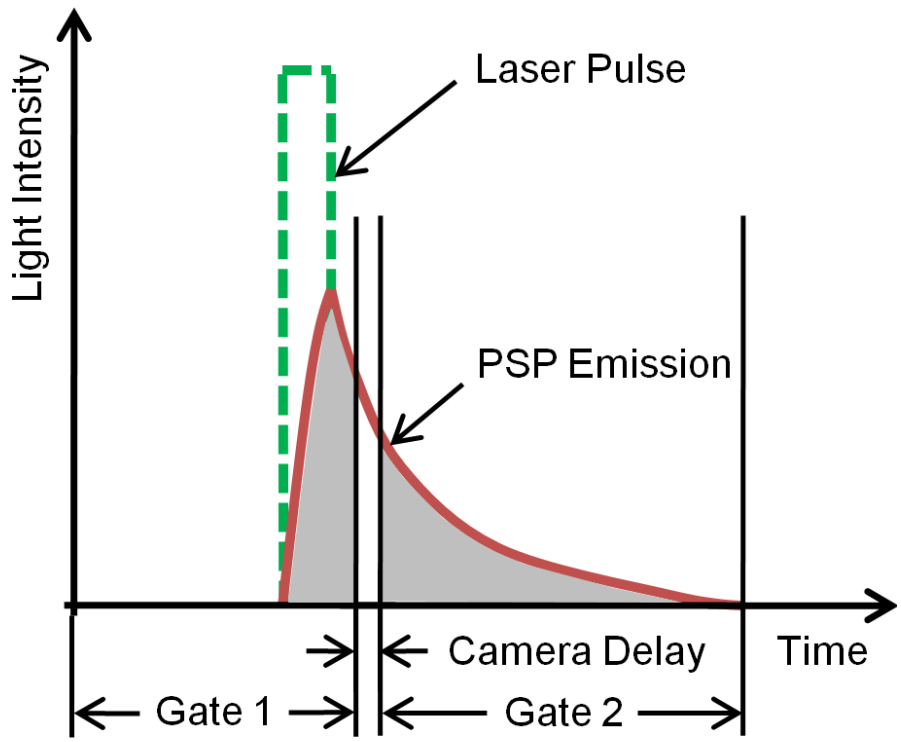
Ideal PSP with linear calibration preferred

Fast Radiometric System



- Fast Cameras
  - Faster with better QE
- LED
  - >1,000X brighter
- Data processing
  - PC technology

Single-Shot Lifetime System



- Lifetime PSP on rotating surfaces
- Demonstrated in 2000
  - Crafton and Carter
  - Kodak ES4, DCR4
- Frame Transfer Camera
  - Faster shift, better QE
- Fire-on-demand laser
  - Smaller, more power
- NASA Rotorcraft

Radiometric Fast PSP Data Processing

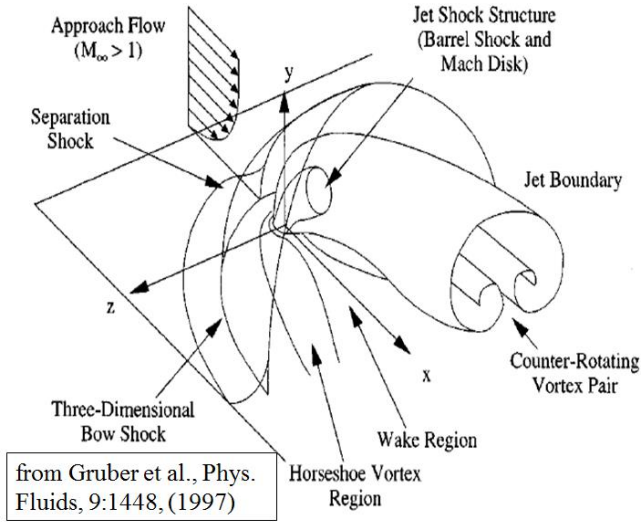
- Fast PSP data set is extremely large
  - Multiple Megapixel cameras with 5000-200,000 frames
  - Get the data off of the cameras and store it
  - Acquire for 2 sec. download for 15 min.
- Data processing
  - Conversion to pressure is linear algebra
    - +, -, *, / a 3D matrix, map data to mesh
  - GPU not terribly effective
    - not compute bound, data transfer is the issue
  - Get a workstation
    - lots of processors and lots of ram (64 Gig minimum)

Marvin can do it faster

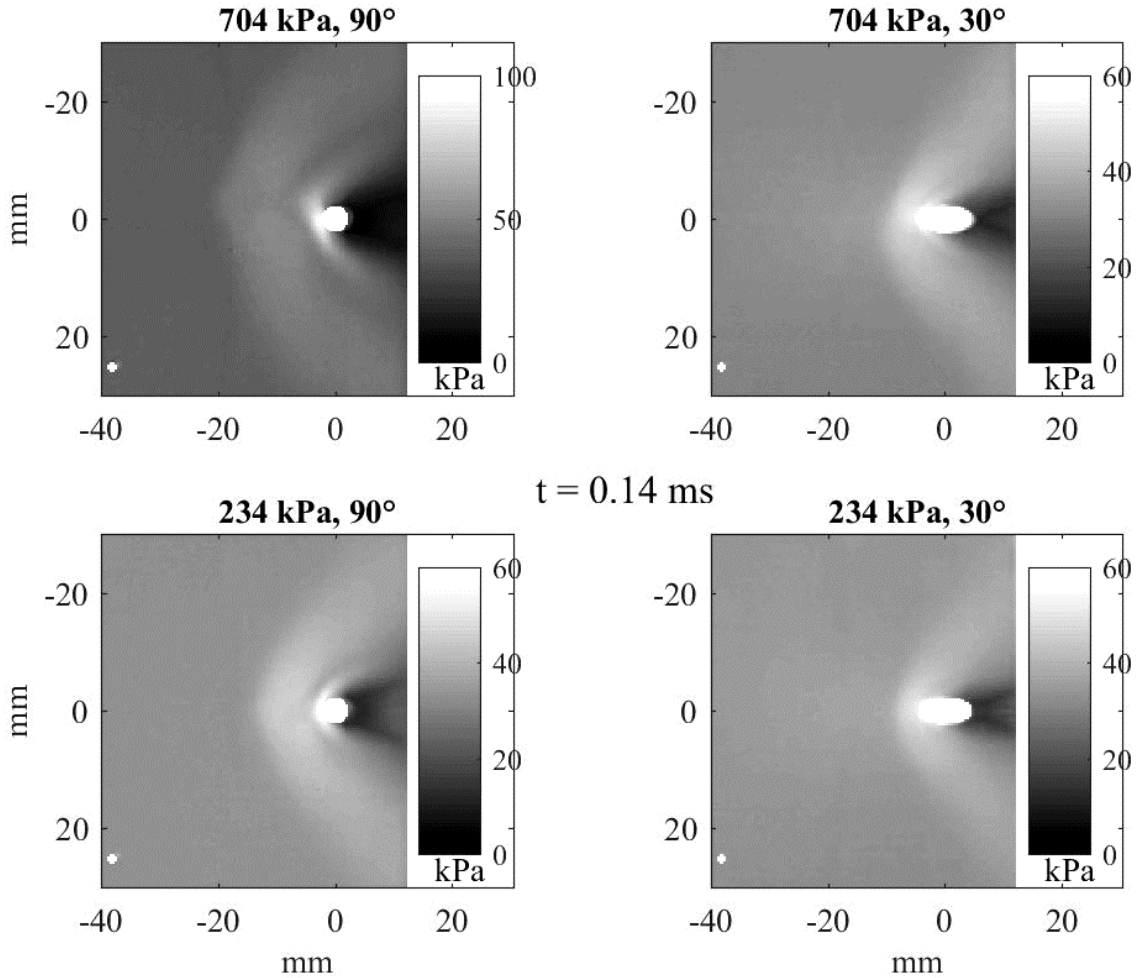
Takes longer to load image than to process

Fast PSP Demonstration

Transverse Jet Injected into a Supersonic crossflow (2009) AFRL, Carter, Gruber



from Gruber et al., Phys. Fluids, 9:1448, (1997)



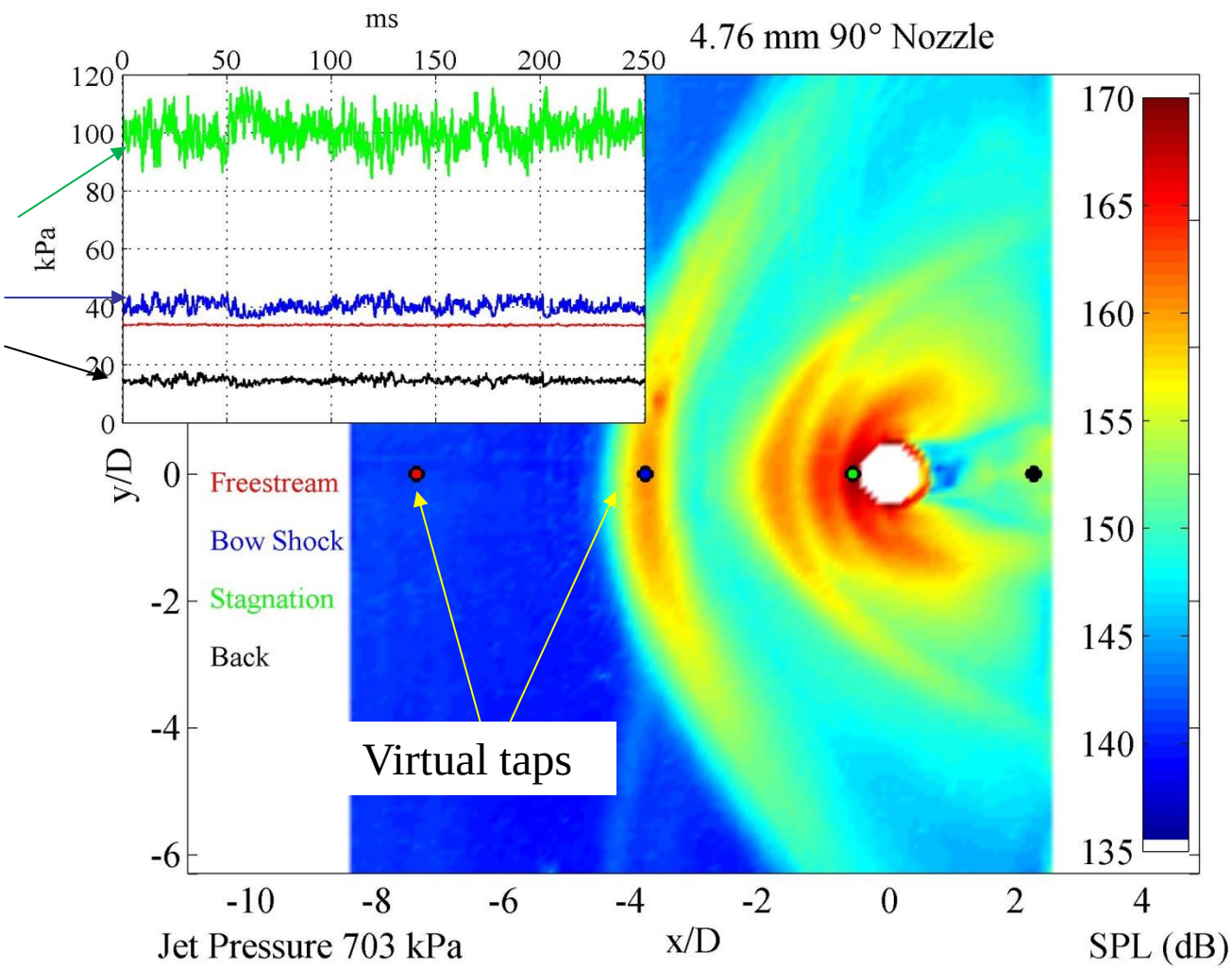
Lots of fast pressure taps.
<u>Sampled simultaneously.</u>
Spatial resolution of mm or better.

Fast PSP Data Analysis

- What can you do with Fast PSP data
  - Anything you can do with traditional fast transducer, you just have a lot more of them, and they were sampled simultaneously
  - Fluctuating pressure, Power spectra, Correlation coefficients, Coherence, Proper Orthogonal Decomposition, Dynamic Mode Decomposition, etc.
- Quick and dirty analysis on bitmap
  - Quickly identify key temporal and spatial frequencies
- Map to mesh to control data size
  - Usually around 100,000 data points per camera

Pressure Fluctuations, Virtual Taps

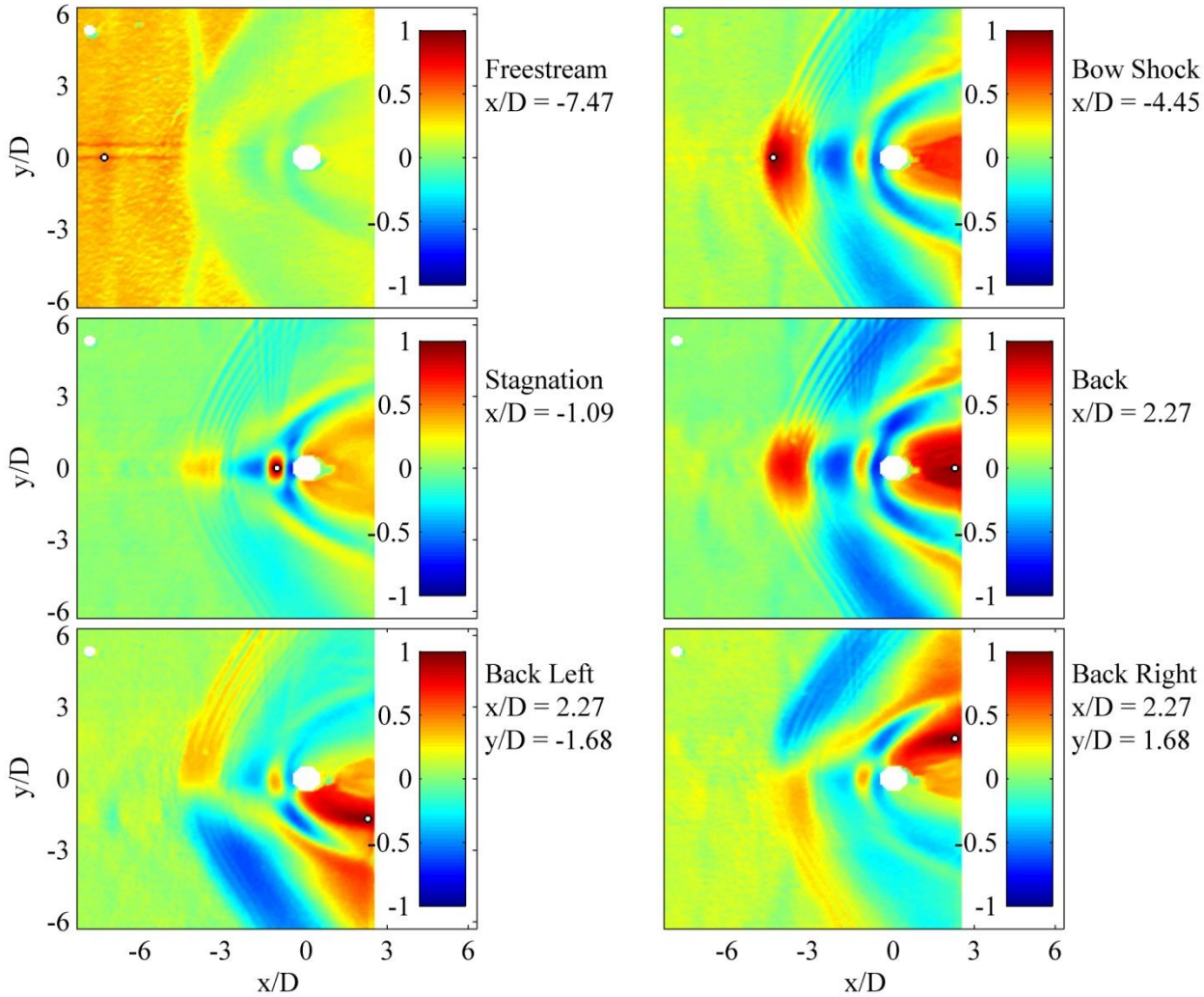
Stagnation
Bow shock
Behind jet



7 kHz
1024 x 1024
5000 images

6 Gig, thought that was a lot

Correlation Coefficients



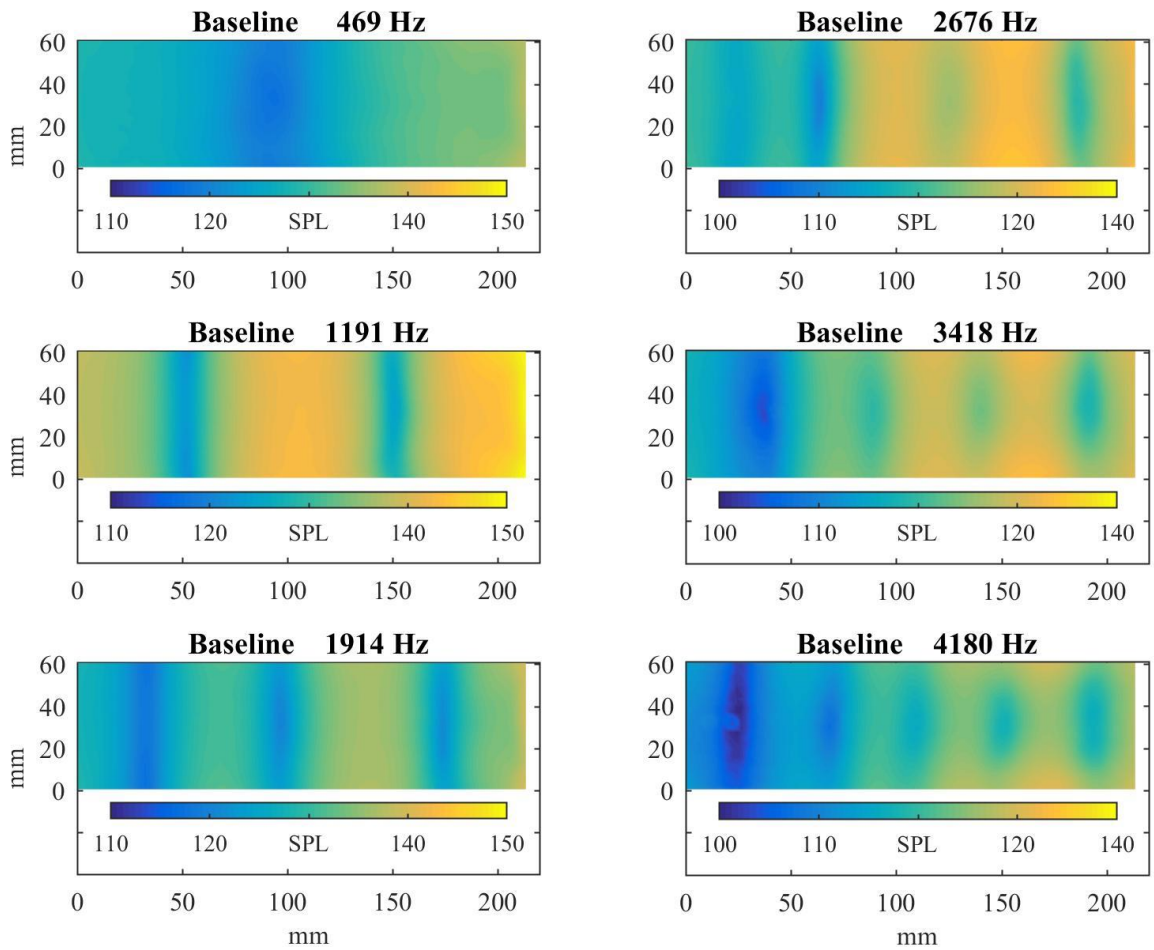
- Correlation Coefficient
  - select control point
  - compute correlation coefficient at every other point in flow
  - 100,000 simultaneously sampled points
  - 100,000 correlation maps?
- Weak pressure fluctuation behind jet
- Strong influence on major flow features
- Stagnation zone of minor importance to flow dynamics

Power Spectra Maps

Rossiter Tones in Supersonic Cavity TGF at AFRL Schmit, Grove (2012)

30,000 images, Map to mesh (2-mm resolution). Extract data at each pixel and compute spectra. Reconstruct map at each frequency.

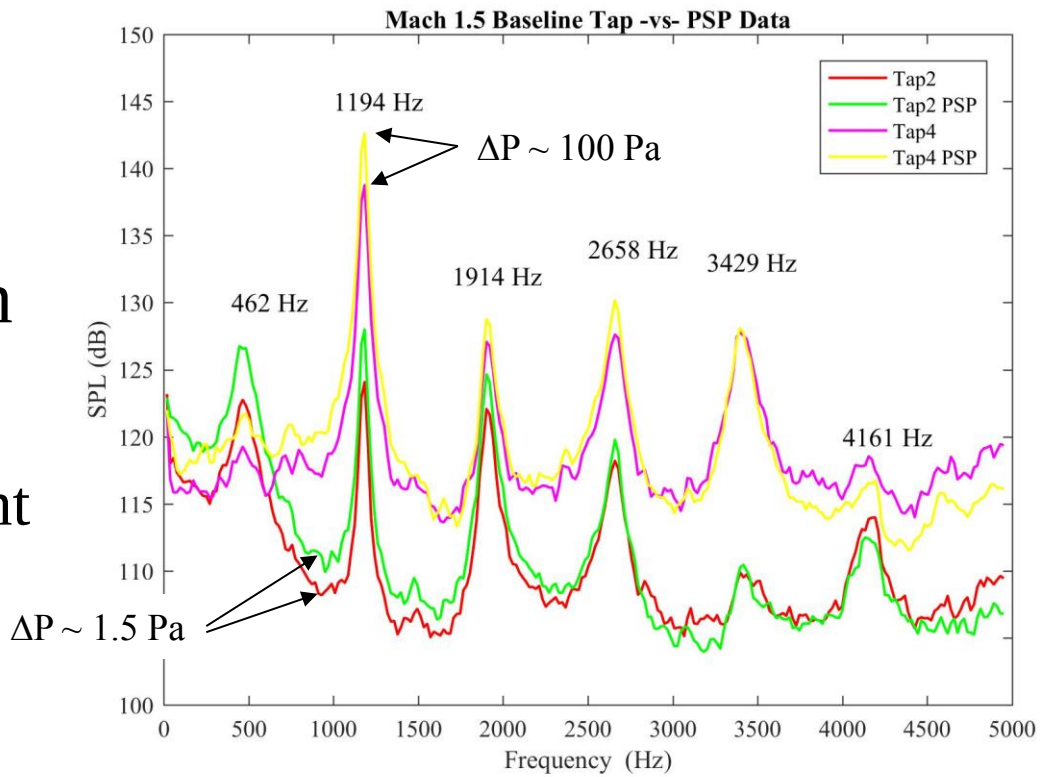
Maps here show amplitude of pressure fluctuations at Rossiter frequencies identified by taps.



Taps –vs- PSP

Traditional PSP
100 Pa error after in-situ correction is very good
1 Pa never happens

- PSP frequency peaks
  - near perfect agreement with taps
- PSP amplitude
  - reasonably close
  - > 4 dB in SPL
- No in-situ correction
- Past fast PSP data
  - frequency > excellent
  - amplitude > good

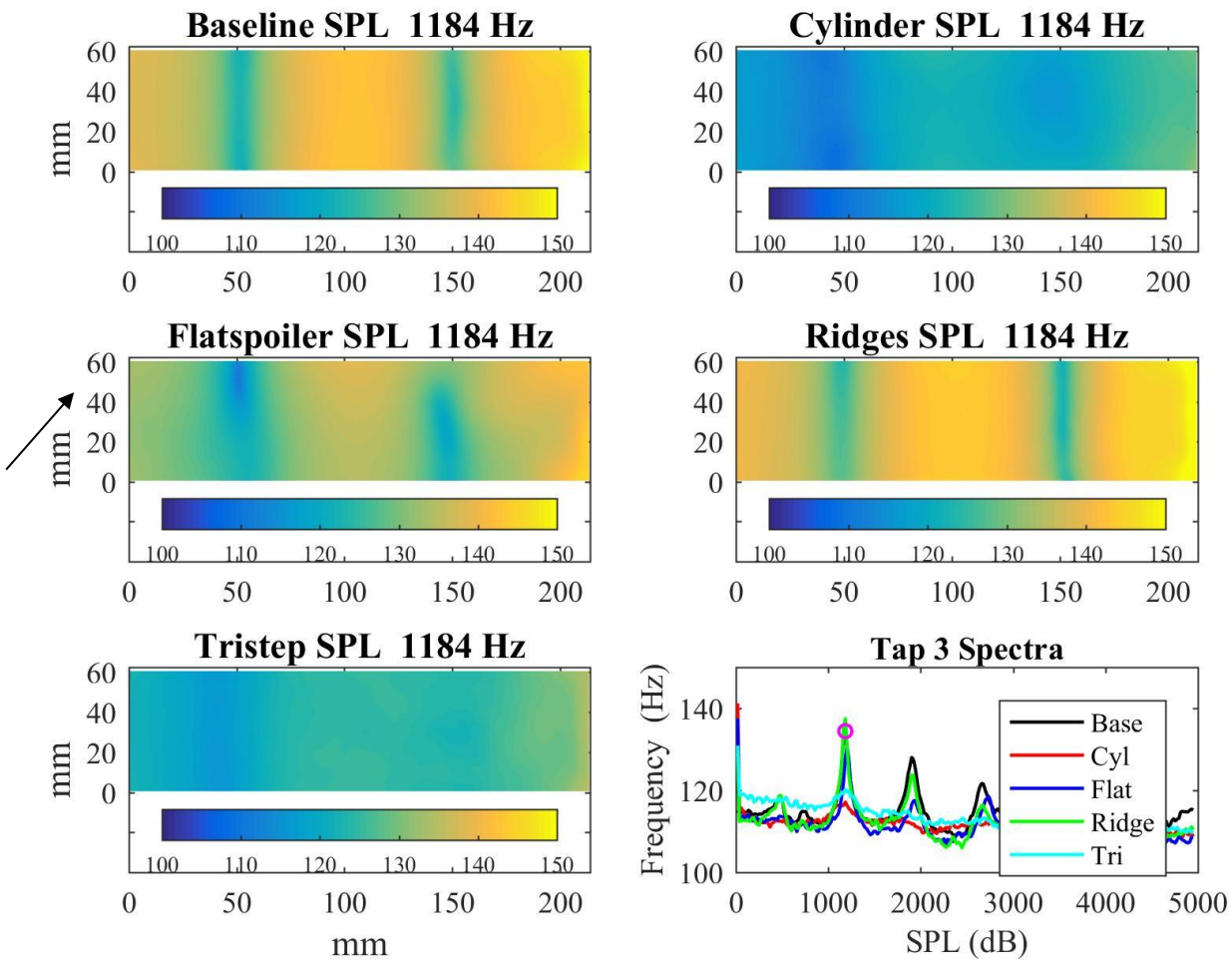


Evaluation of Flow Control Devices

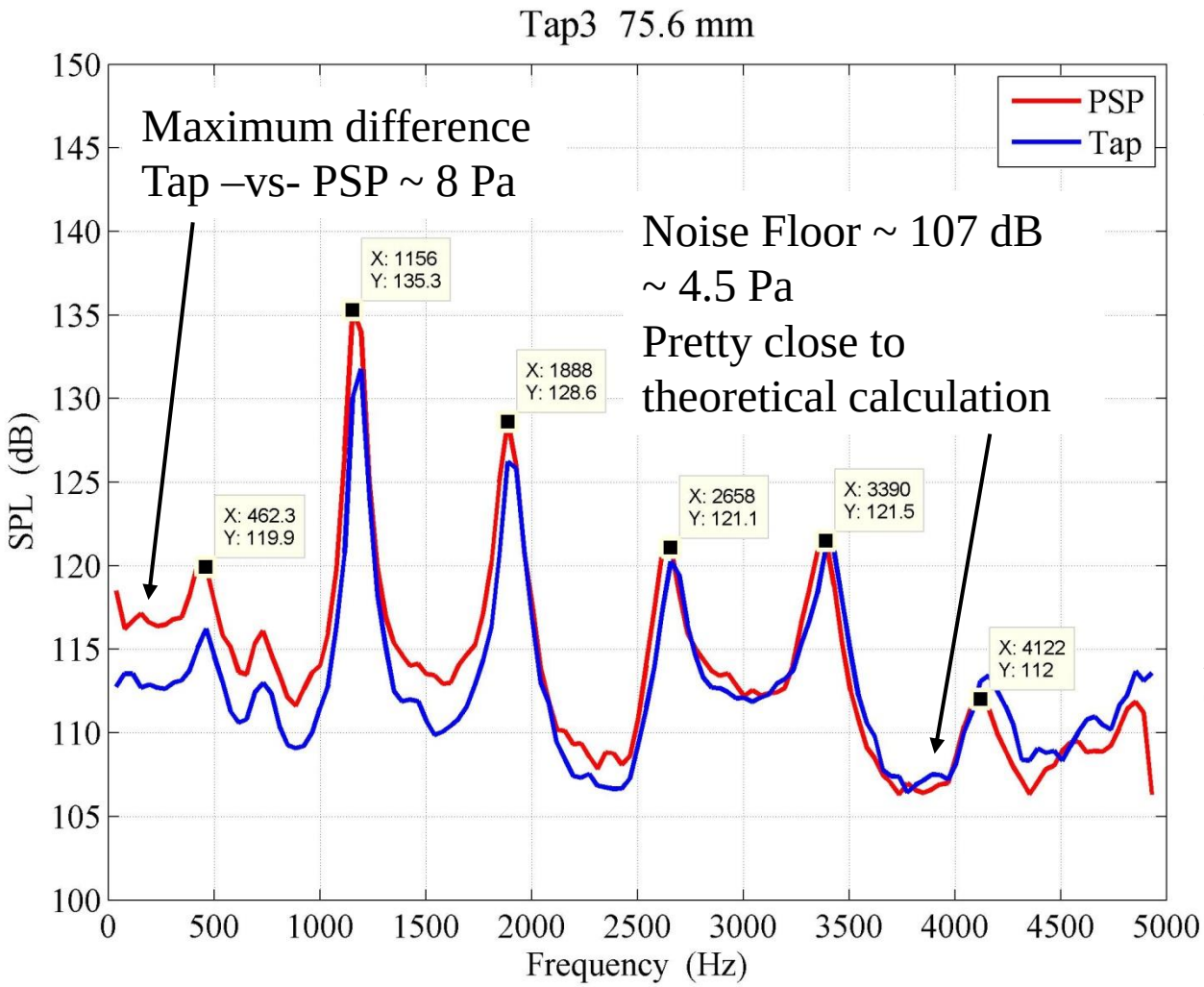
Fast PSP data on ceiling of cavity with several passive flow control devices.

Note asymmetric tone evident with Flatspoiler. Hard to identify with 7 taps along centerline.

Easy to identify effective flow control devices with full map.



Noise Floor of Fast PSP



Acquiring 62,000 images in 2.5 seconds, 8X8 pixel filter

Images at full well (20000 photons), noise ~ 88 Pa

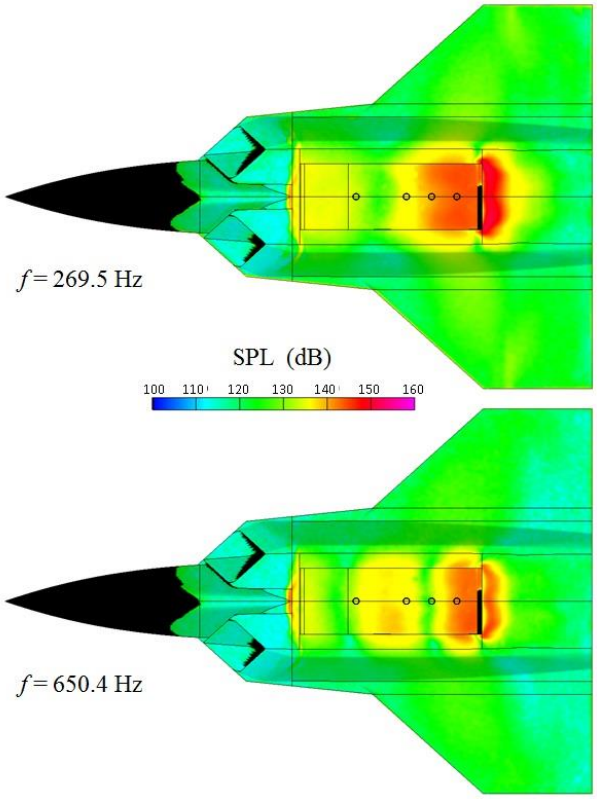
Compute spectra using 256 points (20 Hz bins) 50% overlap

Averaging ~ 484 spectra
Theoretical noise floor ~ 4 Pa

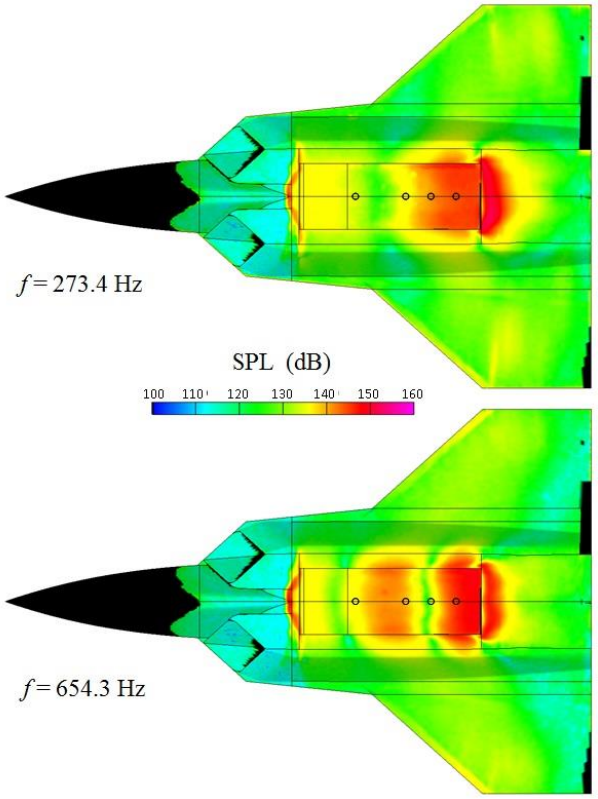
Transition Fast PSP to Large Tunnel

AF RIF Program
ISSI, Marvin Sellers, Wim Ruyten, Ming Chang
June 2014

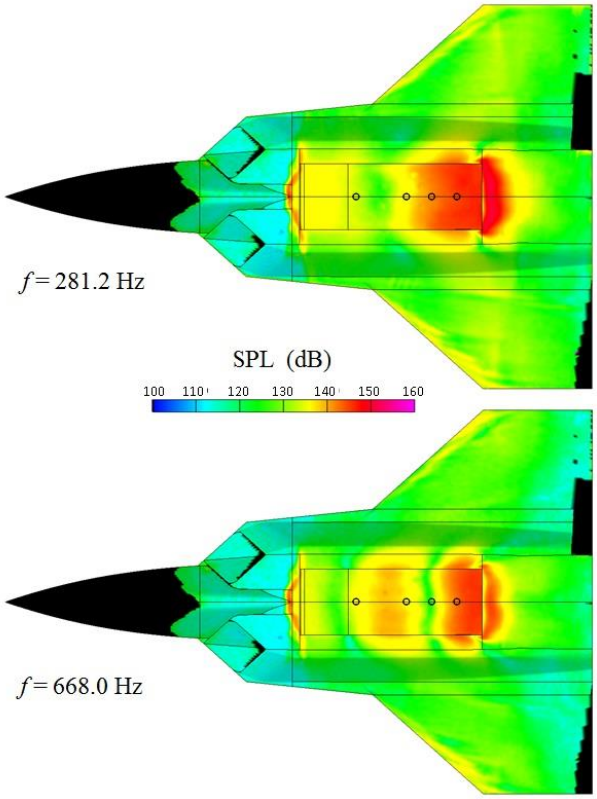
Cavity Acoustics in AEDC 16T



Mach 0.9, alpha 5 deg.

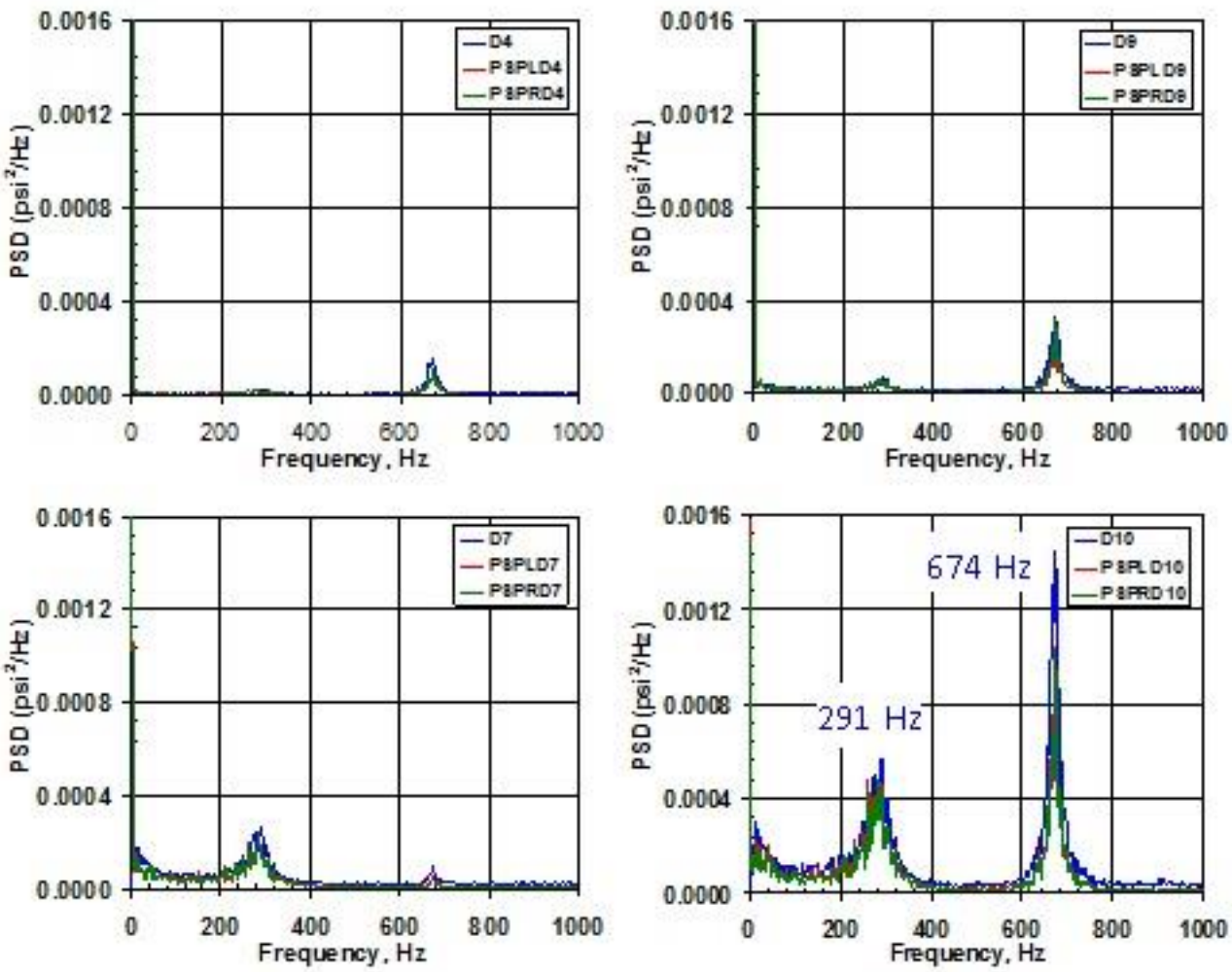


Mach 0.9, alpha 0 deg.



Mach 0.9, alpha -2 deg.

Taps –vs- PSP in 16T



- Frequency peaks
  - near perfect agreement with taps
- PSP amplitude
  - reasonably close
- No in-situ corrections applied

Proper Orthogonal Decomposition

- Extract relevant flow structures
- Suggested by Gregory
  - demonstrated by Sellers

$$\tilde{C} = U^{T} U$$ correlation matrix

$$\tilde{C} A^{i} = \lambda^{i} A^{i}$$ eigenvalue problem

$$p(x,t) = \sum a_n(t) \varphi_n(x)$$ represent flow

$$u^{i} = \begin{bmatrix} u_1^i \\ u_2^i \\ u_3^i \\ \vdots \\ u_M^i \end{bmatrix}$$

extract pressure at grid point m, time step i to form u^i

$$U = \begin{bmatrix} u^1 & u^2 & u^3 & \cdots & u^N \end{bmatrix}$$

U is column vector of u^i MXN matrix

eigenvalue solution to compute POD modes

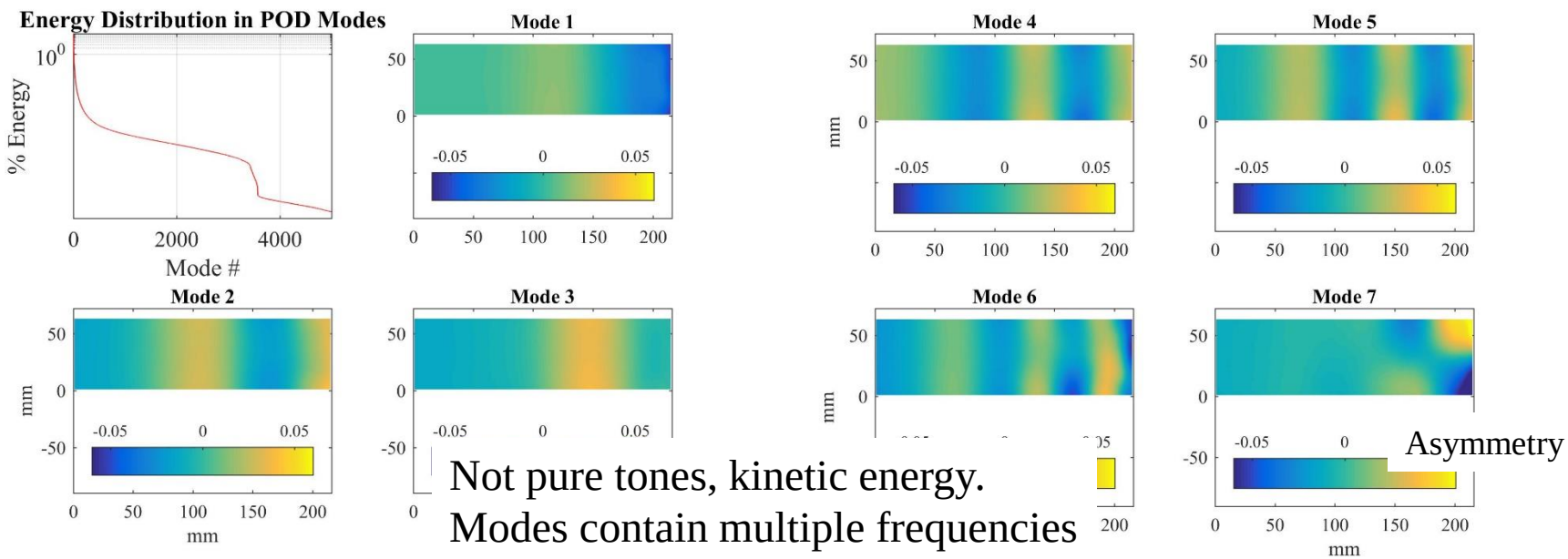
$$\varphi^{i} = \frac{\sum_{n=1}^{N} A_n^i u^n}{\left\| \sum_{n=1}^{N} A_n^i u^n \right\|} \qquad i = 1, \cdots, N$$

compute a_n to reconstruct pressure field with selected modes

$$a_n(t) = diag\left(\sqrt{\lambda_n}\right) A_n^{T}$$

Transverse Mode in Cavity

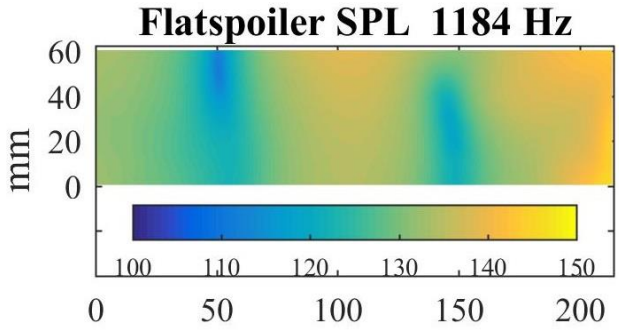
- Compute POD modes using ~ 5000 images
- 95% energy in modes 1-50
  - large pressure structures contain most of the energy
- First several modes resemble cavity tones

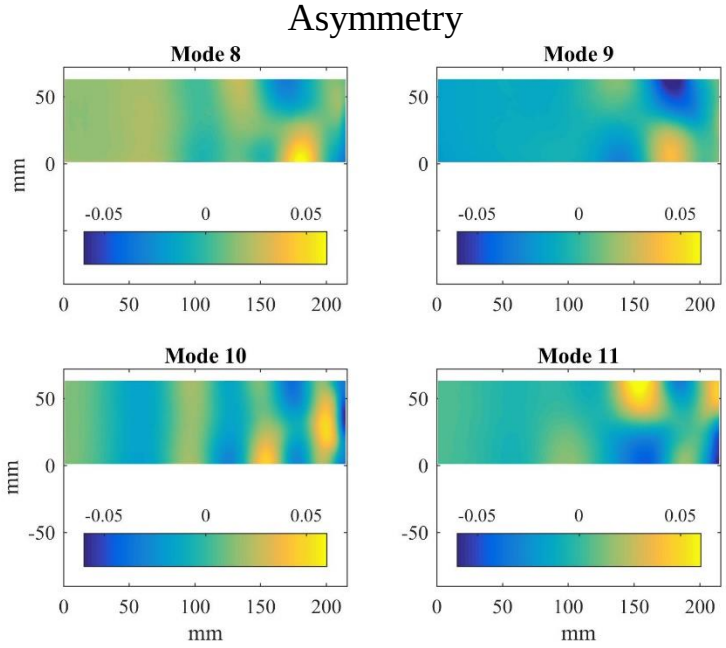


Not pure tones, kinetic energy.
Modes contain multiple frequencies

POD for Data Analysis

- Modes 7 – 11
  - substantial asymmetry
  - Mixed with tones
- Feature not evident in Baseline spectral data
- Asymmetry evident
  - Flatspoiler Tone 2
- Model misalignment?
- Never see without POD
  - Not evident in DMD





Coherence

- Coherence
  - $\gamma(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)\, G_{yy}(f)}$

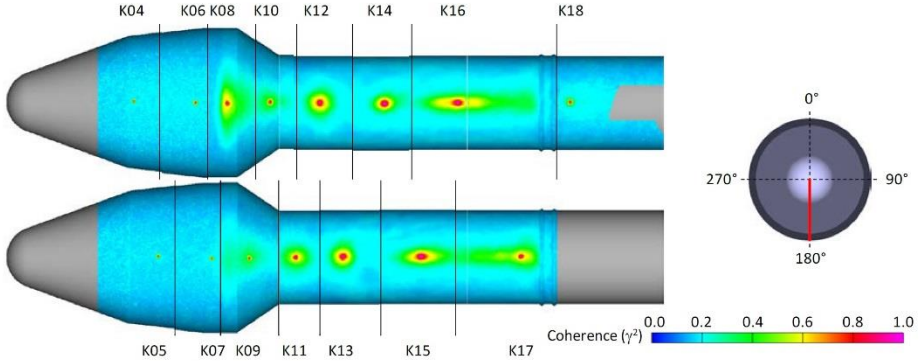
Spatial scale of pressure fluctuations

- Select a specific pixel
  - Compute coherence to each other pixel in flow
  - 100,000 pixels > 100,000 coherence maps
- Spatial scale of unsteady pressure fluctuations
  - How many unsteady pressure taps are needed
    - More kulites?
  - What kind of low-pass filtering can be applied
    - Improve noise floor

Launch Vehicle Buffet Test

NASA Ames 11-foot, Thursday
Sellers, Ross

- 216 Kulites
- Dynamic balance
- 4 camera Fast PSP
- Compare integrated fast PSP, virtual tap PSP, Kulites
- Discrete data overpredicts unsteady loads
- Assumed coherence is 0.5
- Coherence maps
  - Each tap
- Coherence << 0.5
  - Need more taps



Dynamic Mode Decomposition

- Similar to POD with focus on frequency rather than kinetic energy

$$V_1^N = \left[v_1, Av_1, A^2 v_1, \cdots \quad A^{N-1} v_N\right]$$

represent flow with linear growth

$$\tilde{S} = U^H A U$$

eigenvalue solution to compute modes. U is POD basis

$$v^i = \begin{bmatrix} v_1^i \\ v_2^i \\ v_3^i \\ \vdots \\ v_M^i \end{bmatrix}$$

extract pressure at grid point m, time step i to form v^i

$$V = \left[v^1 \; v^2 \; v^3 \; \cdots \quad v^N\right]$$

Modes are eigenvalues of S, complex part is frequency of mode

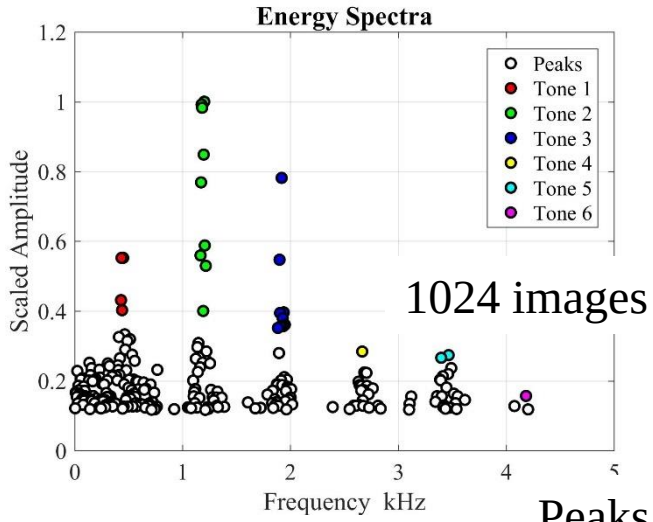
$$\Phi_j = U y_j \qquad \omega_j = \log\left(\lambda_j\right) / \Delta t$$

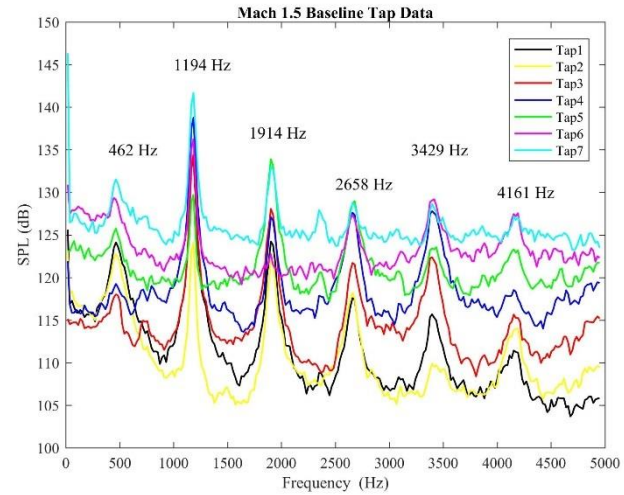
Select S to minimize residual

$$A V_1^{N-1} = V_2^N = V_1^{N-1} S + r e_{N-1}^T$$

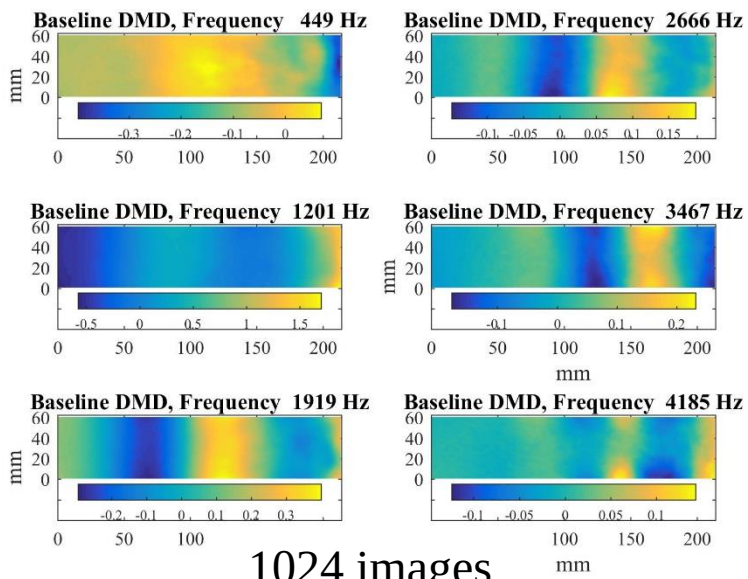
reconstruct pressure field using (or excluding) specific frequencies

Spectral Peaks –vs- DMD Peaks

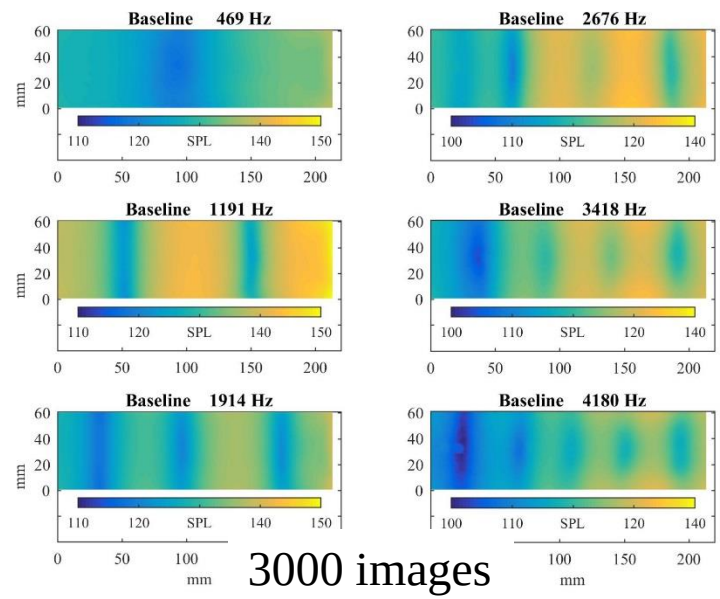




Peaks



1024 images

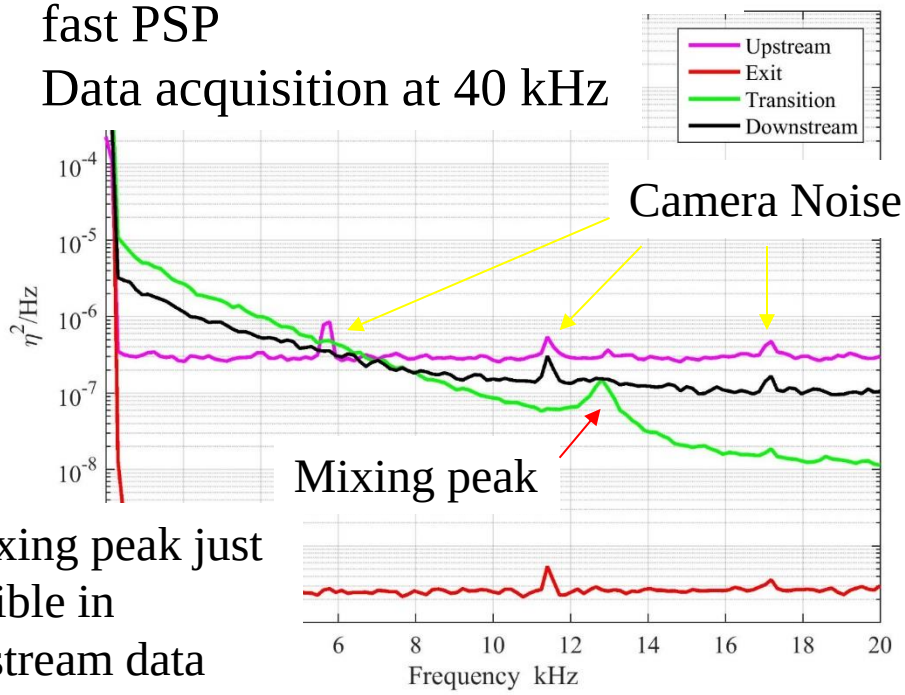


3000 images

DMD/POD Camera Noise Filter

- POD used to isolate structure
- DMD used to isolate frequency

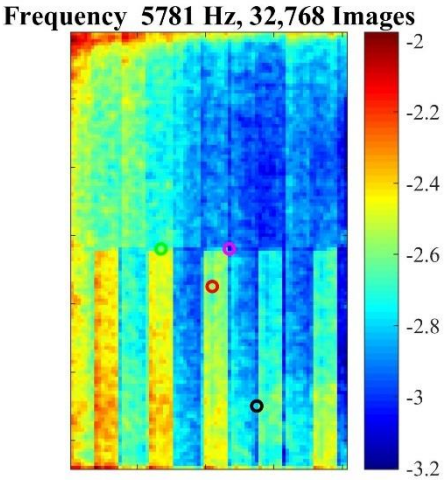
Mixing experiment using fast PSP
Data acquisition at 40 kHz



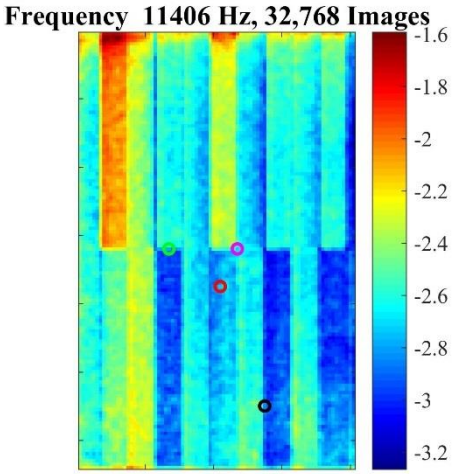
Mixing peak just visible in upstream data

- Spectra computed using ~ 32,000 images
- Fast camera pattern noise at distinct frequencies
- Remove noise from data
  - POD
  - DMD

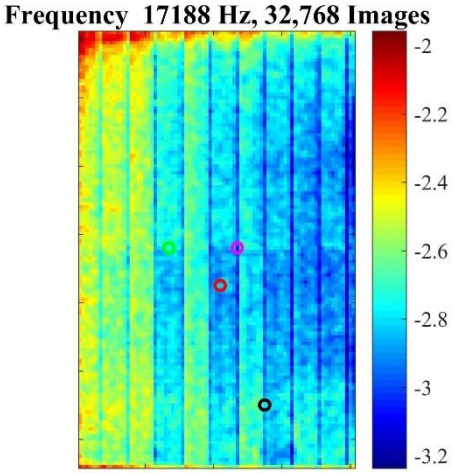
Camera Noise Spectra



- Fundamental and 2 harmonics

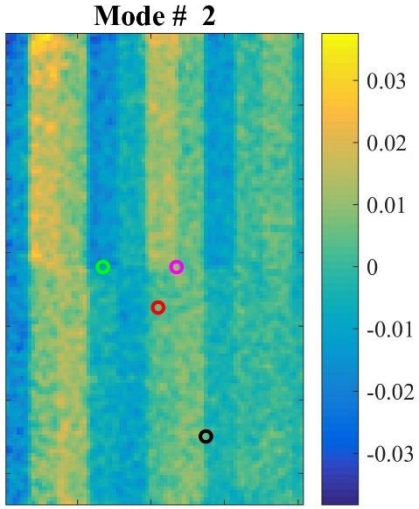


- Focus on upstream ROI
- Cannot show downstream

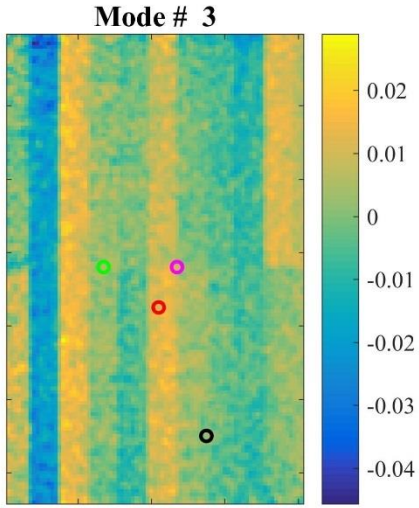


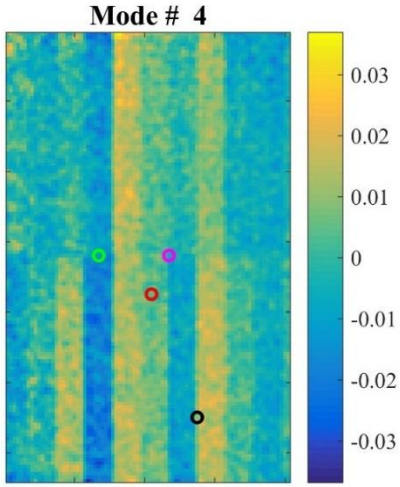
- Common to see noise structures in fast CMOS camera

Camera Noise POD

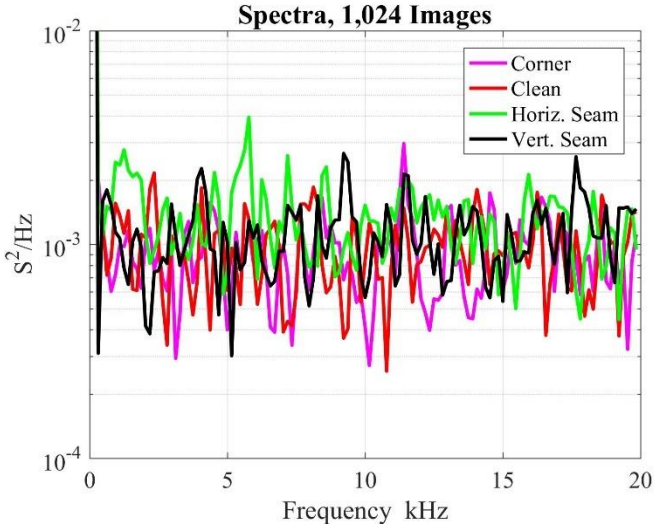


- Reconstruct and remove?
- POD modes using 1024 images



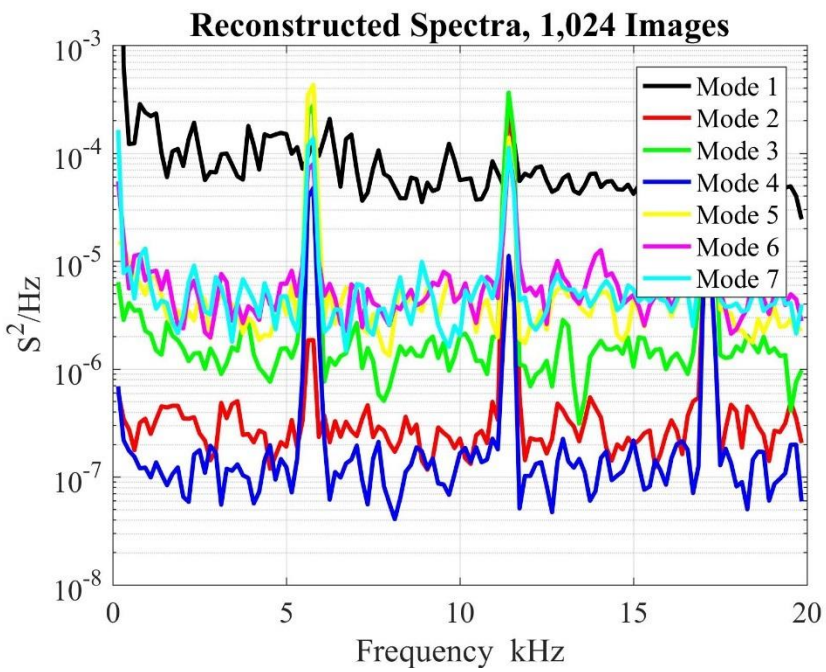


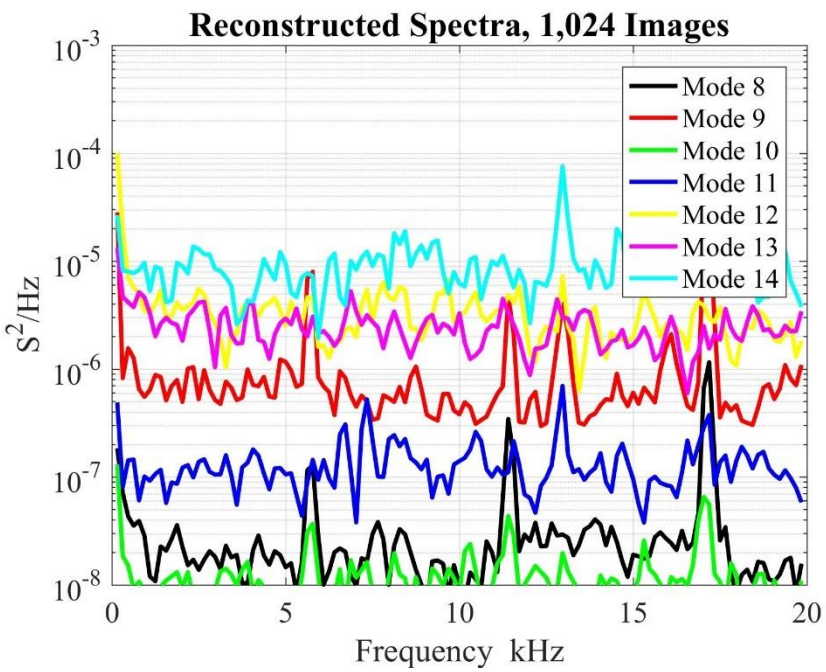
- Structures present in POD modes
- Difficult to ID in spectra



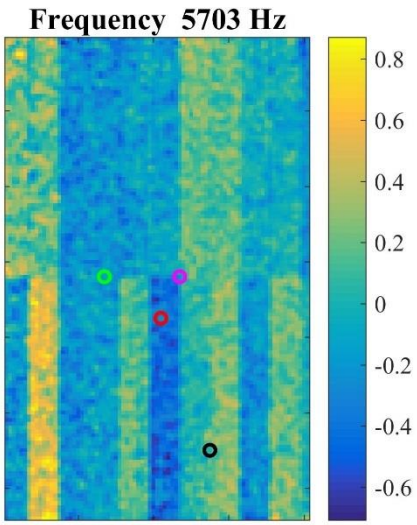
POD Reconstruction

- Reconstruct each mode and compute spectra
- POD modes contain multiple frequencies
- POD good for pattern noise, not frequency

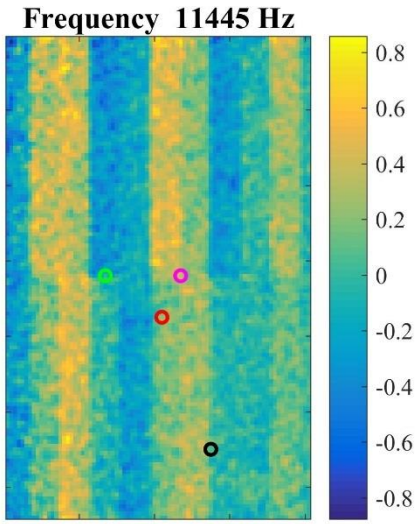


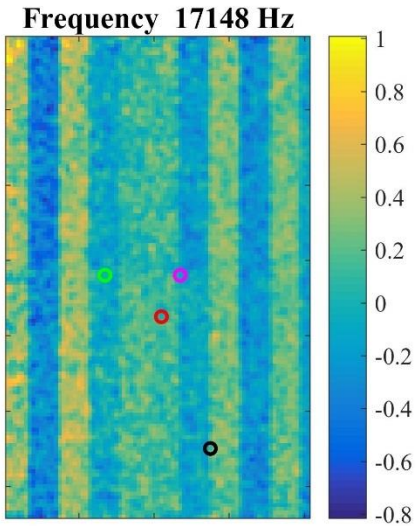


Camera Noise DMD



- DMD modes using 1024 images

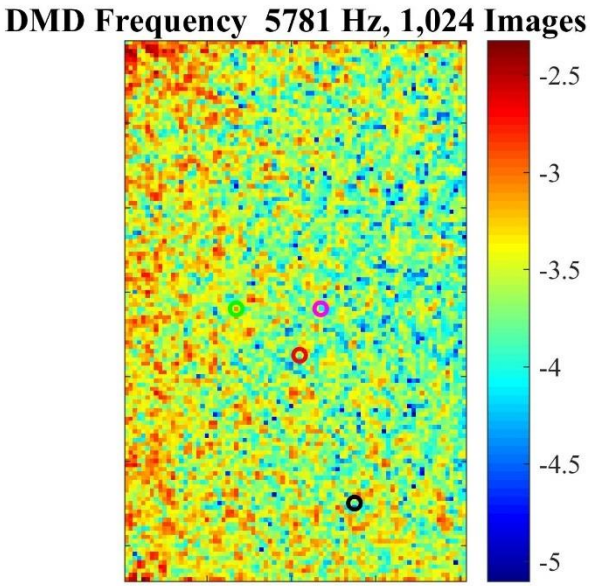


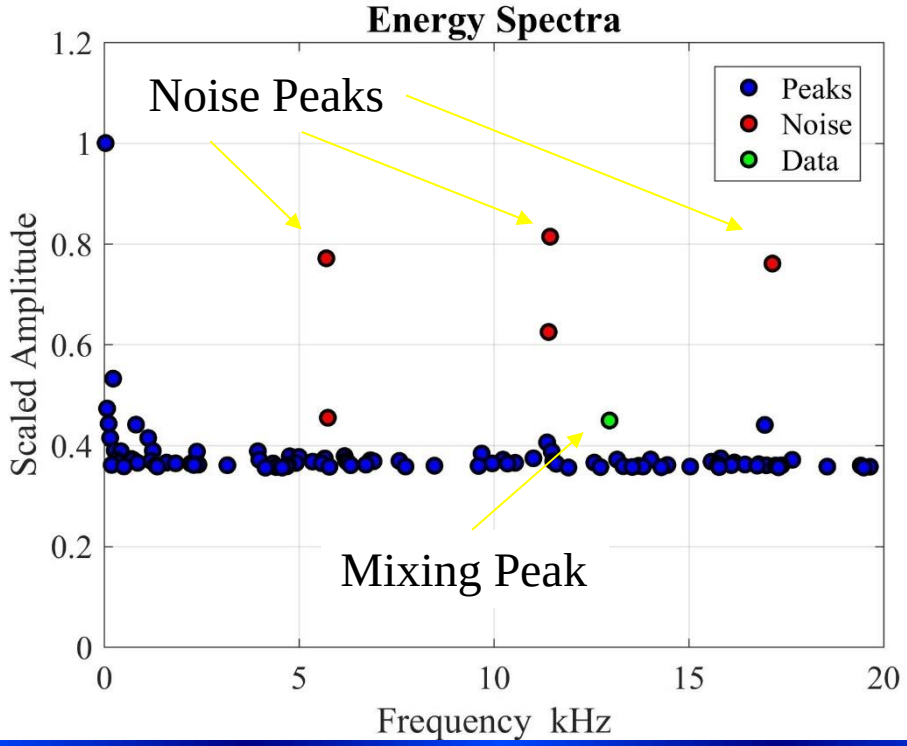


- Noise structures present in DMD modes

DMD Reconstructed

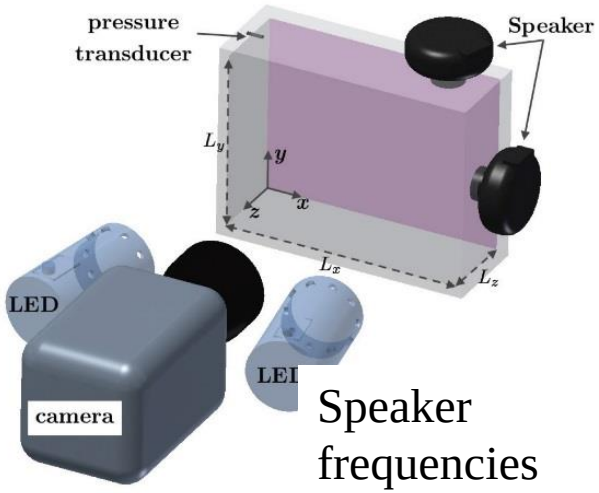
- Camera noise peaks clear in Energy Spectrum
- Downstream mixing peak is also evident
  - Barely visible is spectra (32,000 images)





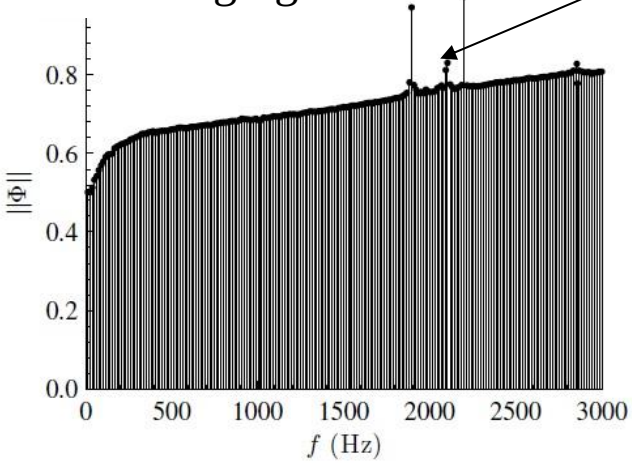
Practical Demonstration

Acoustic box
with 2 speakers

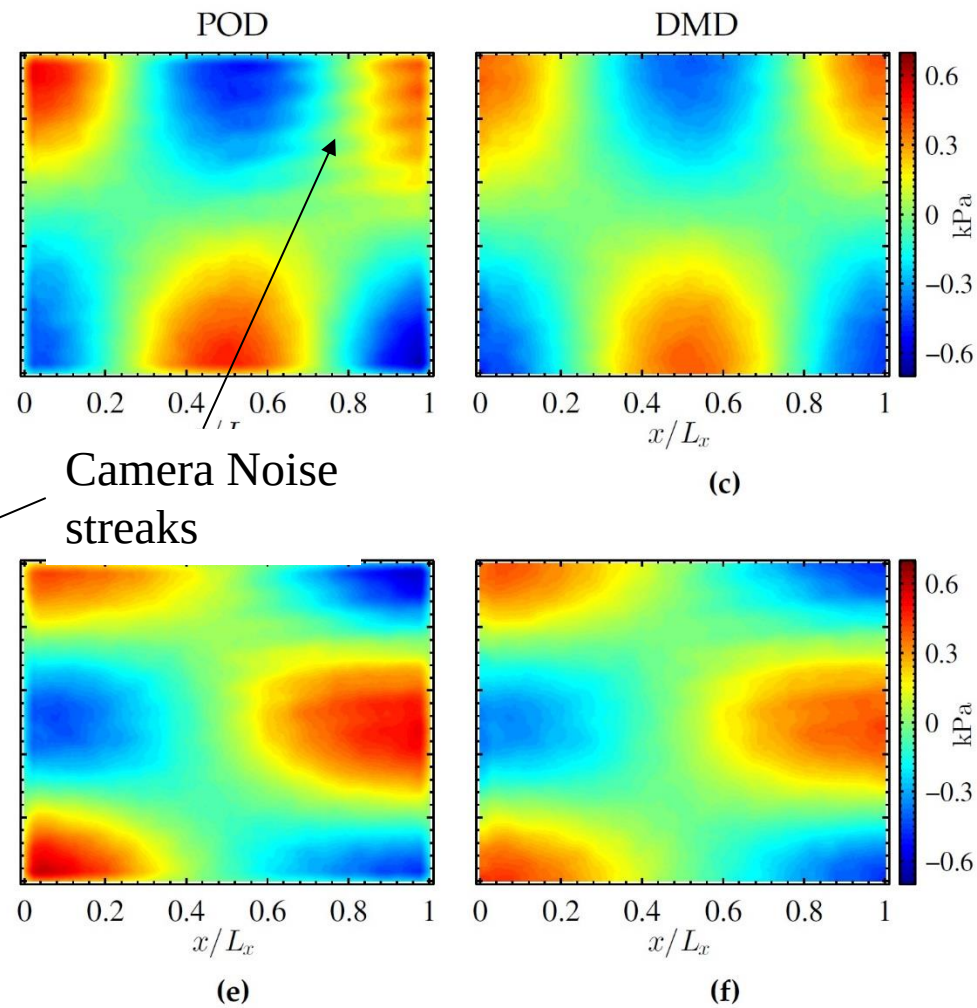


Speaker
frequencies

Mixed mode, no
phase averaging



Camera Noise
streaks



Conclusions and Future Work

- Fast PSP provides high spatial resolution pressure maps
  - frequency content excellent, amplitude data good
  - operation demonstrated in small and large wind tunnels
- Cross-correlation, Coherence, and Spectral maps
  - identify flow scales, frequency content, and relationships
- POD and DMD analysis
  - Identify structures with significant kinetic energy (POD)
  - Identify specific frequency content in the flow
  - Can operate as a filter to remove noise or flow features
- Data mining tools
  - Identify key flow features, noise sources quickly and automatically
- Fast Binary PSP for mean and unsteady in single run
  - Development complete, testing underway