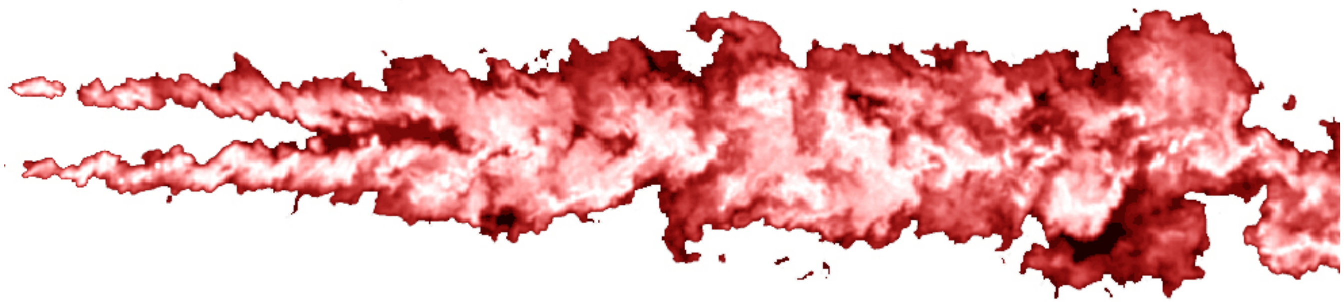
Large-Scale Turbulence Structures and Noise Generation in High-Speed Jets



James I. Hileman
Post-Doctoral Associate
Gas Turbine Laboratory
Massachusetts Institute of Technology

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Work conducted at The Ohio State University
under the supervision of Prof. Mo Samimy.
Sponsored by AFOSR

Seminar Scope

- Objective: relate aft jet noise to the time evolution of large-scale turbulence within a high-speed jet mixing layer.

- Approach: first of its kind measurement using well established techniques of microphone array noise source location and optical flow diagnostics.

- Measurement techniques presented individually and then combined to show mixing layer evolution during noise emission; not previously done in high Re flow.

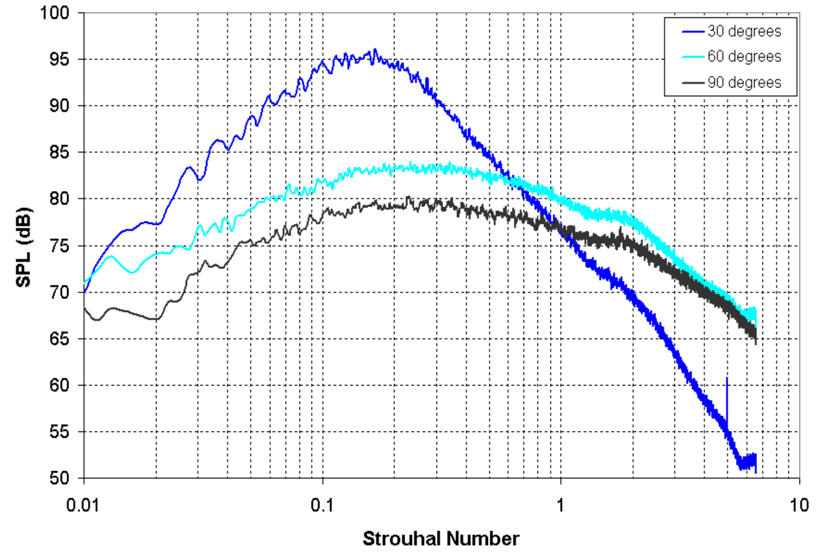
- Examined:
  - Mach 0.9 and ideally expanded Mach 1.3 and 2.0 cold jets.
  - Streamwise vortex generating delta tabs (time allowing).
  - Nozzle diameter of 1 inch, Re ~ 10^6.

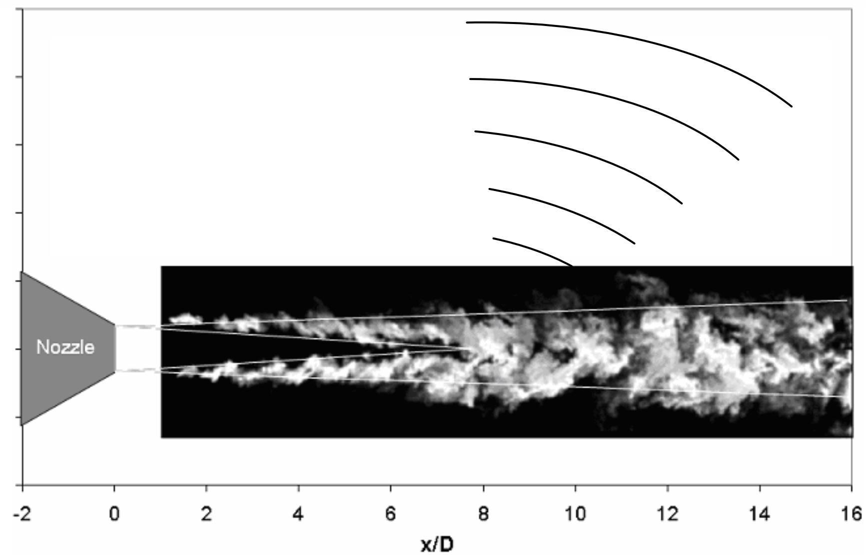
Jet Structure and Noise

Jet Structure
- Jet potential core
- Mixing layer

Large Scale Structures
- Dominate turbulent mixing layer
- Dynamic growth and destruction

Jet Noise
- SPL ~ 10log (U^n A / r^2).
- Created by the turbulence within mixing layer.
- Noise from largest structures originates from potential core and radiates downstream.
- After 60 years of research, jet noise is largely a mystery and predictive methods for aft regions are still <u>entirely</u> empirical.





Hypotheses – New Ideas

- Sound emission from a jet can be directly related to the time-dependent evolution of the turbulence within the jet. Noise emission in low Reynolds number jets thought to be caused by instability breakdown [Morrison and McLaughlin, 1979] – has not been visualized at high-speeds.

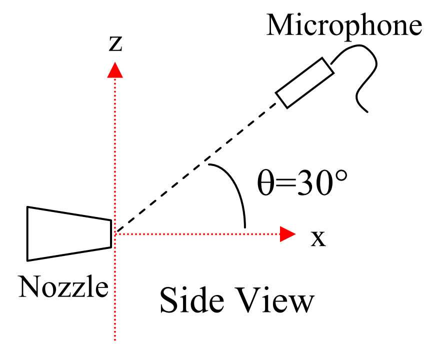
- Dominant sound emission from a jet is a short duration phenomenon interspersed among periods of lesser sound intensity.

- Jet turbulence has different properties during periods of sound emission than prolonged periods lacking such sound emission.

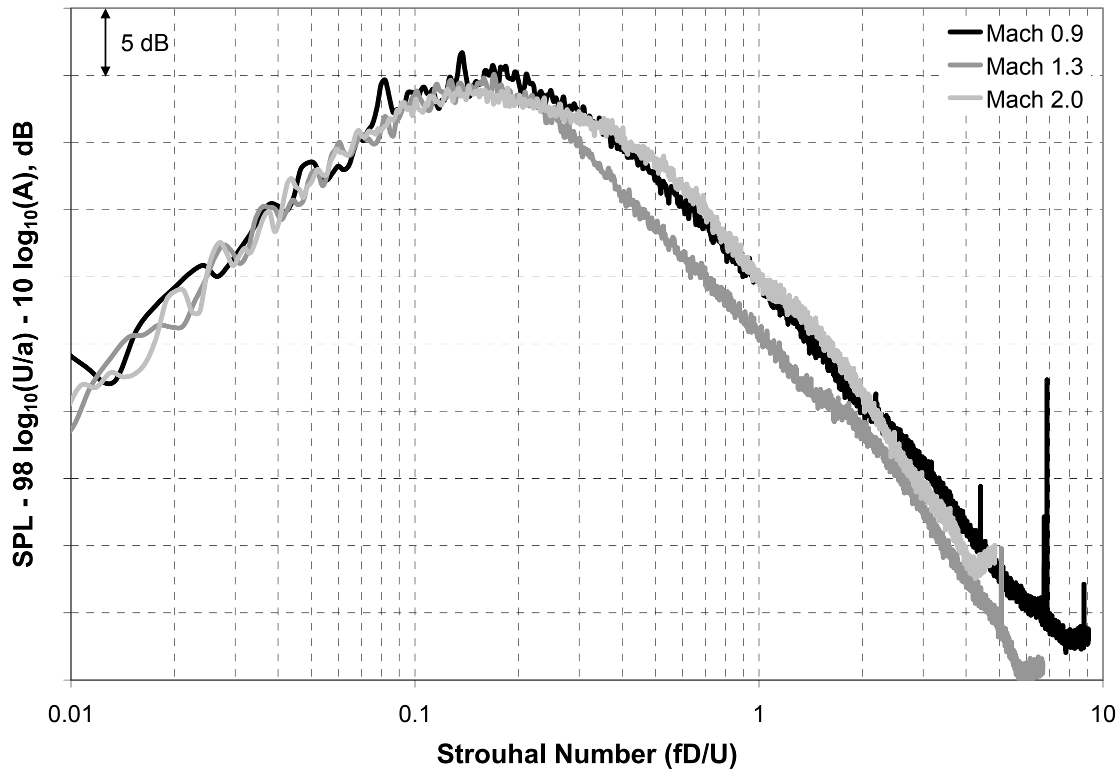
- Jet noise modification by streamwise vorticity can be identified.

Sound Data Spectra

Aft jet noise collapses with $U^{9.8}$ (Viswanathan, AIAA 2005-2935) and Strouhal number (not Helmholtz).



Traditionally analyze sound with spectral domain data – hard to relate to flow.

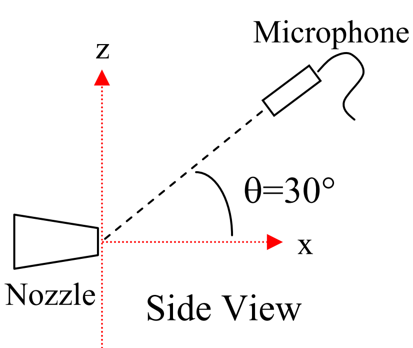


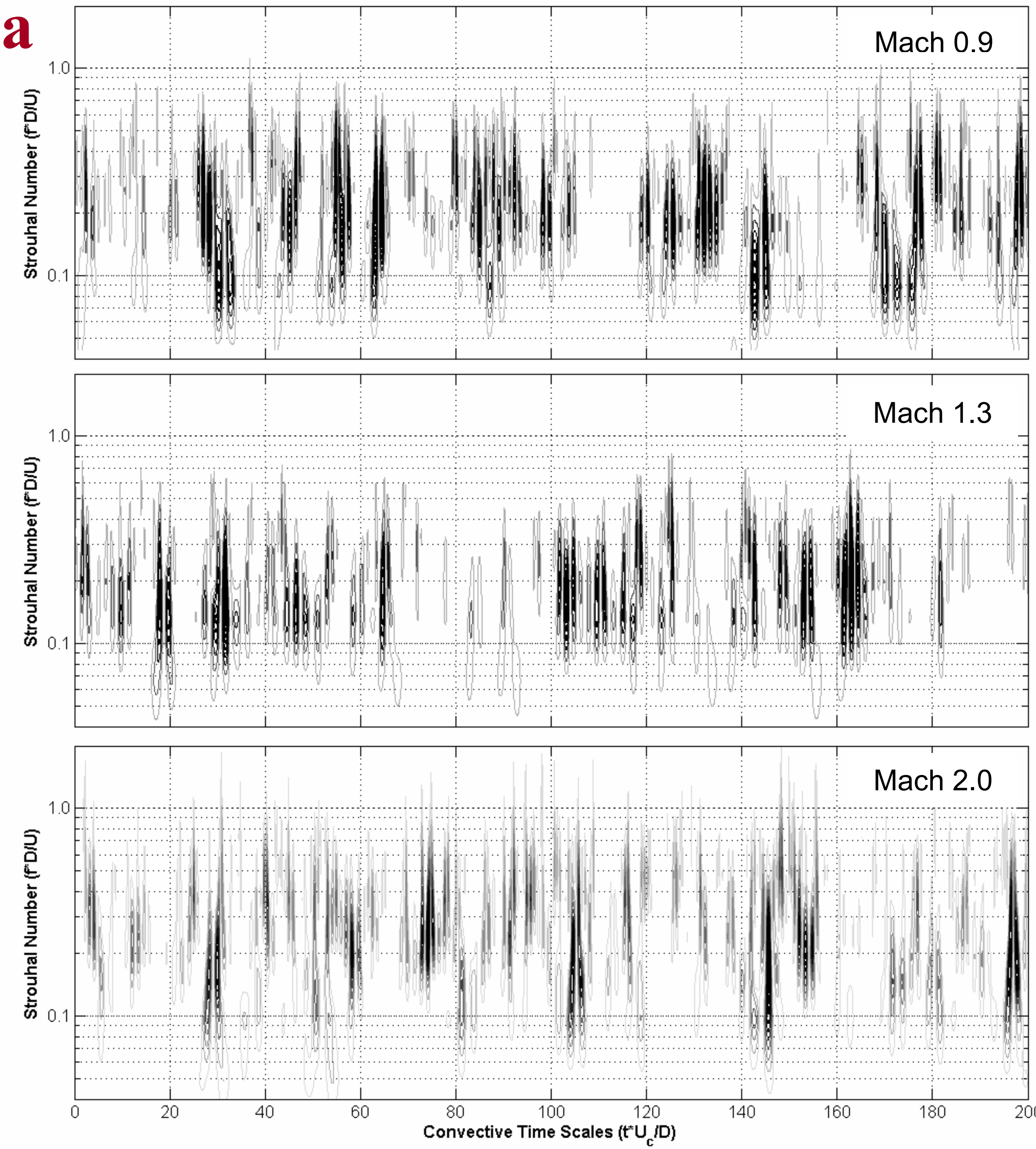
Time Domain Data

When viewed in time domain, the acoustic signal consists of bursts of sound waves interspersed among periods of "relative" quiet.

Subsonic to Mach wave emitting jets all similar.

Research focused on "noise events" and "relative quiet" periods.





Noise Source Localization

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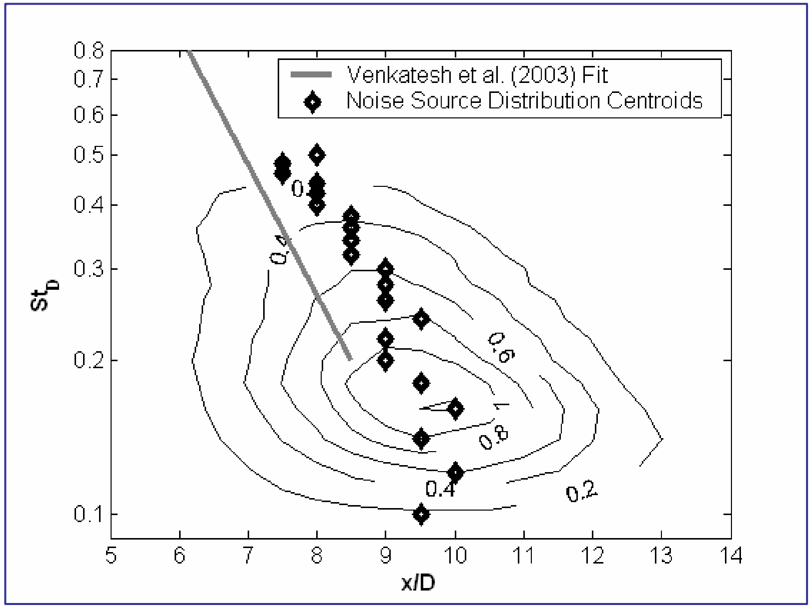
- Determine apparent origin of *individual* acoustic peaks in three dimensional space.
- Measure phase shift of large amplitude peaks between microphones within *time domain*.
- Use this shift with geometry to determine apparent sound origin.
- Six azimuthal mics determine cross-stream (y-z) location.
- Two pair of inline mics determine streamwise (x) location.
- Validated with plasma spark and small fluidic actuator.
- Accurately locate frequencies under 10 kHz (peak is 2.5 kHz).

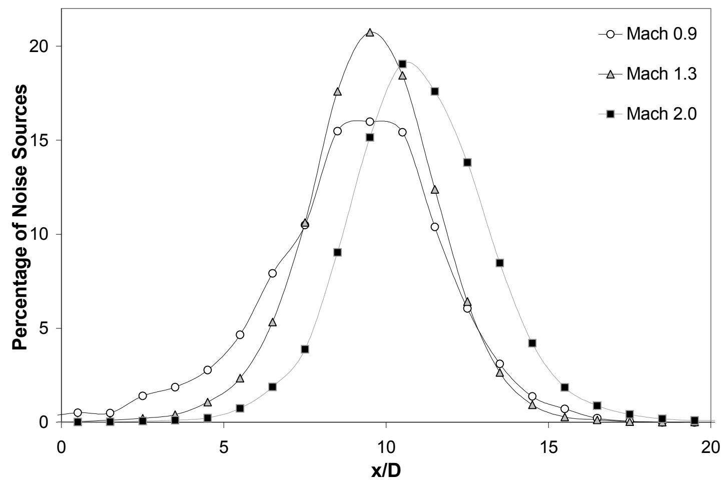


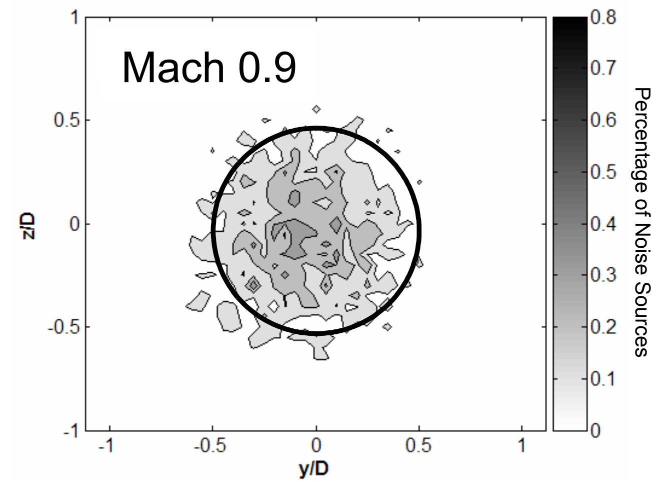
Mach Number and Noise Emission

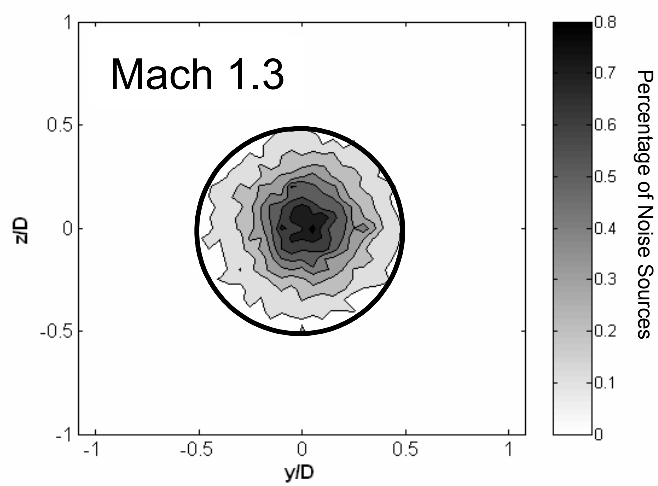
Noise emission corresponds to ellipsoid shaped region past end of potential core.

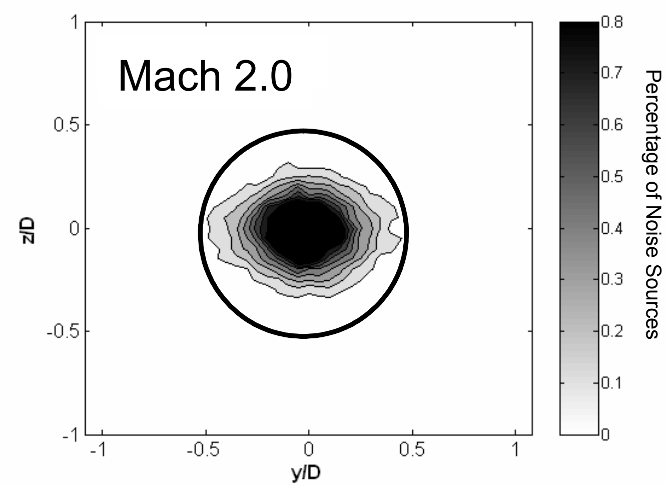
Potential core:
M=0.9 – 7 x/D
M=1.3 – 8 x/D
M=2.0 – 11 x/D

Mean x-noise source location:
M=0.9 – 9.0 x/D
M=1.3 – 9.6 x/D
M=2.0 – 11.3 x/D









Optical Flow Diagnostic: Flow Visualization

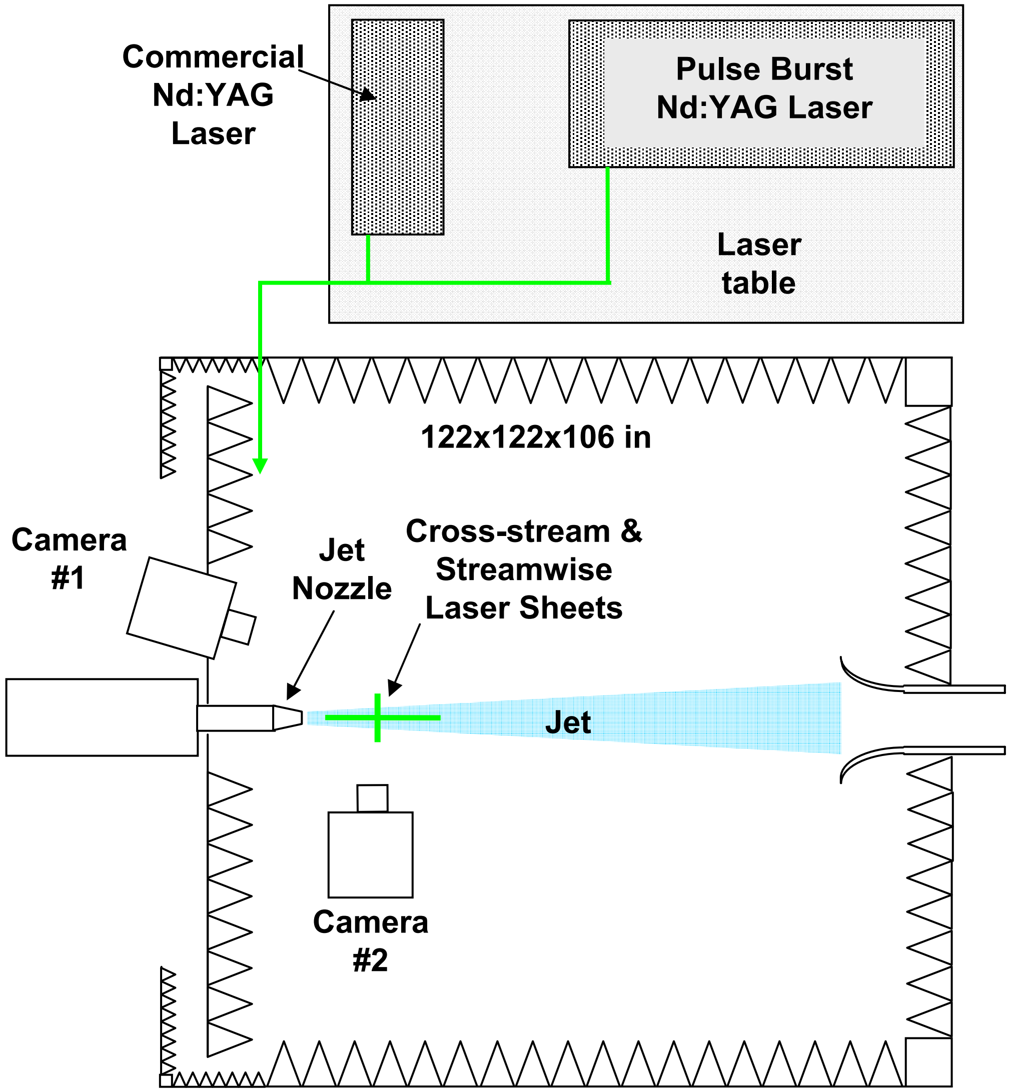
Slide 9

Single flow images

- Commercial pulsed laser
- Scientific grade CCD camera
- Acquire images at 10 Hz

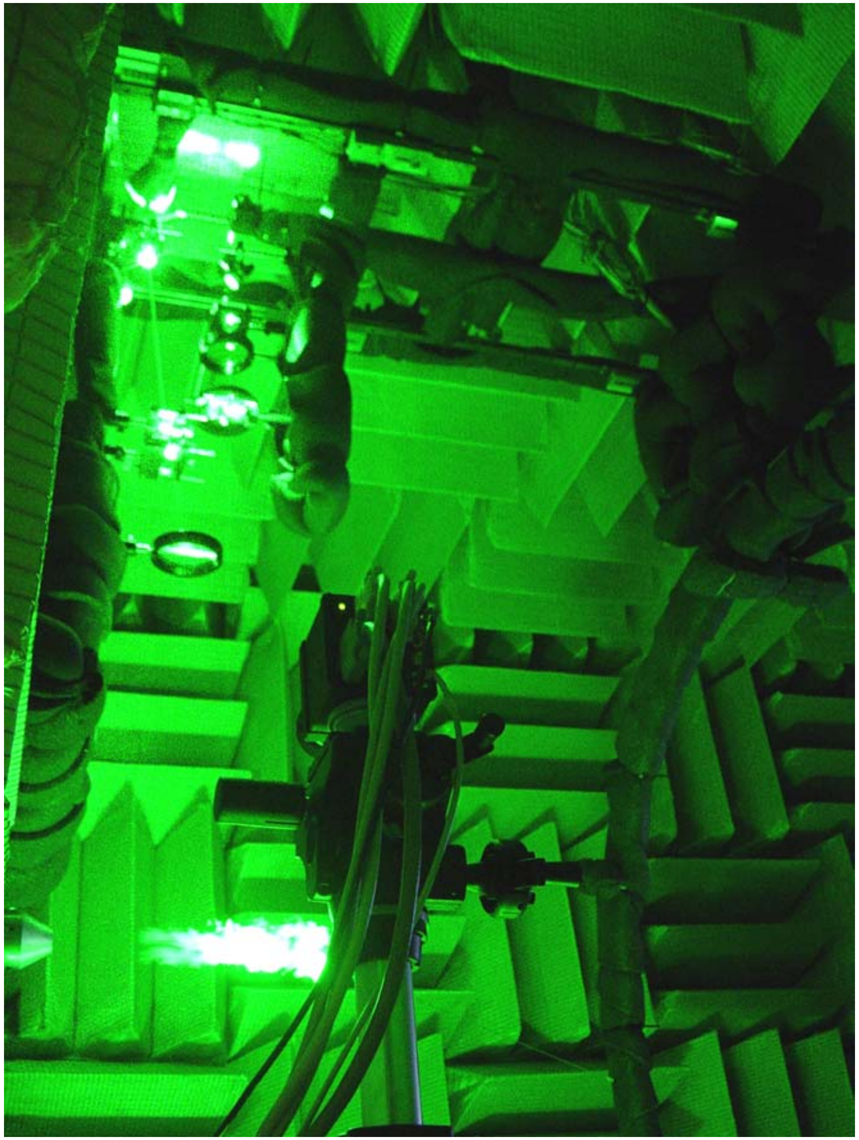
Temporally-resolved flow images

- Custom-built, pulse-burst laser
- Scientific grade high-speed camera
- Acquired 17 images with 4 to 10 μs time spacing
- Successive image bursts acquired at 5 Hz



Flow Visualization

- Relies on ambient humidity.
- Condensation marks majority of mixing layer.



Flow Visualization

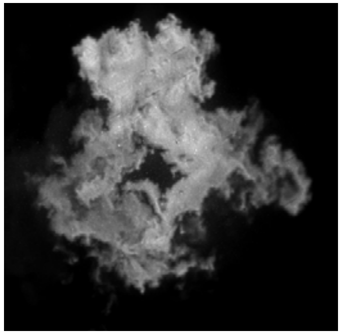
Slide 11

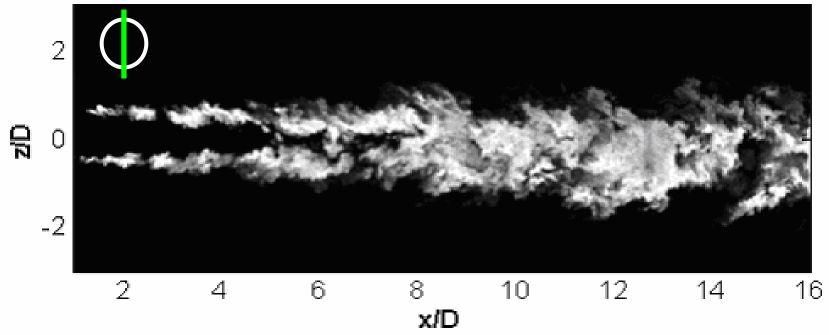
Relies on ambient humidity.

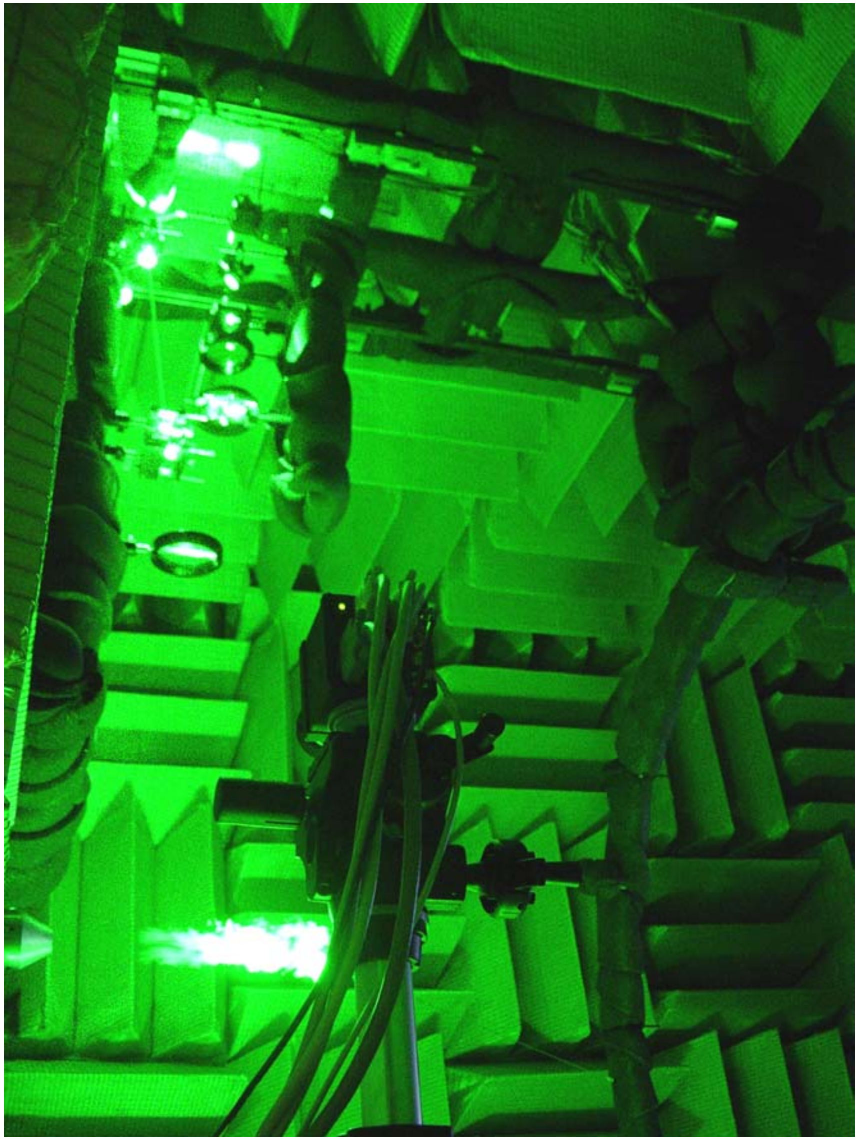
Condensation marks majority of mixing layer.

Instantaneous flow images.

<u>Images:</u>
Cross-stream - 9 x/D
Streamwise - 1 to 16 x/D

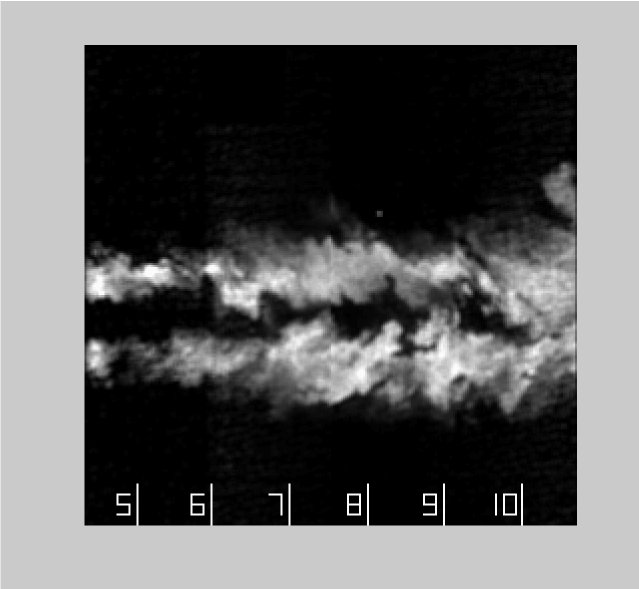


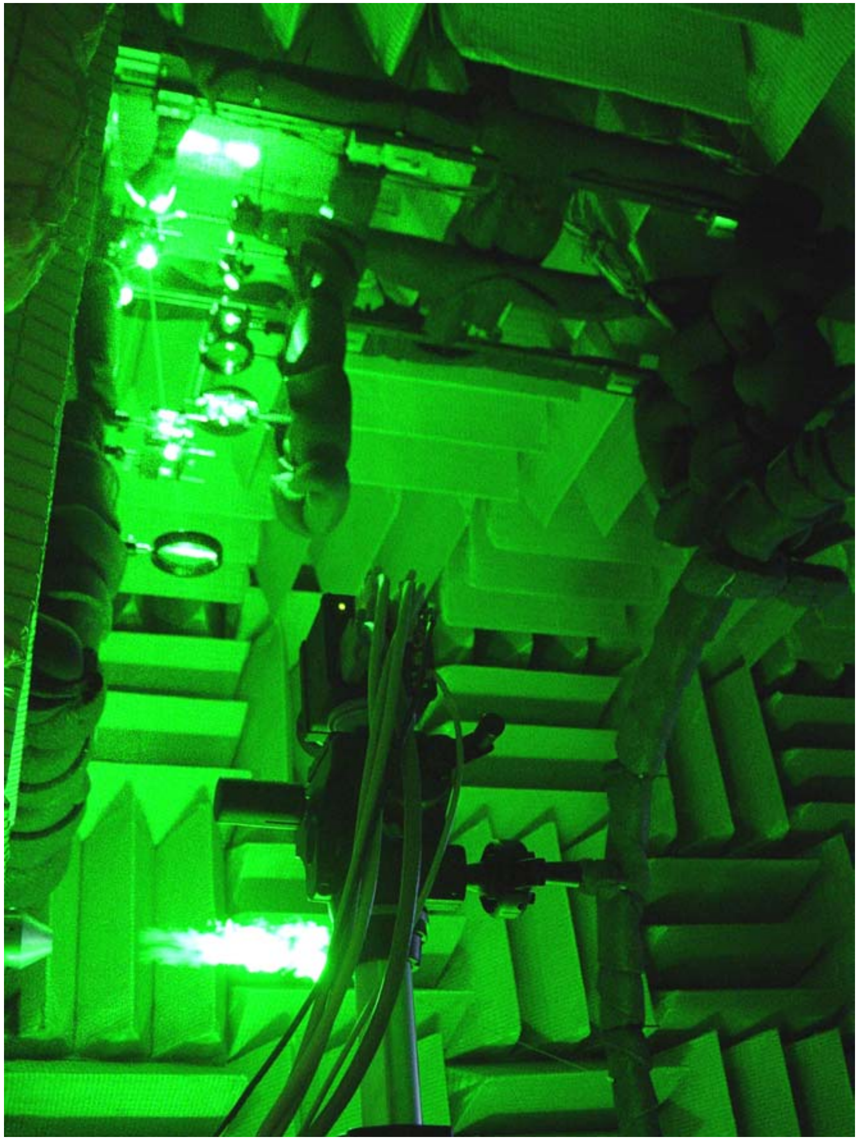




Flow Visualization

- Relies on ambient humidity.
- Condensation marks majority of mixing layer.
- Temporally-resolved flow images.

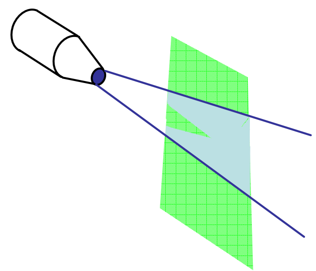




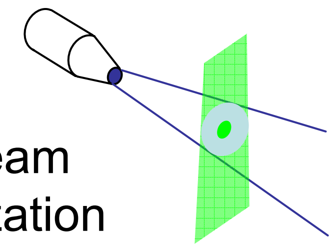
Flow Visualization

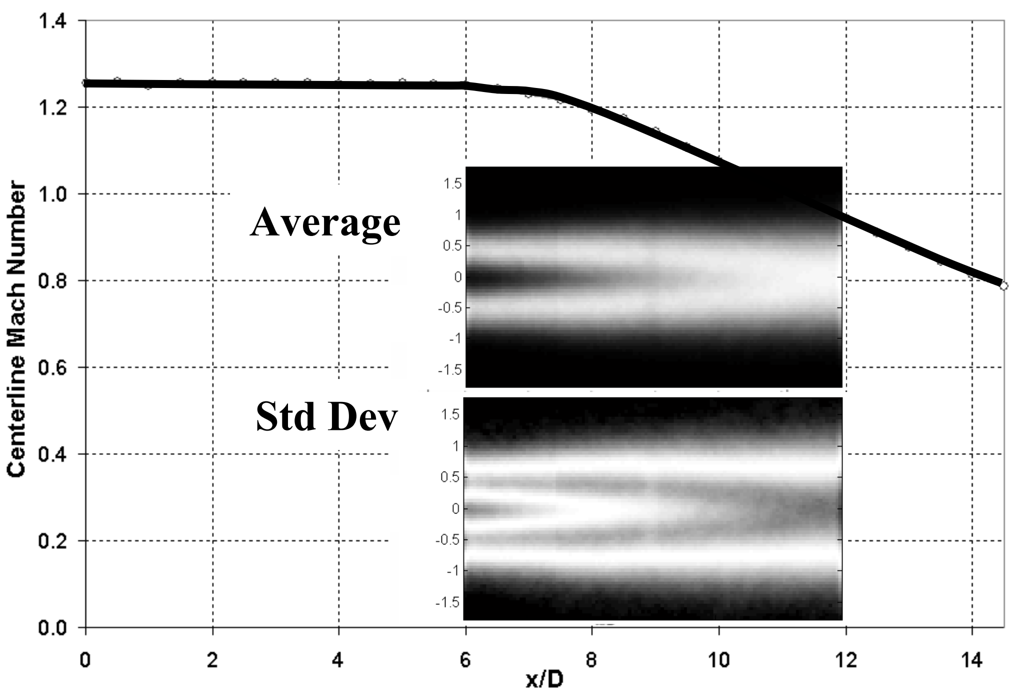
Streamwise flow visualization images capture end of potential core. Cross-stream have expected shape.

Streamwise flow visualization images

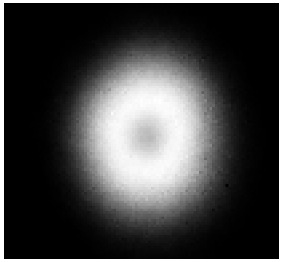


Cross-stream flow visualization images

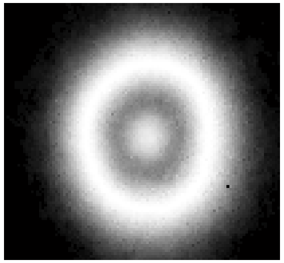




Average



Std Dev



Proper Orthogonal Decomposition

- Used for objective identification of flow features (i.e. large-scale turbulence) within the mixing layer.

- POD Modes
  - Create basis describing relative size, shape, and distribution of large-scale structures within mixing layer.
  - Using image intensity fluctuation from mean.
  - Based on snapshot method of Sirovich, 1987.

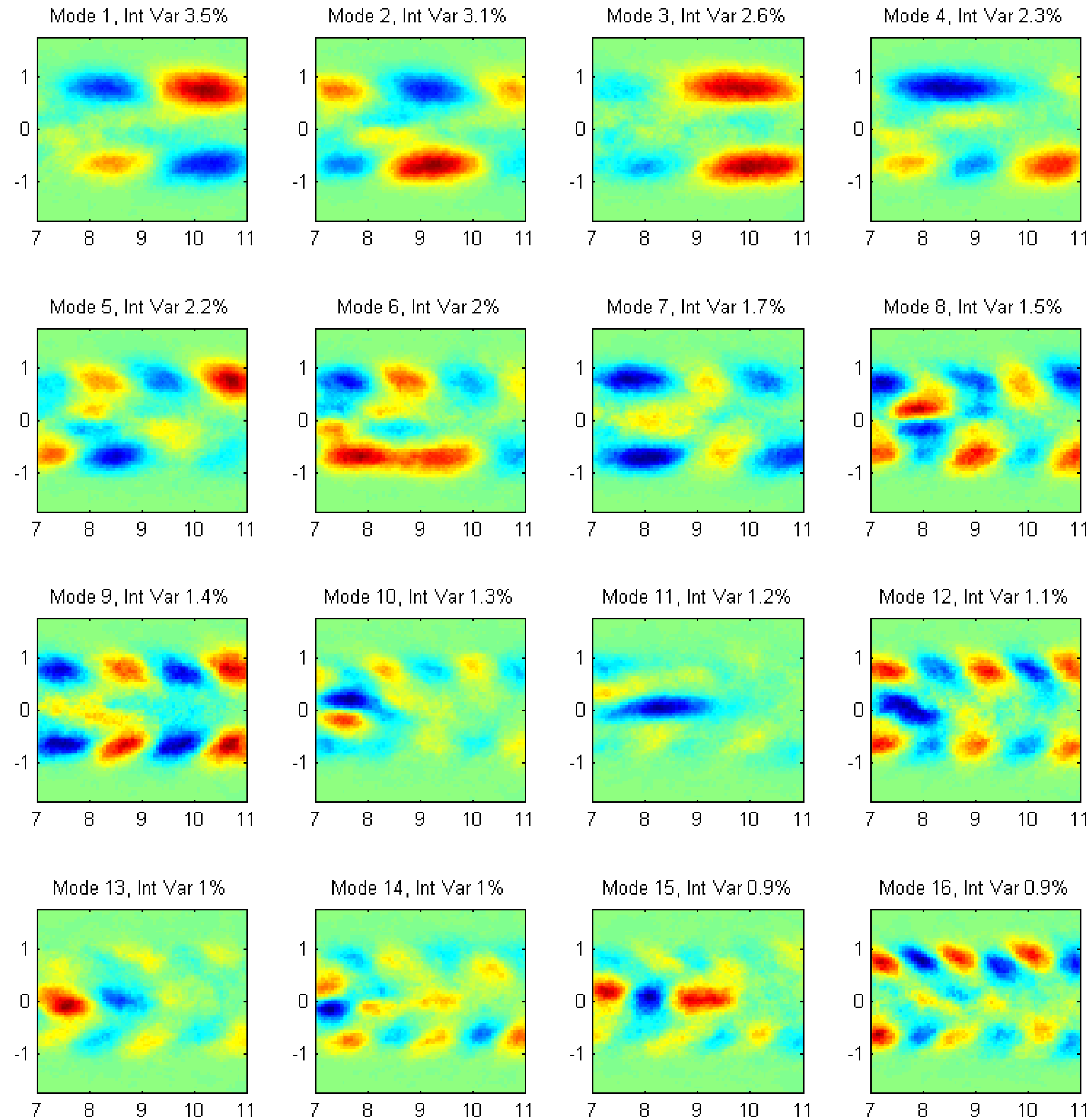
- Image Reconstruction
  - Use POD modal basis to reconstruct any individual image.
  - Selecting different modes for reconstruction spatially filters an image

Streamwise POD Modes – Mach 1.3 Jet

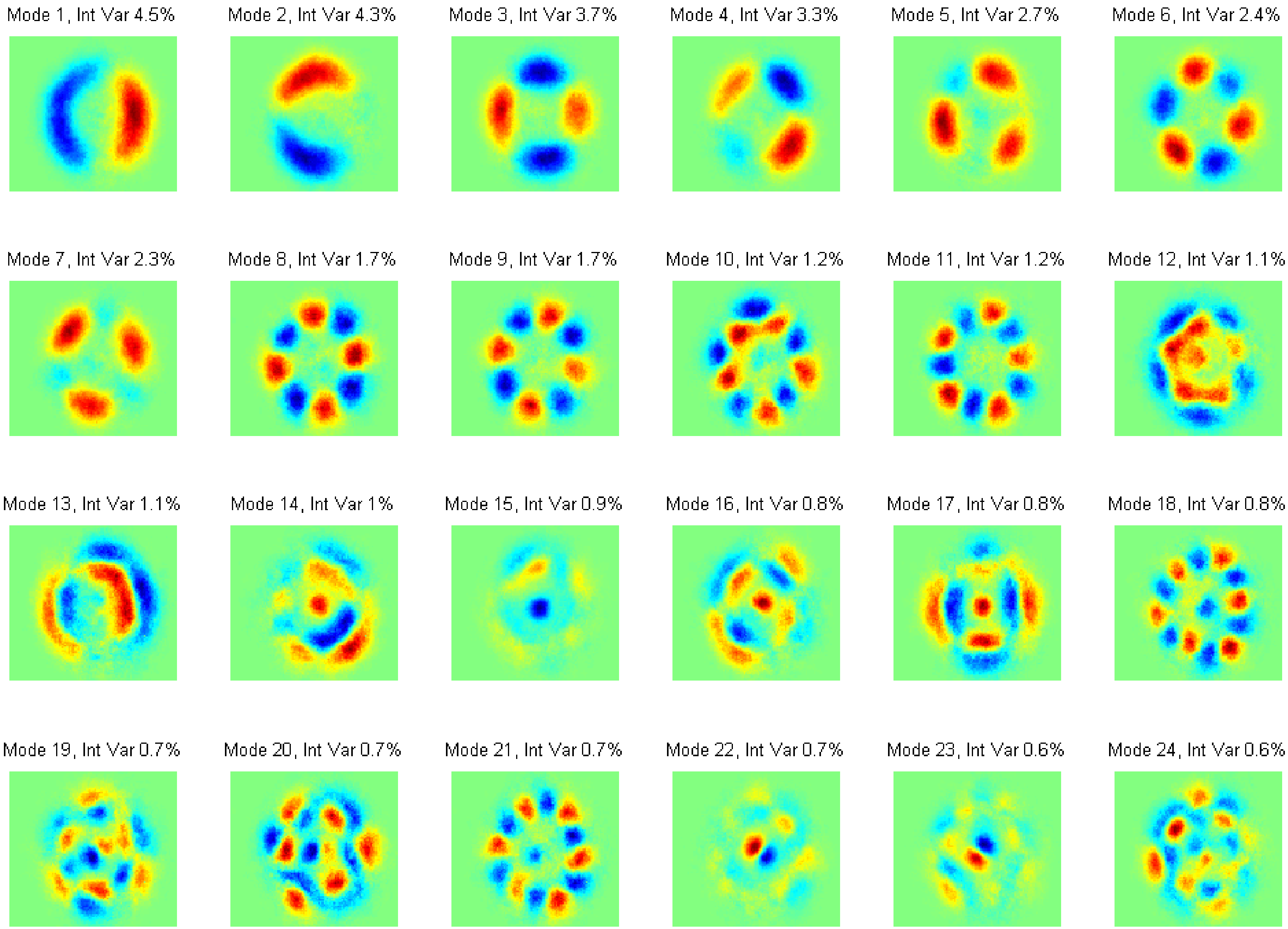
- Intensity fluctuation
- 2000 images

- Modal asymmetry
- Complex structure
- Inner vs. Outer

- Basis of large structure dynamics
- Will bed used later for image reconstruction



Cross-stream POD Modes – Mach 1.3 Jet

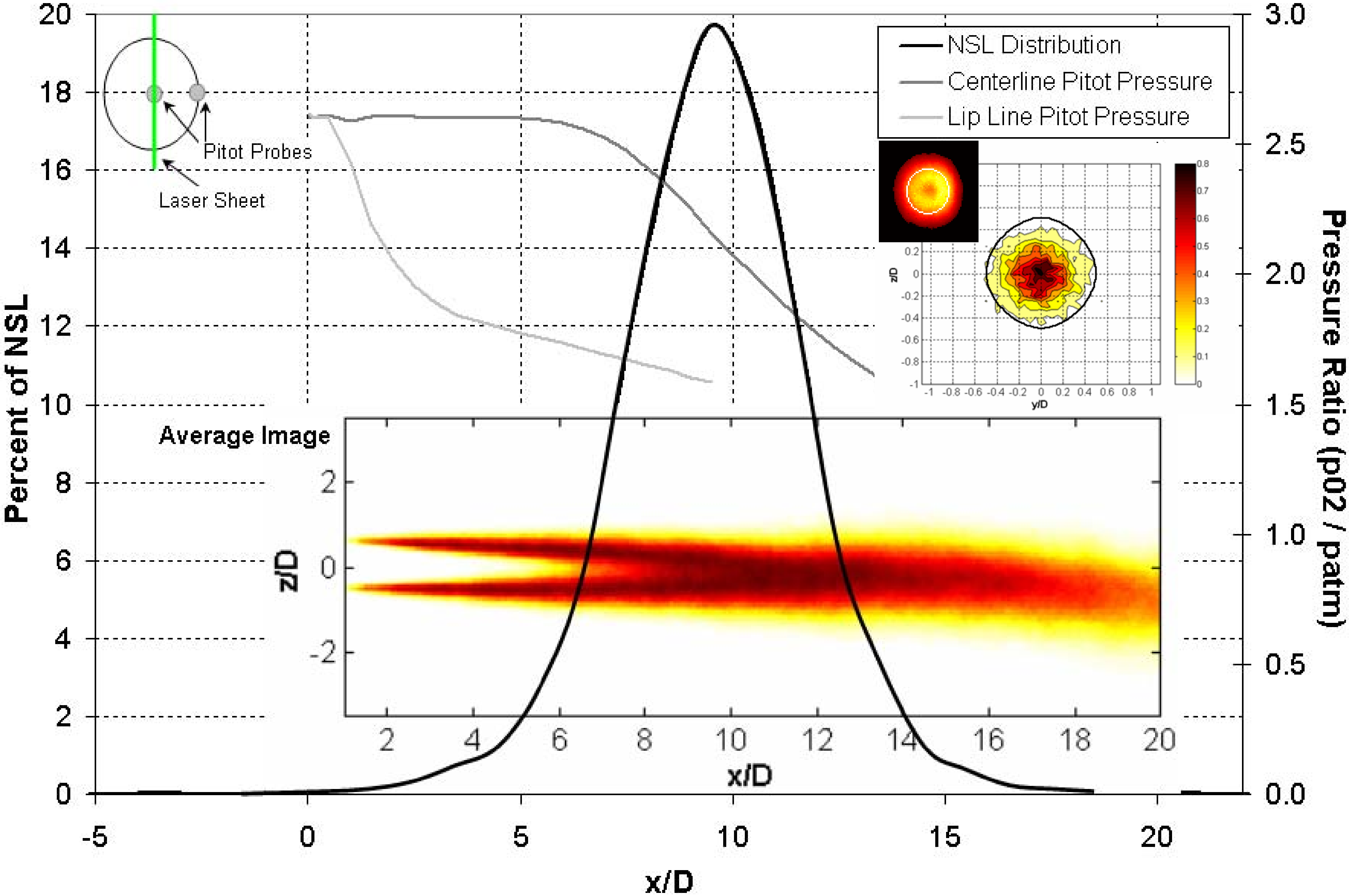


Results

- What occurs in the region of maximum noise source concentration?

- In an average sense...
  - Look at average noise source concentration and statistical flow data.
  - Basically, combine individual measurements that you've already seen.

Mach 1.3 Jet Noise Generation (average sense)



Results

- What occurs in the region of maximum noise source concentration?

- In a time-dependent sense...
  - Want to relate the individual acoustic peaks to simultaneously acquired flow visualization images.
  - Need statistically significant number of flow visualization images that capture noise emission and extended periods of relative quiet.
  - To extract common flow features, create an ensemble average reconstruction of the image sets using POD modal basis.

Capturing the noise generation process

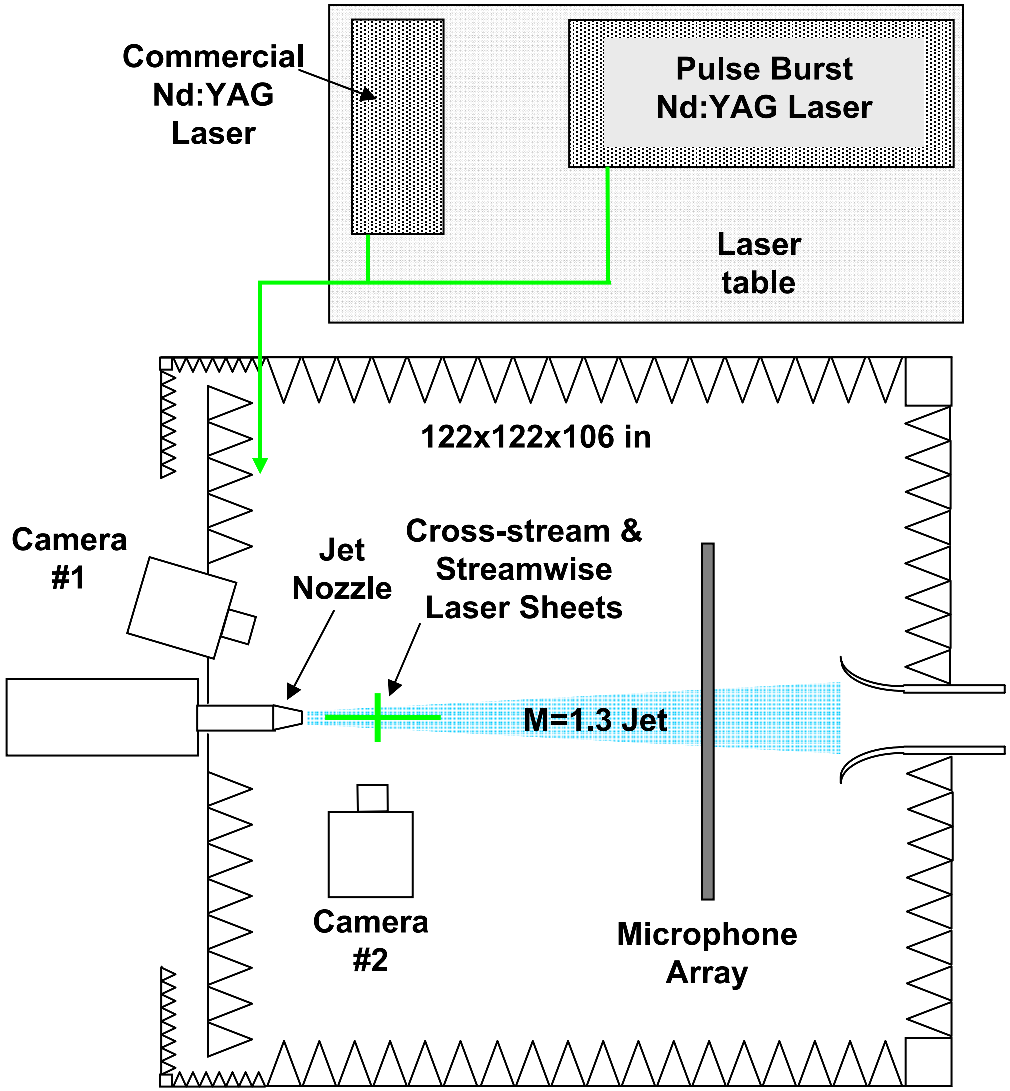
First of its kind experiment:

- Microphone array to determine noise source location in time and space.
- Simultaneous planar flow visualization captures fluid dynamics in region of noise emission.

Acquired: 1 cross-stream image, 16 temporally-resolved streamwise flow images with 90 μs duration, and 4.4 ms of acoustic data.

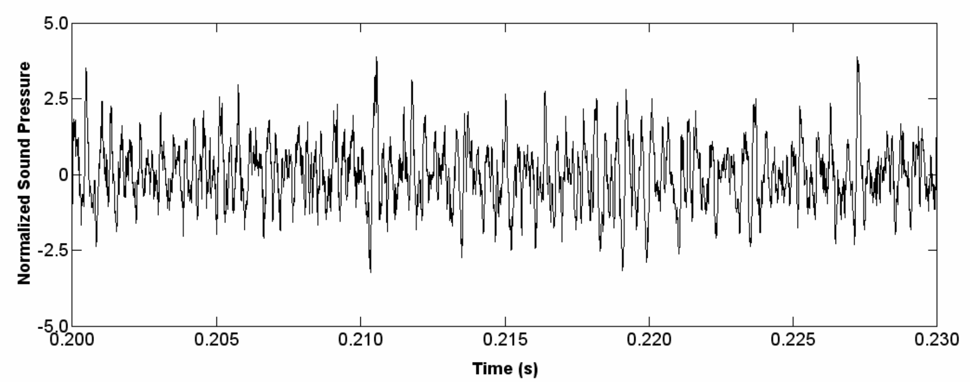
Convective time scale ~100 μs

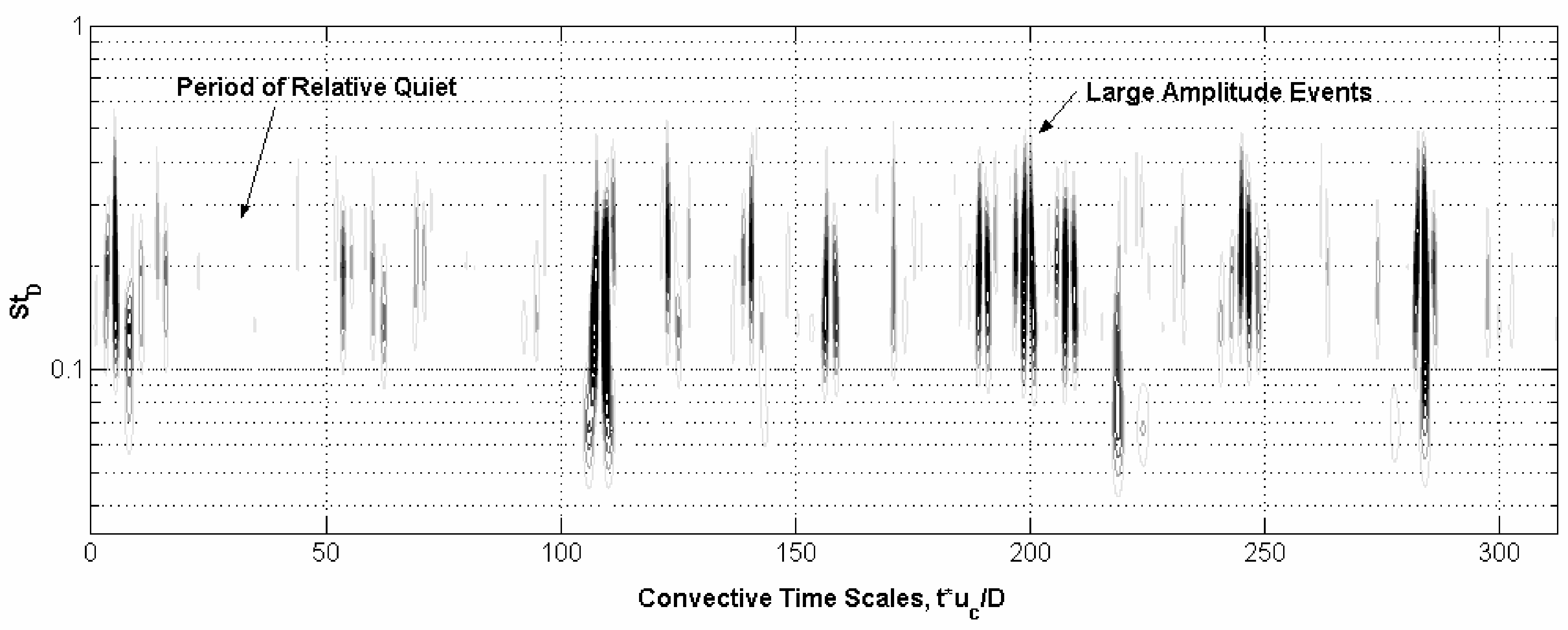
Dominant acoustic period ~ 400 μs.



Noise Generation vs. Relative Quiet

Focused on time domain analysis of relative quiet (RQ) and noise generation (NG).

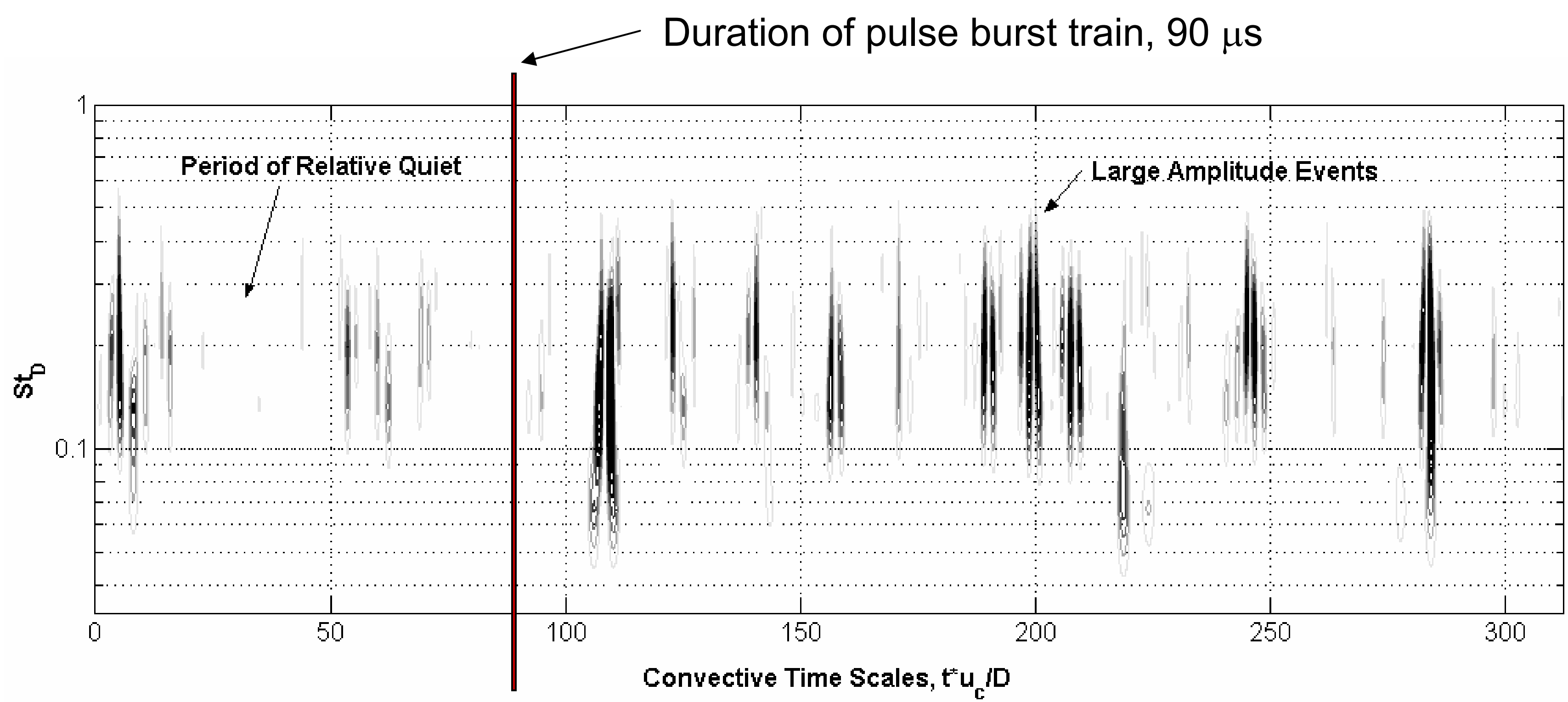




Need for large data set size

Pulse burst flow visualization system creates µs duration pulse train at a rate of 5 Hz; hence consecutive pulse trains are uncorrelated in time.

Effectively hunting for a needle in the haystack, results to come are based on 200 best of 19,750 data sets.



NG versus RQ – Using NSL to Select Images

Noise Generation

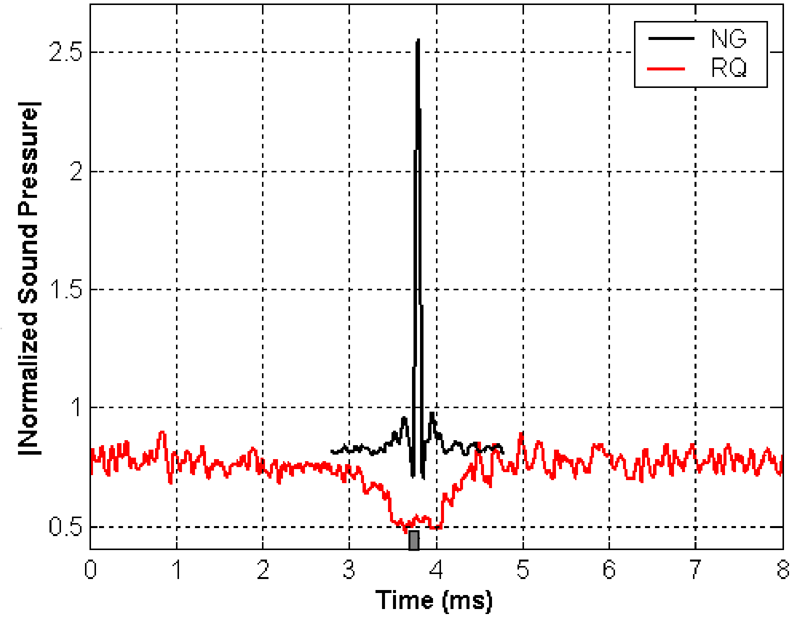
- Magnitude above 2.0σ
- Source within time and space of image
- Source above centerline & all sides recorded event

Periods of Relative Quiet

- Centered on acoustic retarded time
- Minimum width of 0.5 ms (5 convective time scales)

Data Sets

- Cross-stream: 200 ‘best’ large amplitude events (NG) and 200 longest periods (RQ).
- Streamwise: time series pseudo phase-locked onto noise generation (NG) and time series within well of relative quiet (RQ).



Sample Noise Generation Data Set

Slide 24

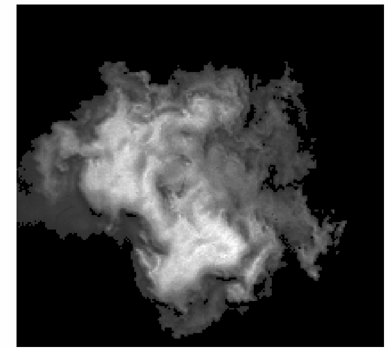
Mach 1.3 baseline jet.

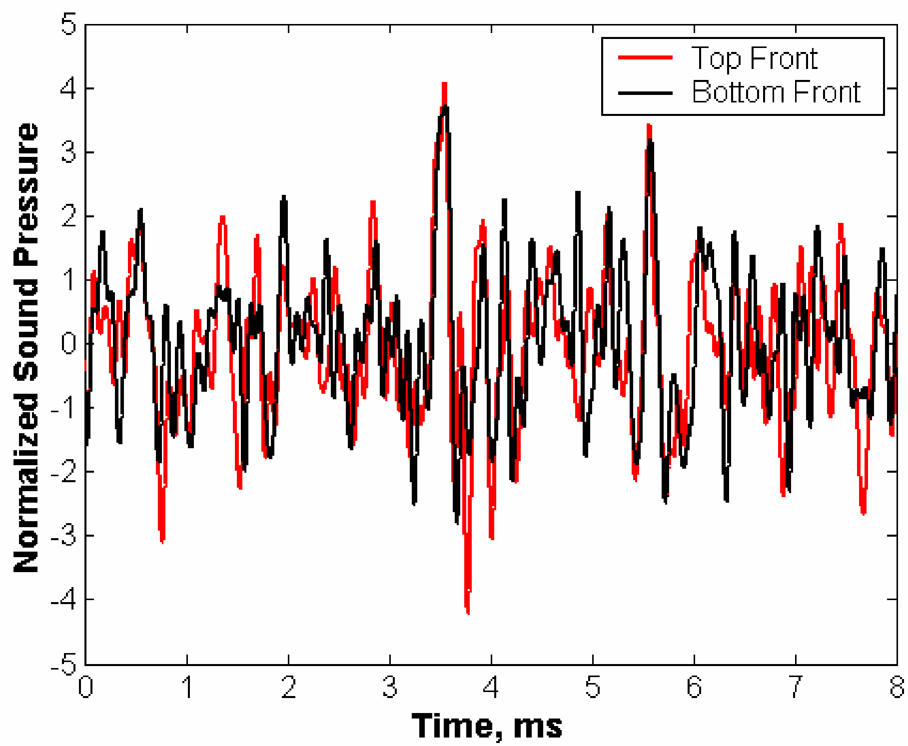
Large negative acoustic peak created 3.874 ms at location of [9.6, -0.2, 0.4] and it was created 8 μs before cross-stream frame acquired.

Flow Specifics:

- Cross-stream image acquired 6 μs after last streamwise image (6 μs separation as well).
- Much interaction across mixing layer.

9 x/D





Sample Relative Quiet Data Set

Slide 25

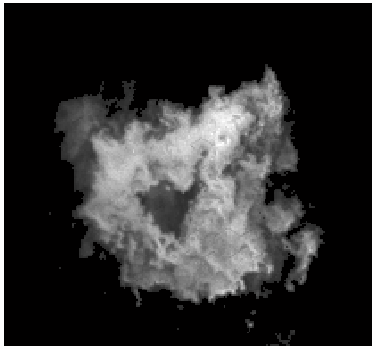
Mach 1.3 baseline jet.

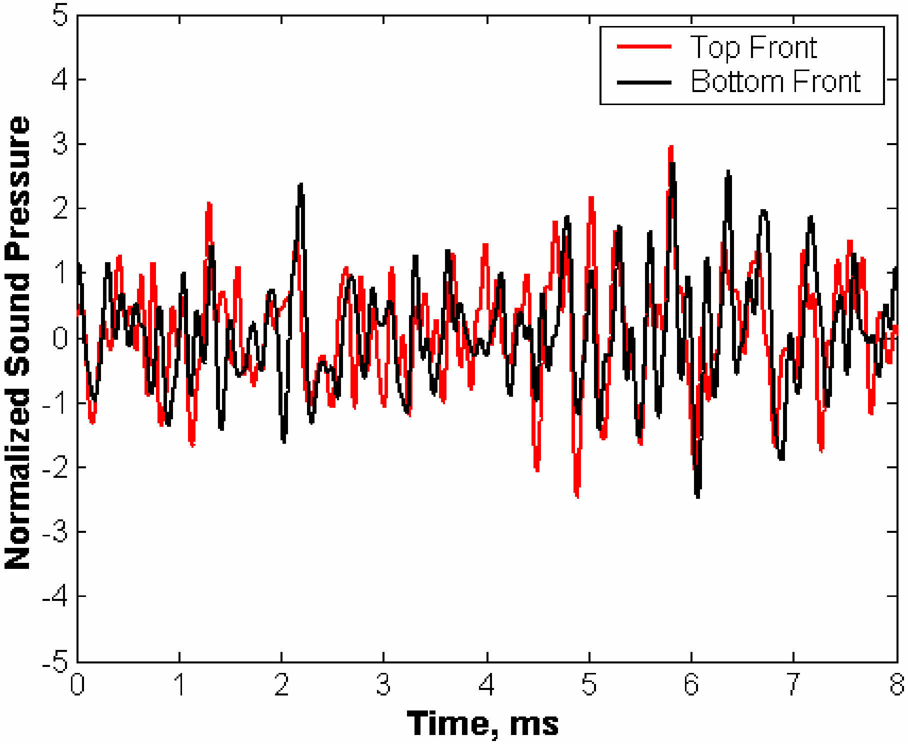
RQ Period lacks 1.5σ events:

- Centered on retarded time
- Top: 2.94 ms
- Bottom: 2.40 ms

Relative quiet duration over 24 convective time scales of the jet!

9 x/D





Cross-stream Reconstructions

Analyzed 200 images based on condition that the flow visualization image captured either noise generation (NG) or period of relative quiet (RQ).

Used 2D POD basis to spatially filter images. Location of 9 x/D.

Red / Blue regions: greater / lower than average image intensity.

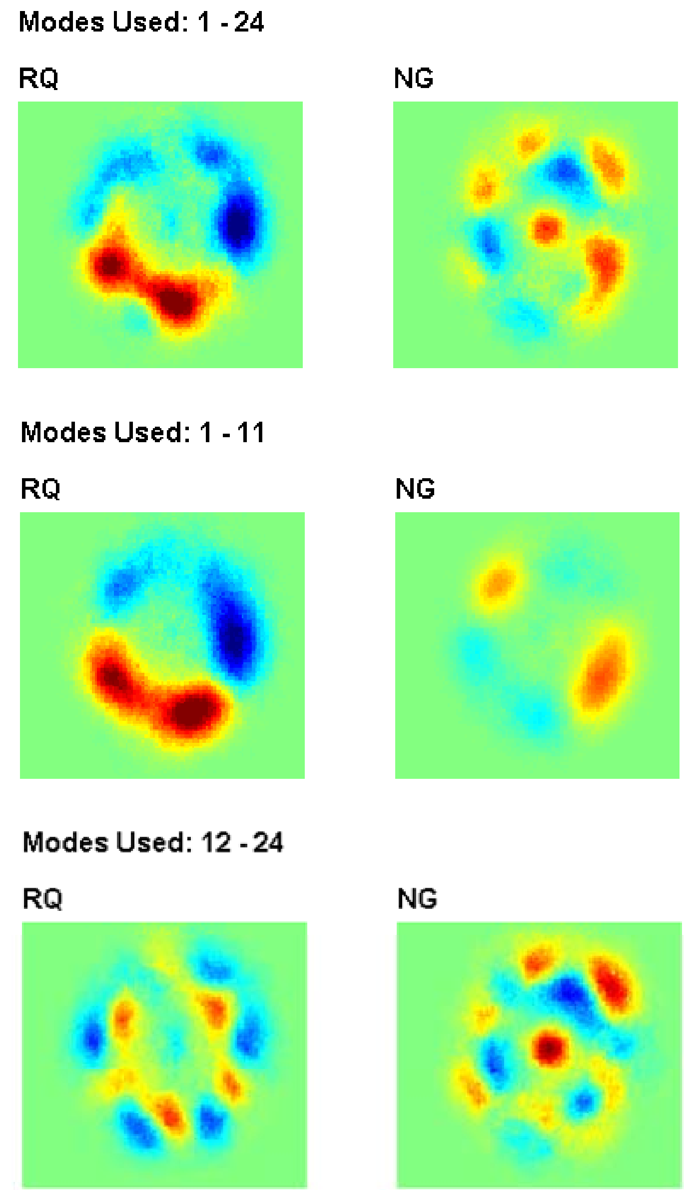
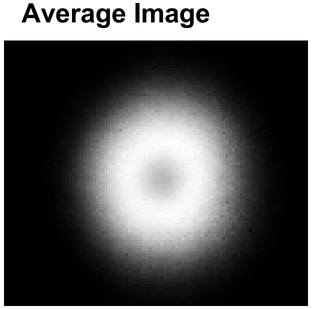


Image Set Description:

RQ: exceed 13 τ.

NG: $8 < x_s/D < 10$ & ½ τ.



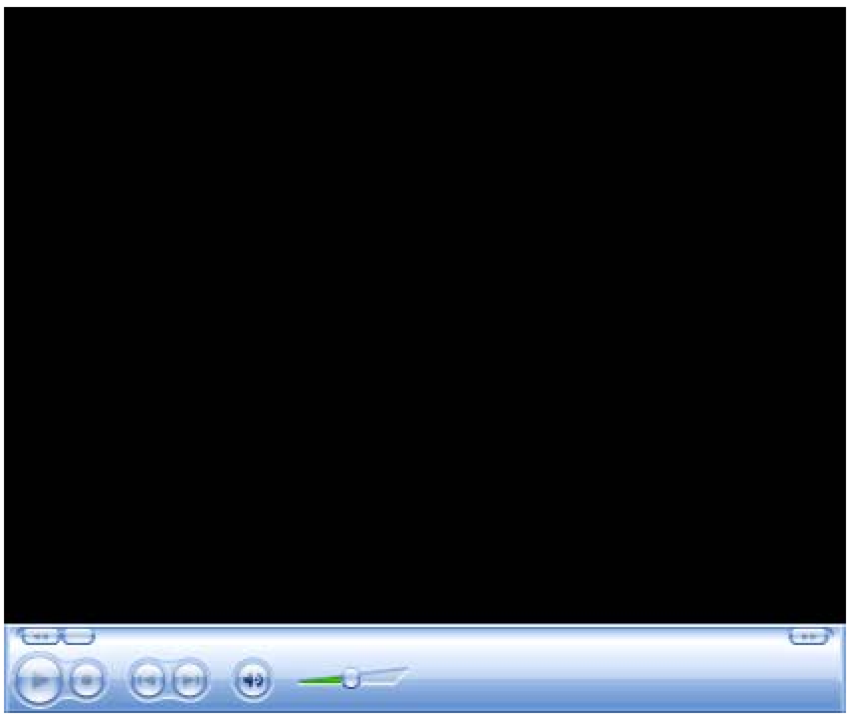
Streamwise Reconstruction

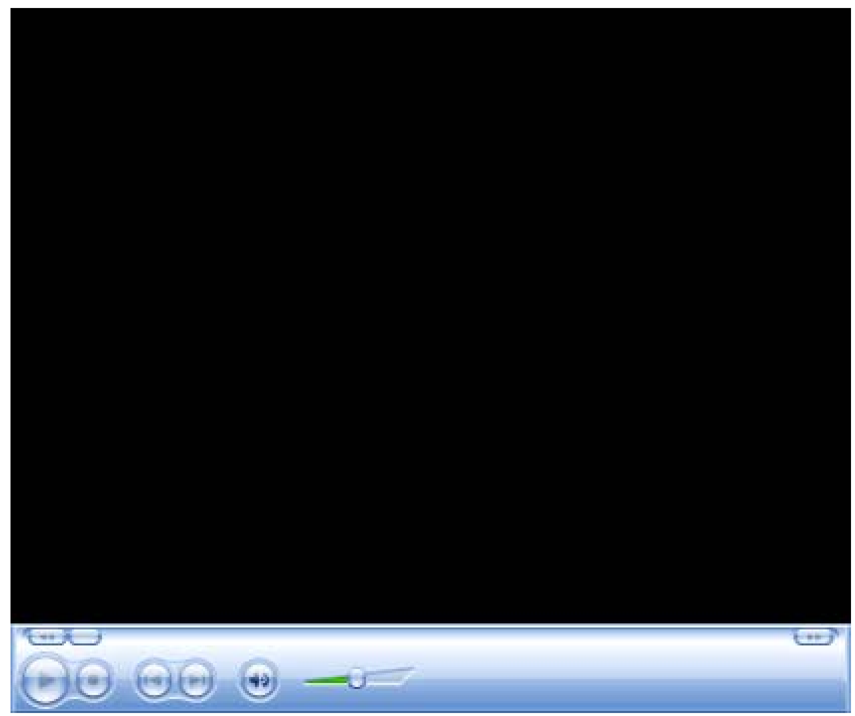
Use streamwise image basis with temporally resolved images.

Phase align noise generation images to moment of noise emission and then ensemble average.

Red / Blue regions: greater / lower than average image intensity.

Using modes 5-16 (spatially filtering larger flow features).



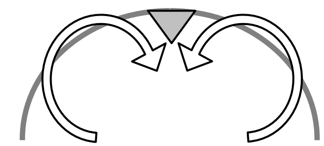


Summary

- Distinct difference between Noise Generation and periods of Relative Quiet.

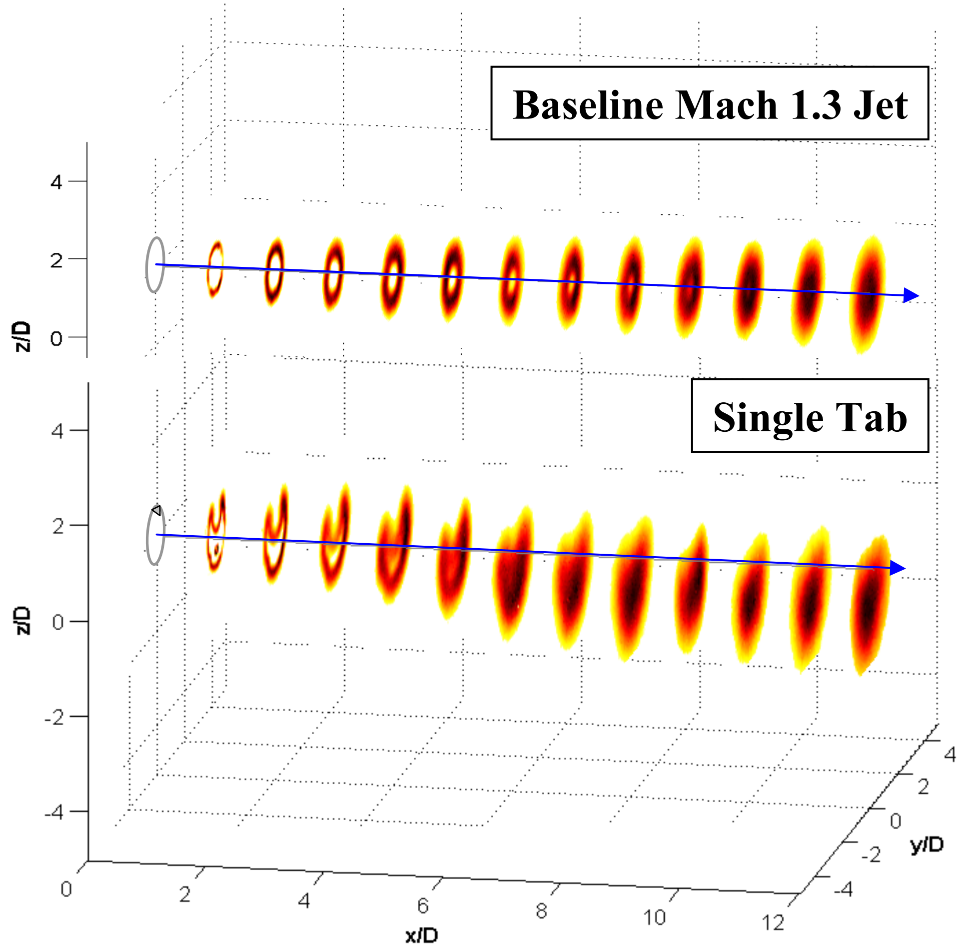
- NG: dominated by higher order modes consisting of smaller large-scale structures with larger than average intensity at the jet core. Series of structures entrain fluid to jet core prior to noise emission, and then the order is lost at moment of noise emission.
- RQ: dominated by lower order modes consisting of larger large-scale structures that interact less. There is an unmixed core between structures.

An Aside: Impact of Streamwise Vorticity



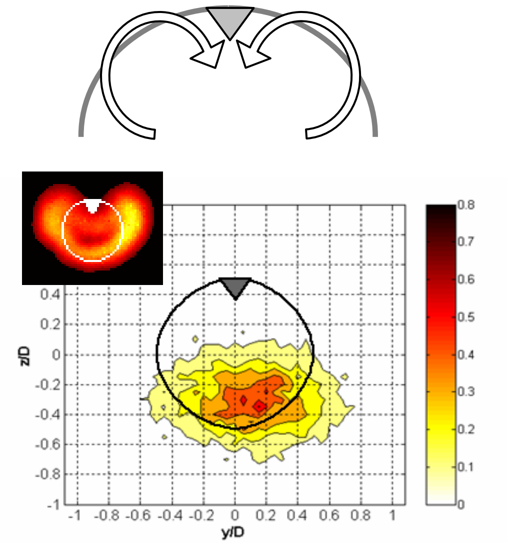
- Use chevron/tab to add streamwise vorticity to flow to enhance mixing and modify noise

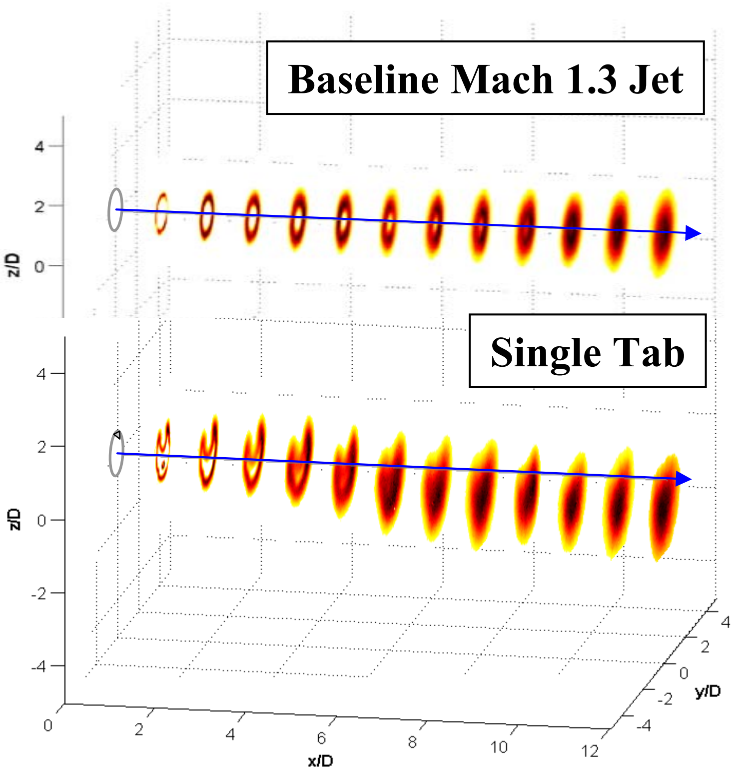
- Analyzed large delta tab

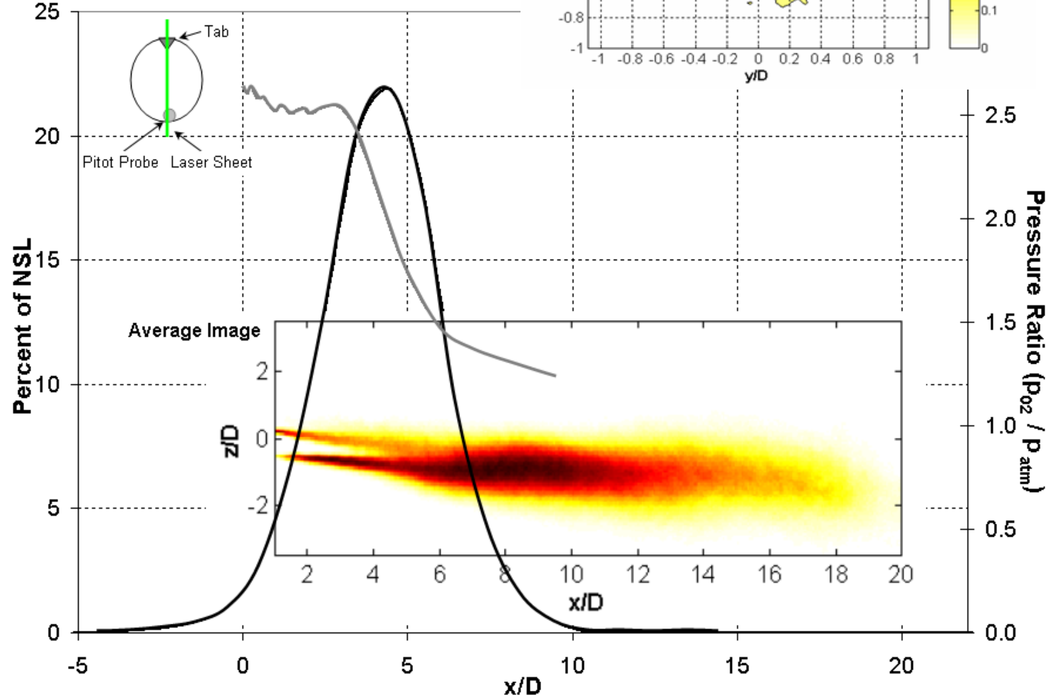


Streamwise Vorticity and Noise Generation

• Noise originates from collapsed potential core and not from the streamwise vorticity.

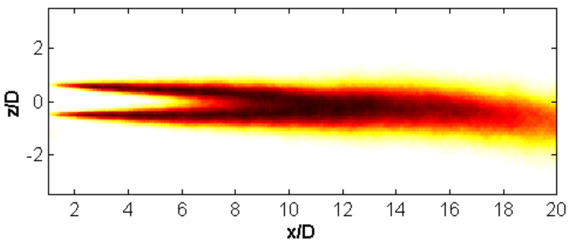


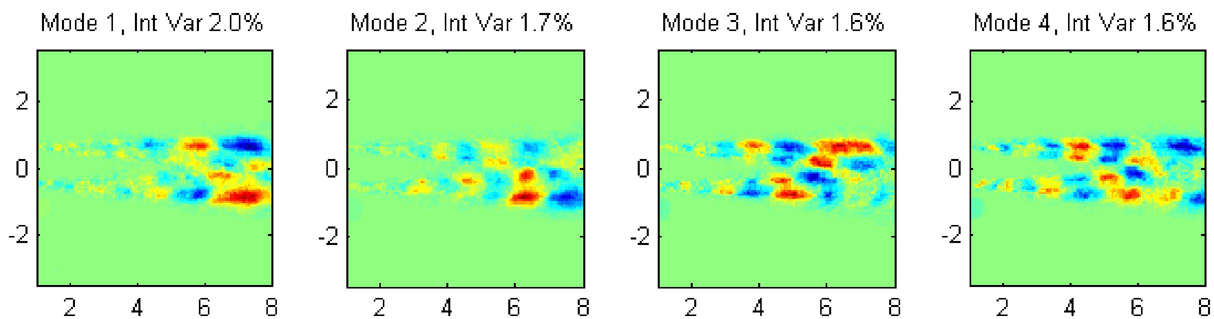




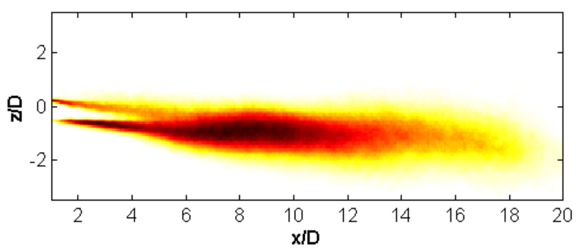
Streamwise Vorticity and POD Modes

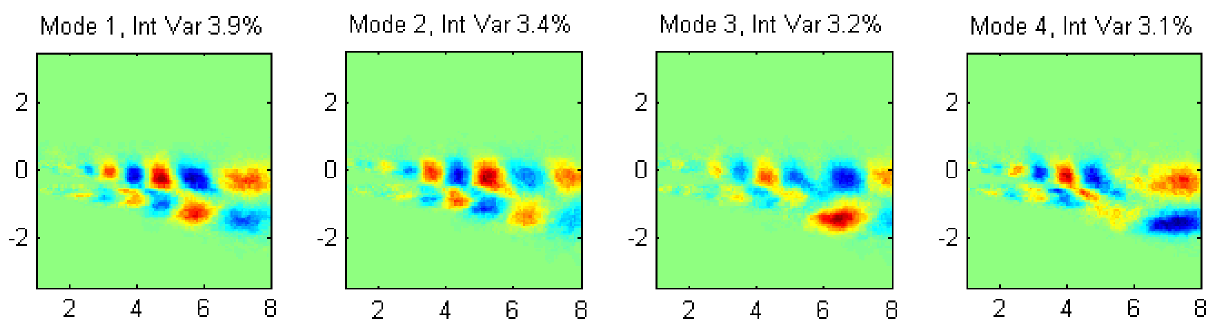
No-tab, Mach 1.3 Jet

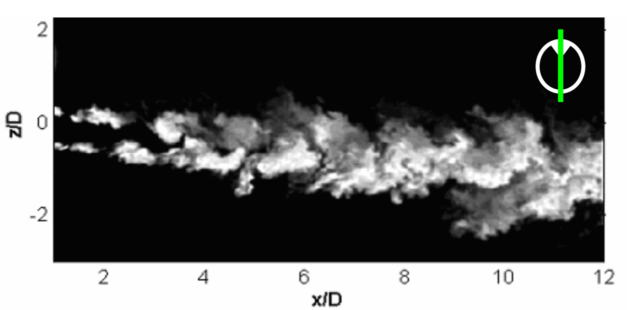




Single-tab, Mach 1.3 Jet







Streamwise vorticity leads to regulation of spanwise vorticity.

Strong spanwise vorticity dominates region of noise emission.

Contributed Knowledge

Noise generation similar in low and high Reynolds number, high speed jets. Both have destruction of a wavelike, large turbulence structures leading to noise emission.

Distinct difference between Noise Generation and periods of Relative Quiet in flow feature size and unmixed core length.

Delta tabs cause both streamwise and spanwise vorticity. Regions dominated by streamwise vorticity do not directly radiate significant noise aft.

Techniques have also been applied to low Reynolds number jet DNS of Freund [2001] – Kastner et al. AIAAJ 2006.

Acknowledgments

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References:

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Kastner, J., Samimy, M., Hileman, J. and Freund, J., "Comparison of Noise Sources in High and Low Reynolds Number High Speed Jets," accepted to **AIAA Journal**, 2006.

Hileman, J. and Samimy, M., "Mach Number Effects on Jet Noise Sources and Radiation to Shallow Angles," accepted to **AIAA Journal**, 2005.

Hileman, J., Thurow, B., Caraballo, and Samimy, M., "Large-scale Structure Evolution and Sound Emission in High-Speed Jets: Real-time Visualization with Simultaneous Acoustic Measurements," **Journal of Fluid Mechanics**, Vol. 544, pp. 277-307, 2005.

Hileman, J., "Large-Scale Structures and Noise Generation in High-Speed Jets," Ph.D. Dissertation, The Ohio State University, Department of Mechanical Engineering, 2004.

Hileman, J., Thurow, B., and Samimy, M., "Development and Evaluation of a 3-D Microphone Array to Locate Individual Acoustic Sources in a High Speed Jet," **Journal of Sound and Vibration**, Vol. 276, pp. 649-669, September 22, 2004.

Hileman, J., and Samimy, M., "Effects of Vortex Generating Tabs on Noise Sources in an Ideally Expanded Mach 1.3 Jet," **International Journal of Aeroacoustics**, Vol. 2, No. 1, pp. 35-63, 2003.

Hileman, J., Thurow, B., and Samimy, M., "Exploring Noise Sources Using Simultaneous Acoustic Measurements and Real-Time Flow Visualizations in Jets," **AIAA Journal**, Vol. 40, No. 12, pp. 2382-2392, December 2002.

Hileman, J. and Samimy, M., "On Turbulence Structures and the Acoustic Far-Field of a Mach 1.3 Jet," **AIAA Journal**, Vol. 39, No. 9, pp. 1716-1727, September 2001.