Effect of Mixing Enhancement Devices on Turbulence in Separate Flow Nozzles

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Work presented here was accomplished through the efforts of a team of skilled technicians, engineers, researchers, and managers at NASA Glenn Research Center and its industry partners, General Electric Aircraft Engines and Pratt & Whitney. Dr. Mark Wernet of NASA Glenn was key to PIV work presented here.

AST Program

- NASA Pillar Goals
  - Reduce engine noise by 10dB in 10 years
  - Reduce engine noise by 20dB in 20 years
- Programs
  - Advanced Subsonic Technology (AST) 1994—2000
    - Airframe noise
    - Fan noise
    - Jet noise—Goal: 3EPNdB
      - Low—Mid Bypass Ratio, internally mixed nozzles
      - Mid—High Bypass Ratio, separate flow nozzles
        - » SFNT97 Test program
  - Base R&T (BASE) 2000—
    - Jet Noise Reduction
      - SFNT2K Test program

Test Programs SFNT97 and SFNT2K

- Collaborative test with GE, Pratt & Whitney as primes, Allison, Boeing as subcontractors
- Organization:
  - Industry and NASA brought in ideas
  - Industry designed and built hardware
  - NASA did testing at Glenn Research Center and ASE/FluiDyne Labs
  - Industry and NASA did analysis.
- Many noise reduction concepts screened, first analytically, then in acoustic tests.
- Best (and most interesting) measured using IR, Schlieren, Pt/Tt survey rakes, and phased arrays.
- NASA returned in 2000 (SFNT2K) with few additional concepts and PIV to better understand *why* reductions found or not found.

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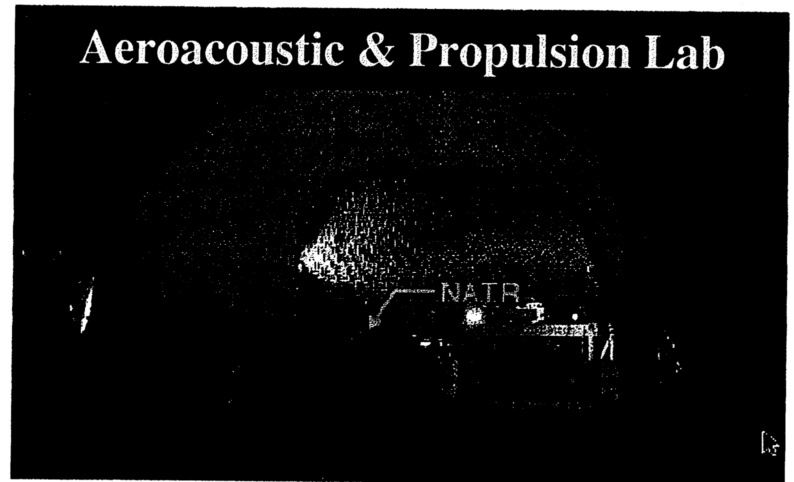
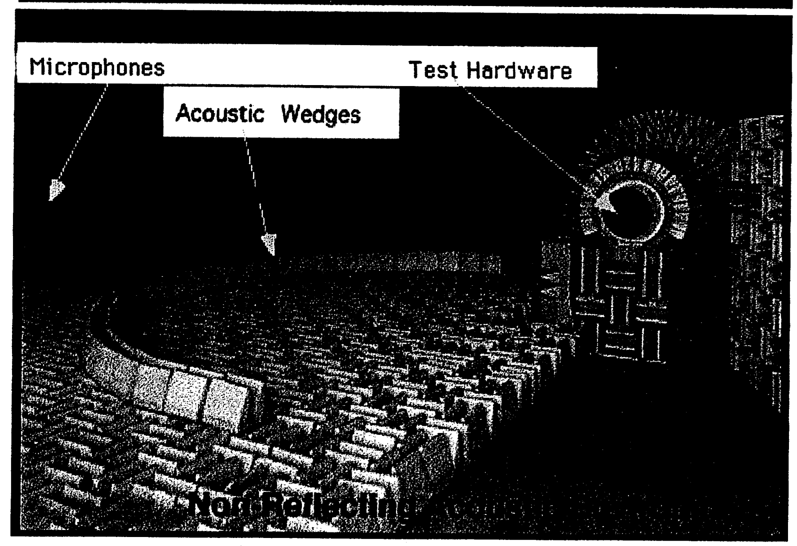
Facility

- 65ft. radius geodesic dome
- Anechoic environment
- Up to 0.3 Mach freestream
- Dual stream engine flow simulation
  - Core: 5lbm/sec@1500°R
  - Fan: 25lbm/sec@600°R
- Acoustic measurements
  - 26 1/4" B&K microphones at 50' R
  - 63 element 2D phased array
- Flow visualization
  - Infrared, Schlieren,
- Flow measurements
  - Pressure-Temperature survey rakes
  - Pressure-Sensitive Paint (PSP)
  - Particle Image Velocimetry (PIV)





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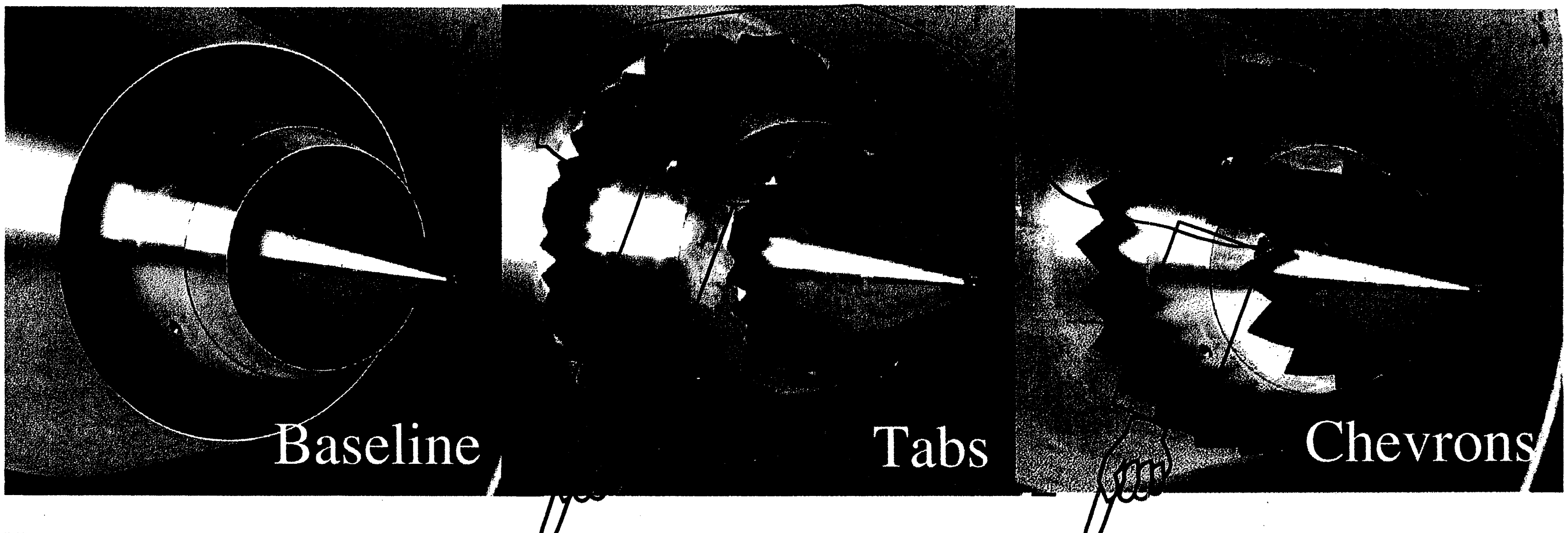
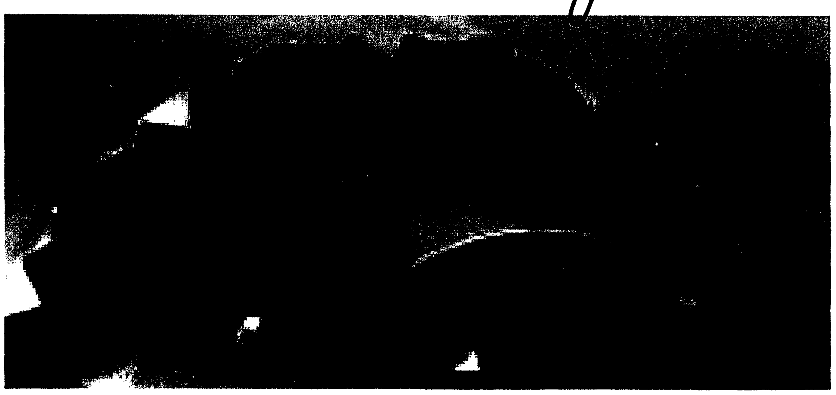
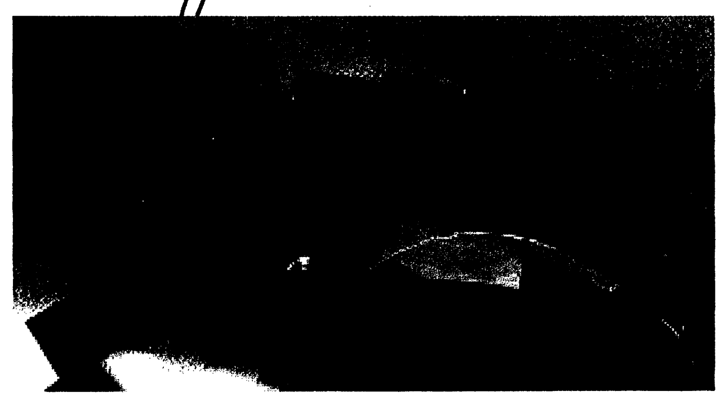
Mixing Enhancement Nozzles

A few representatives of the 43 configurations studied in SFNT97.







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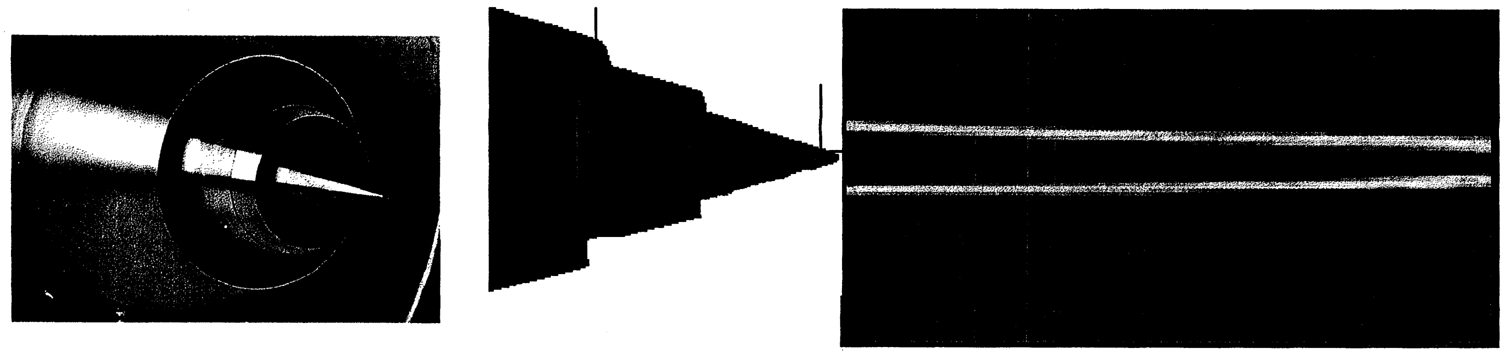
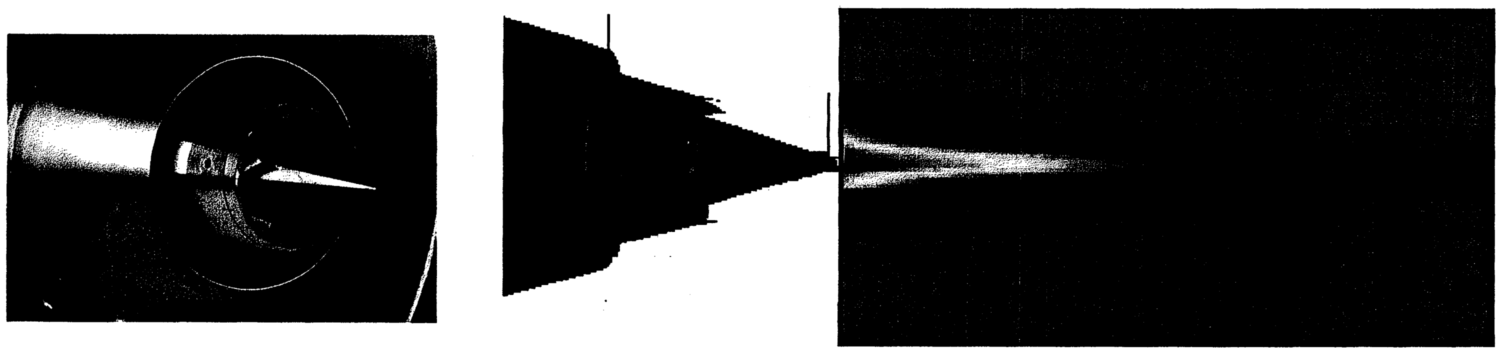
IR reductions

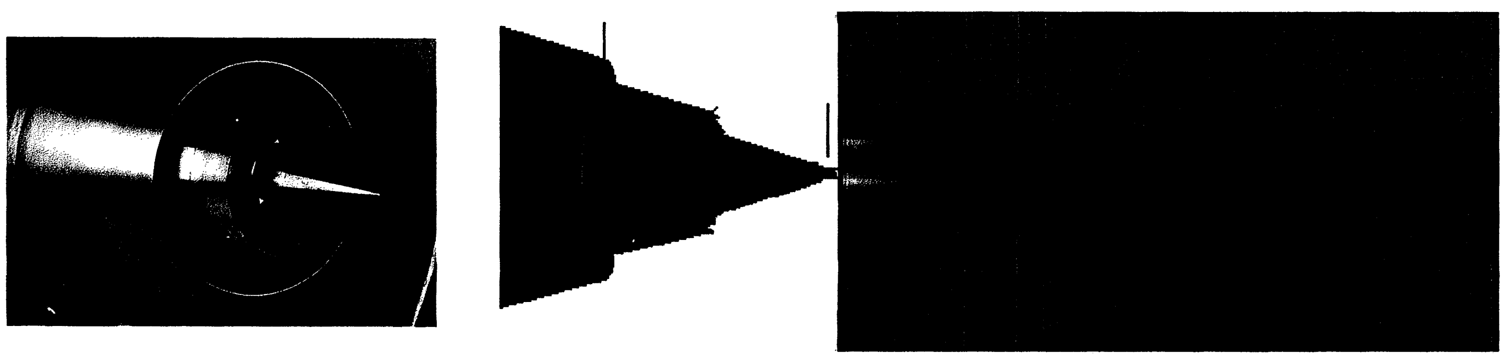
3BB



3AB

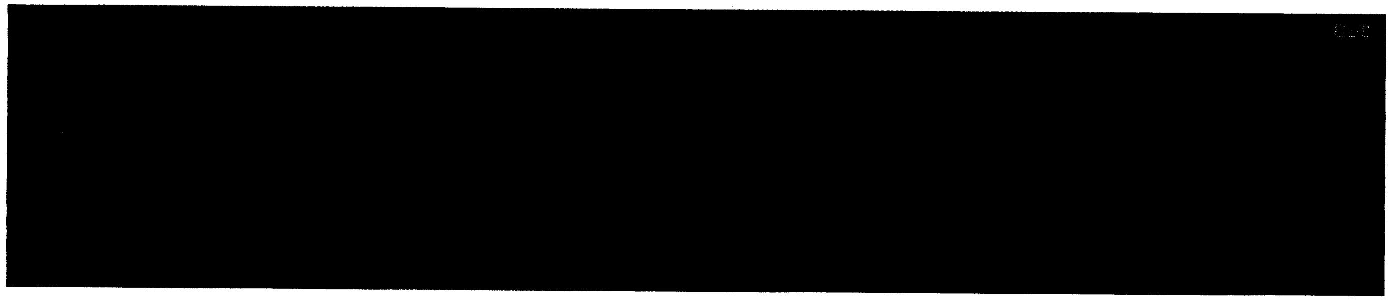


3TB



Schlieren of Chevrons

3BB



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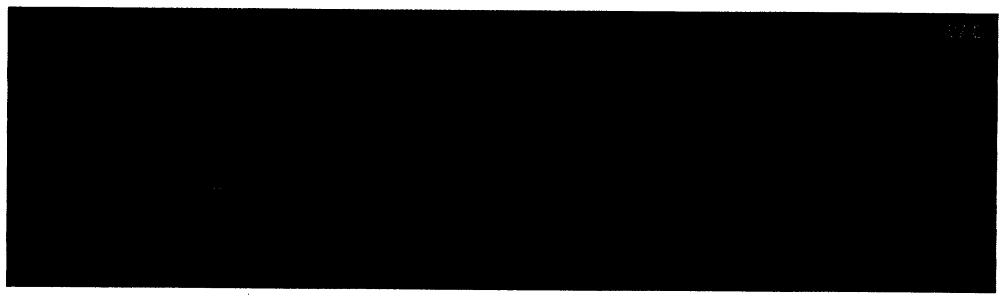

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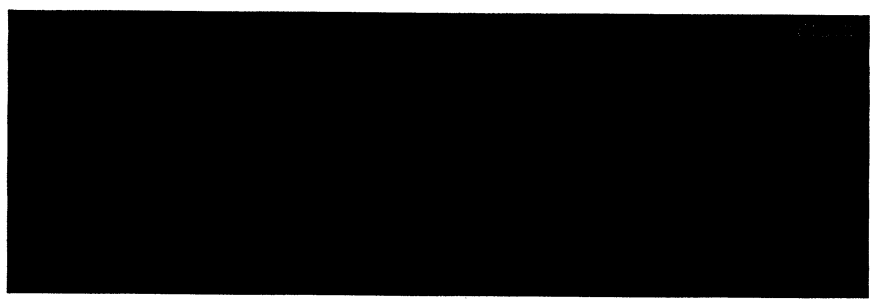
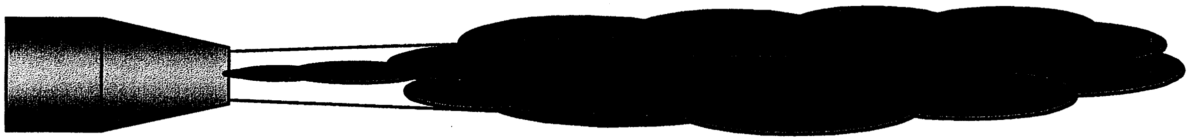


- Increased jet spread
- Axial streaks ('vortices')

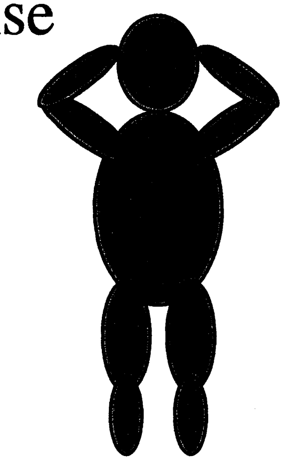
Aeroacoustics of Enhanced Mixing—Paradigm



Jet Exit Velocity U

→ **Acoustic Generation**

→ Noise



Physics known:
Scaling laws
(Lighthill's U^8 'law')

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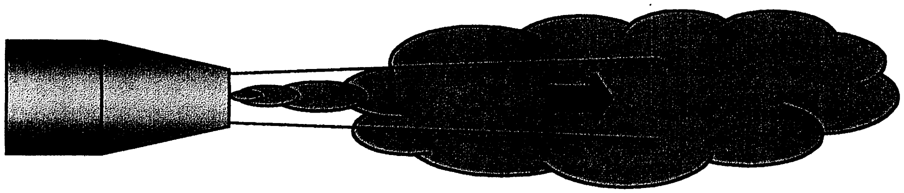
Aeroacoustics of Enhanced Mixing—Reduction Paradigm

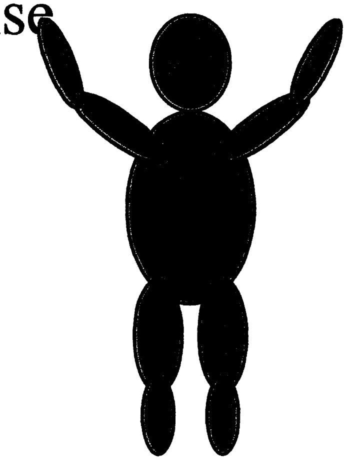


Lowering Effective Jet Velocity...

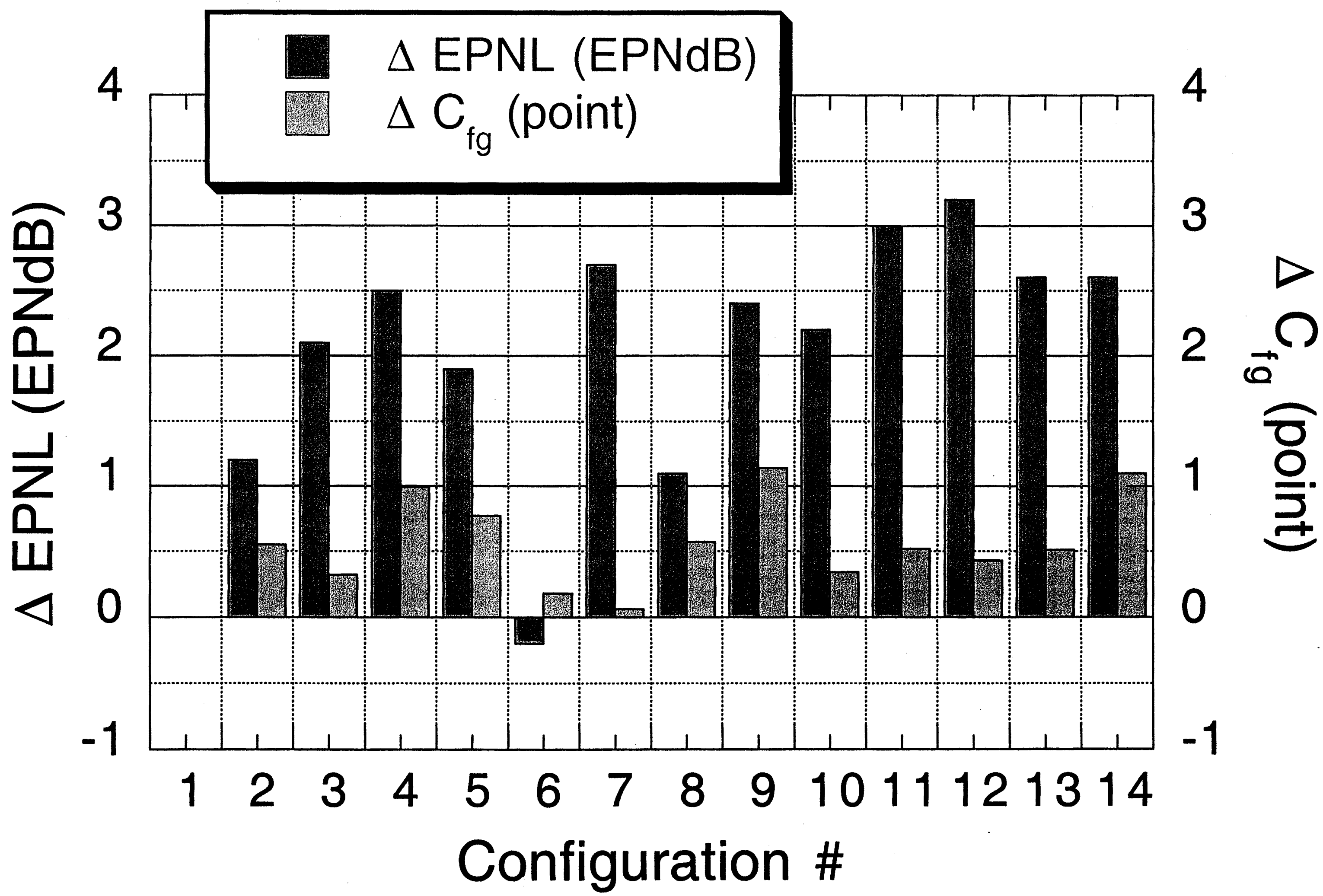
Acoustic Generation

Physics known:
Scaling laws
(Lighthill's U^8 'law')

… Lowers Noise

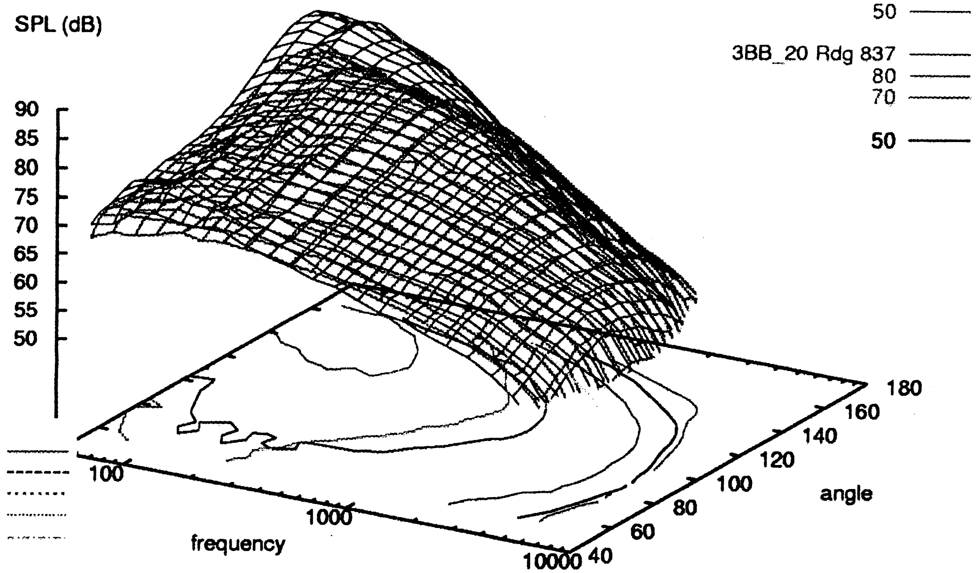


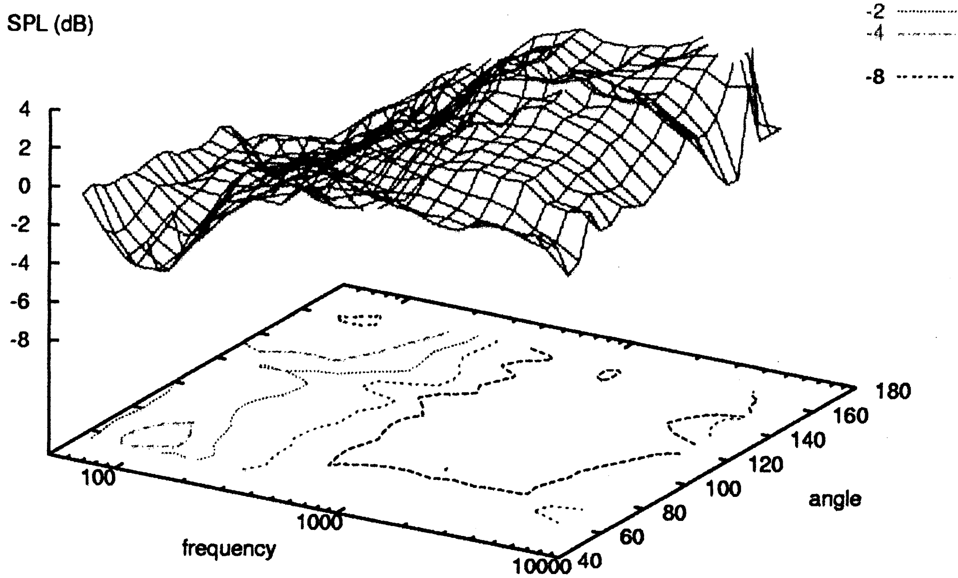
Acoustic and Thrust Performance of Enhanced Mixing Nozzles



Aeroacoustics of Enhanced Mixing—Data

- Enhanced mixing by chevrons
  - Decreases low frequencies near jet axis.
  - Increases high frequencies.





Net reduction is an optimization problem.

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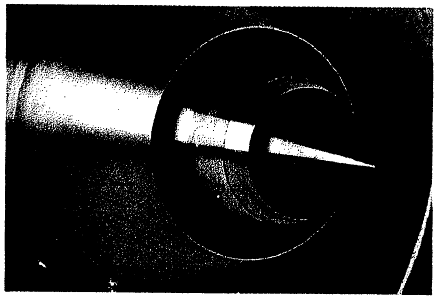
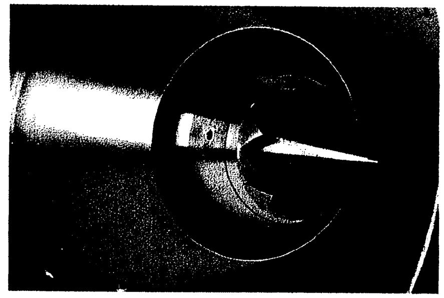
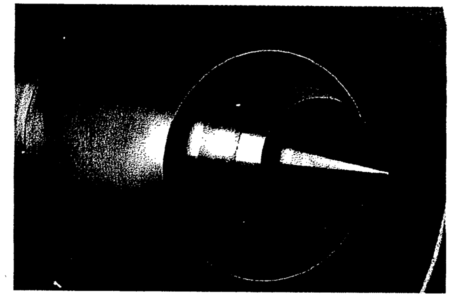
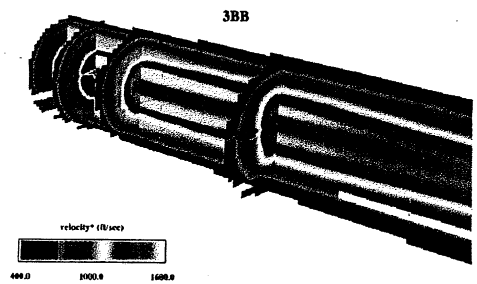
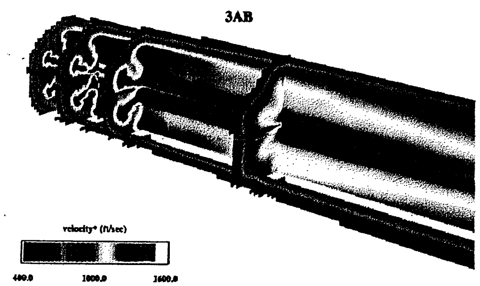
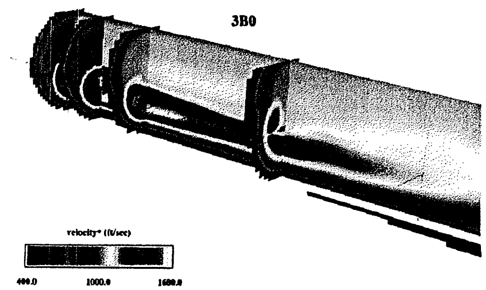
Enhanced Mixing == Less Noise?

Baseline	Alternating Chevrons	Offset Bypass



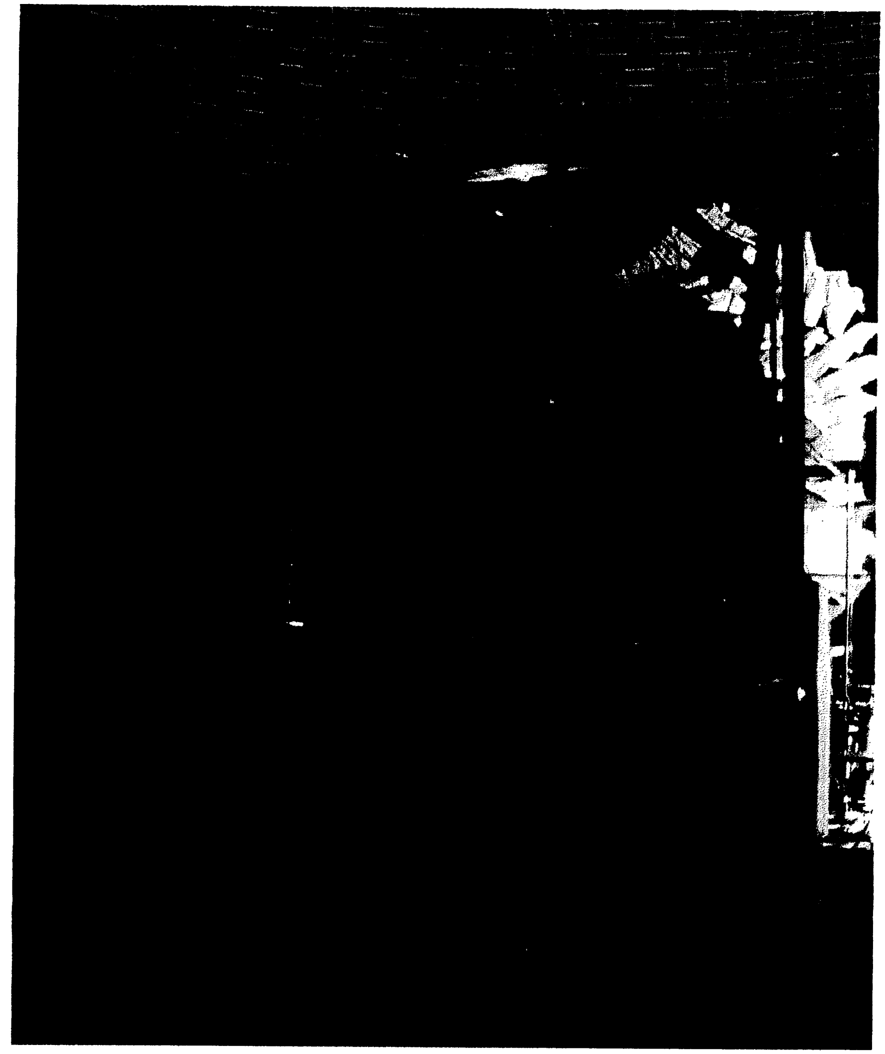




Baseline Nozzle technology being manufactured on quietest jet aircraft in late 1990's.	Quietest by 2.5EPNdB! Good mixing reduced noise sources without producing additional sources!	Noisiest by 3EPNdB! Good mixing, but method of mixing introduced new noise source!

PIV Instrumentation

- Large Traversing frame setup to axially traverse
  - Laser and optics
    - 400mJ/pulse PIVdual-head laser
    - 0.2mm thick sheet
  - Two cameras
    - Dual frame PIV cameras
    - 2.5μs between pulses
  - Visual Background
- Seed
  - Core and fan flows
    - 0.7μm Al_2O_3
    - fluidized bed seeders injected in rig supply pipes
  - Freestream
    - 0.2μm oil droplets
    - commercial fogger injected at inlet to freejet tunnel.



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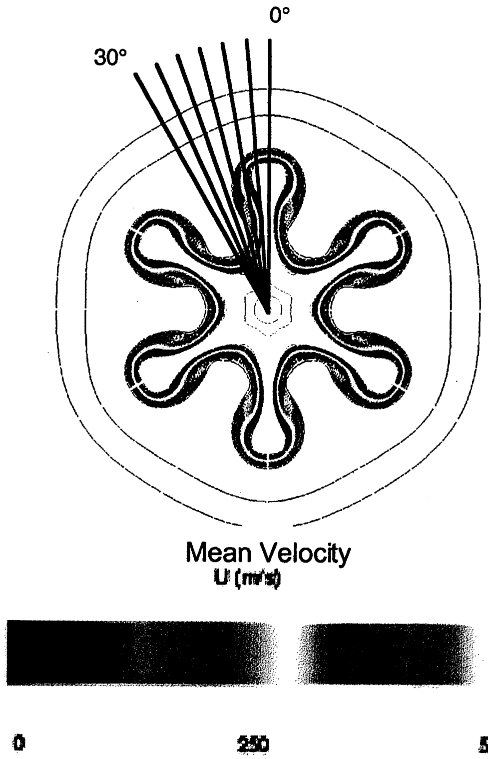
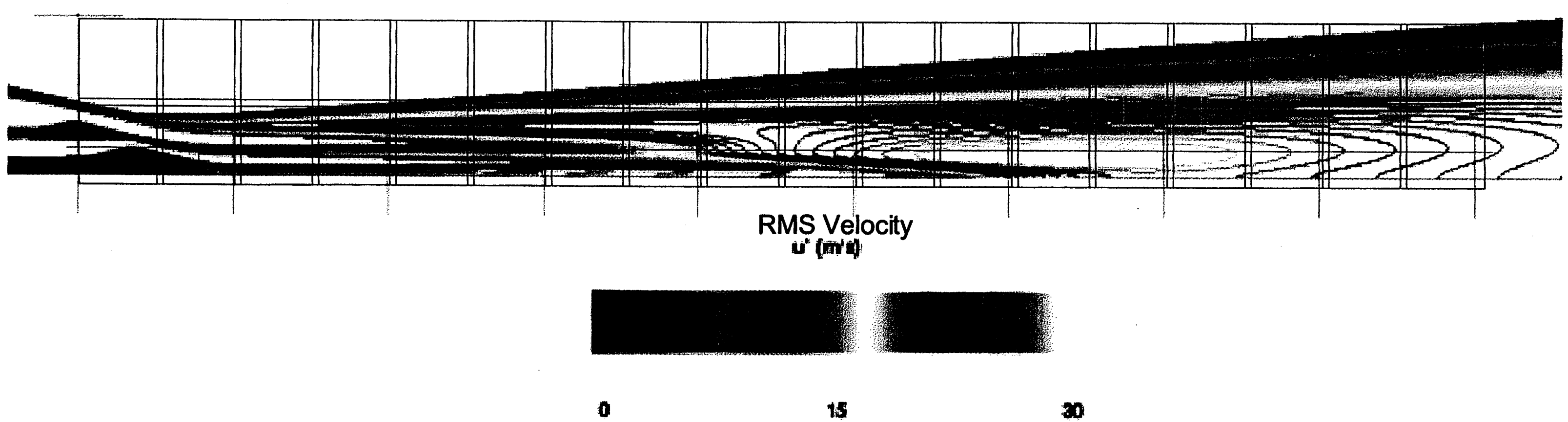
PIV Measurement Layout



- 3BB:
  - one radial (x,r) plane
  - 10 × 1 fan diameters
- 3A12B/ 3T24B:
  - 7 radial planes (5° increment)
  - 10 x 1 fan diameters for 0°,15°, 30°
  - 5 x 1 fan diameters for 5°, 10°, 20°, 25°
- 400 frames used in statistics at each location.

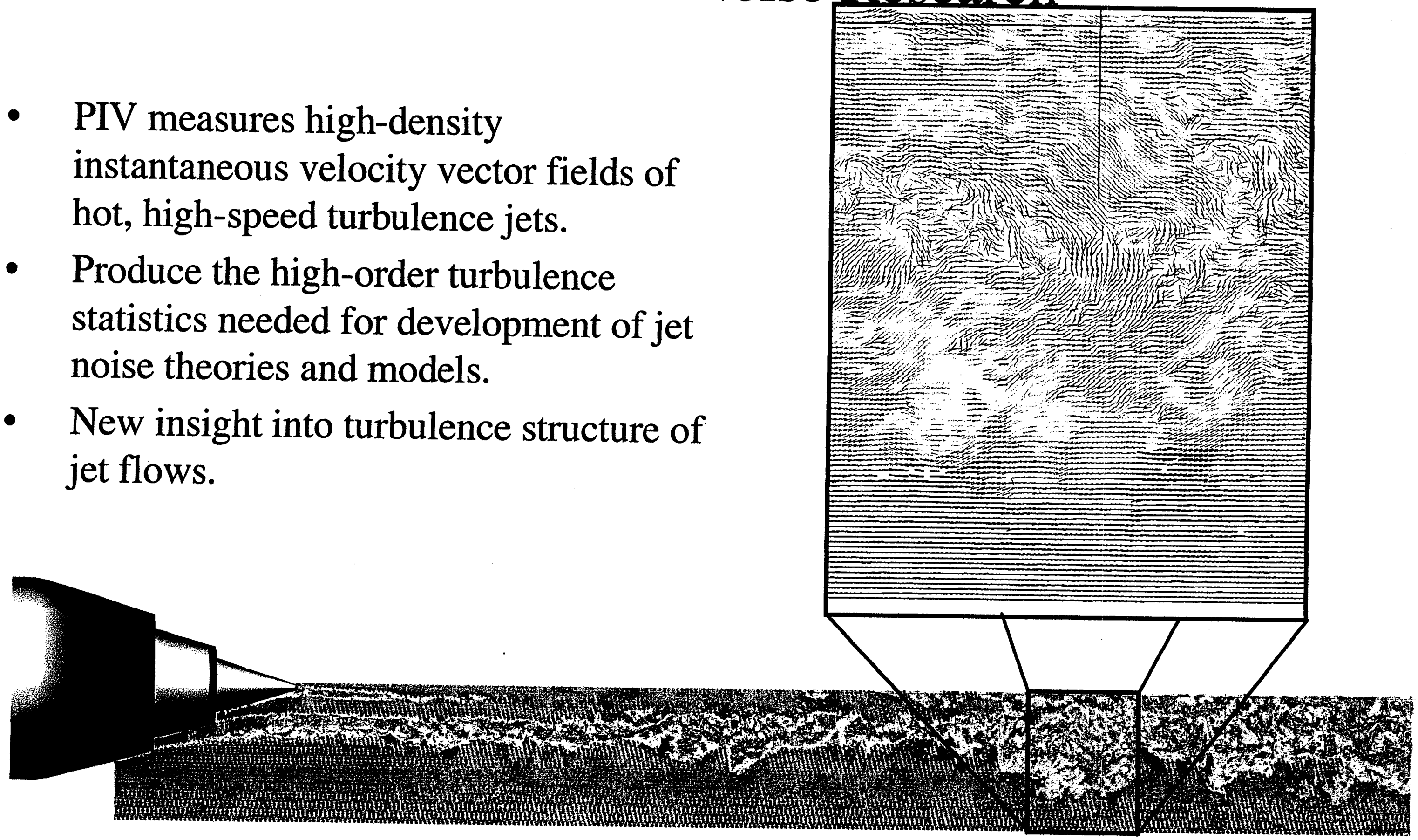


Flow conditions

- All data were taken at the same exhaust conditions:
  - NPRcore = 1.68, Ttcore = 1500°R
  - NPRfan = 1.83, Ttfan = 600°R
  - Freejet Mach = 0.28
- This is an average take off flow condition.

PIV in Jet Noise Research

- PIV measures high-density instantaneous velocity vector fields of hot, high-speed turbulence jets.
- Produce the high-order turbulence statistics needed for development of jet noise theories and models.
- New insight into turbulence structure of jet flows.



Velocity vectors in axisymmetric separate flow nozzle at takeoff.
Structure convection speed subtracted from vectors to enhance structures.
1080 by 120 vectors, 2.25mm/vector density.

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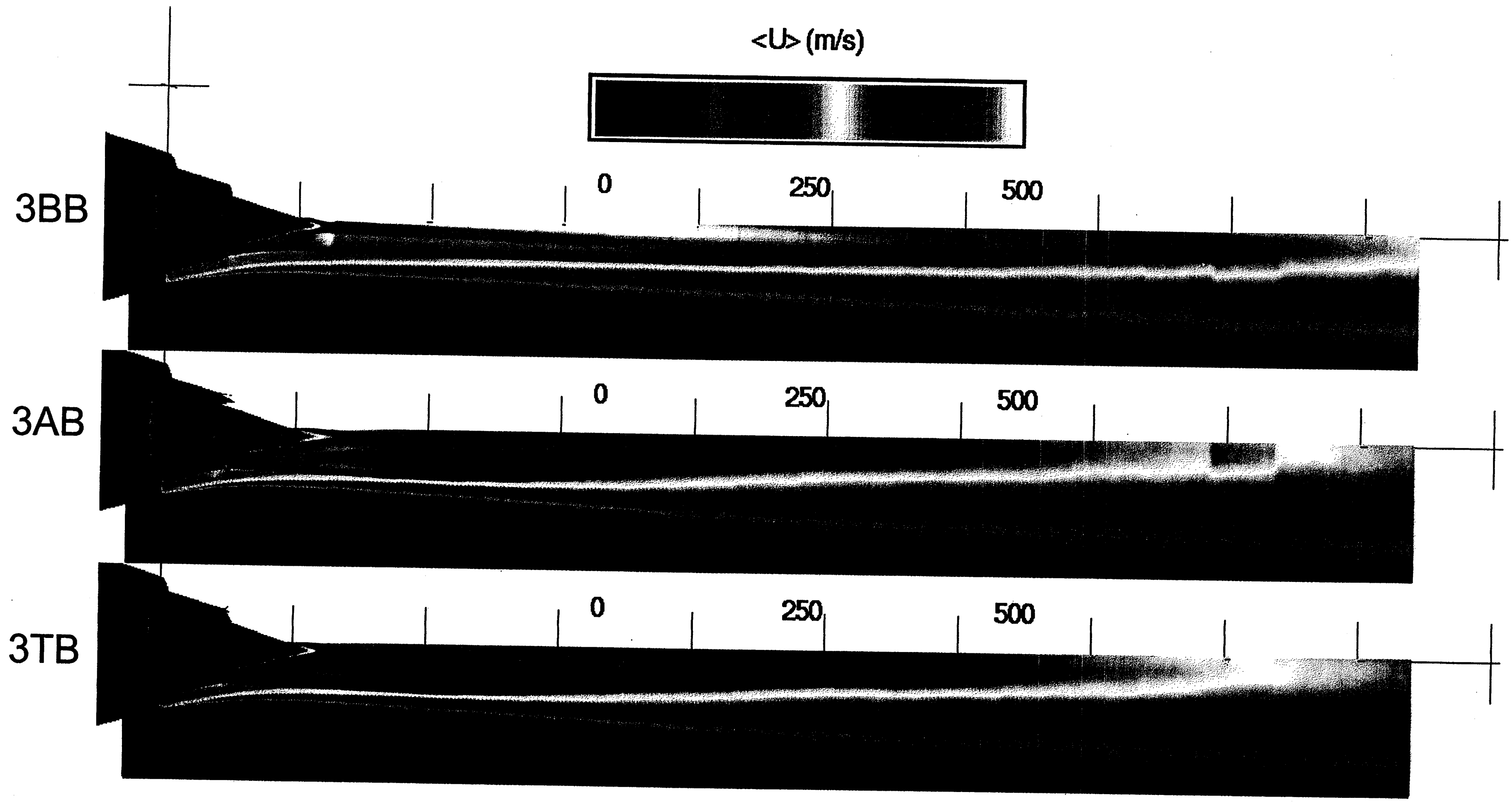
Mean Velocities



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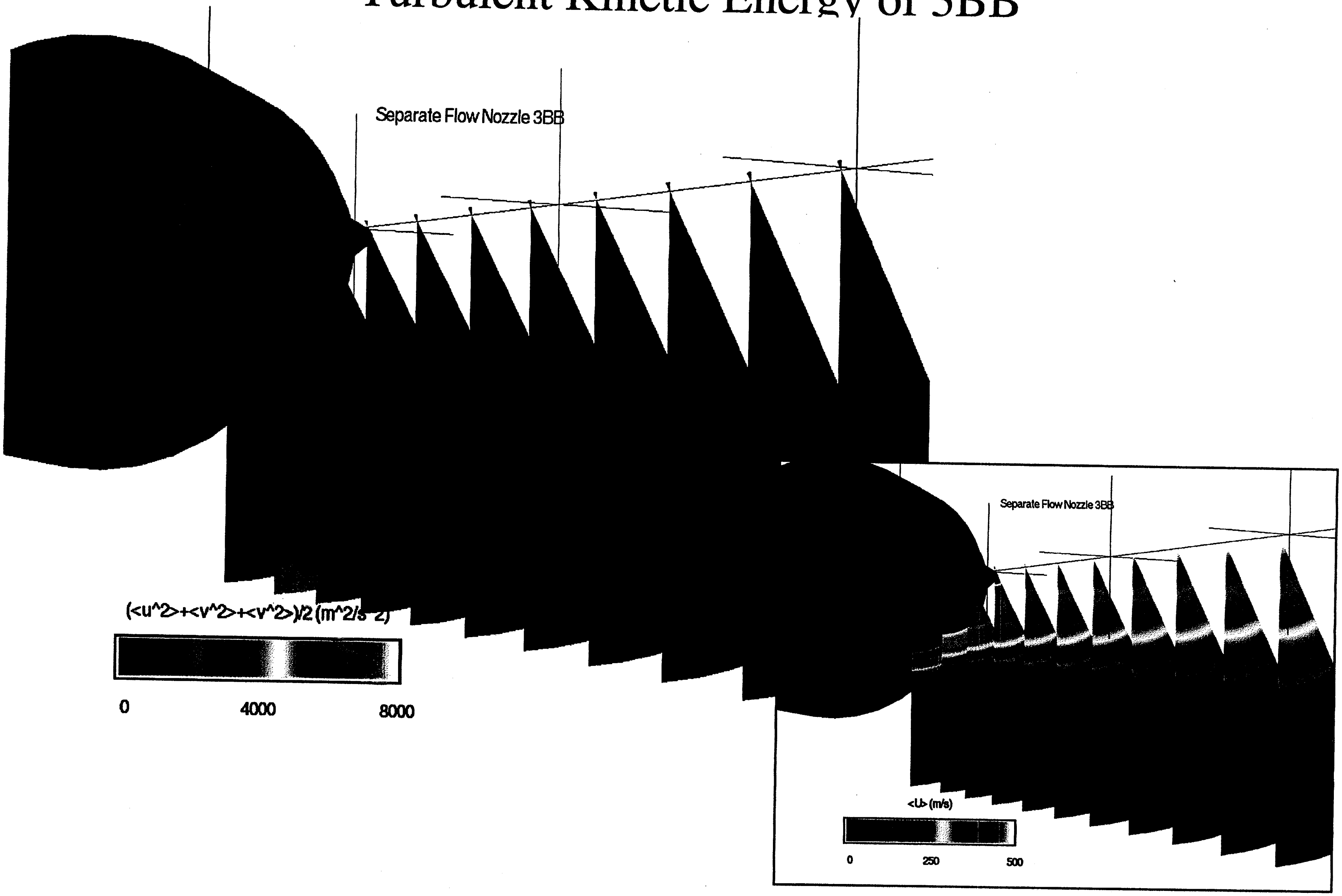
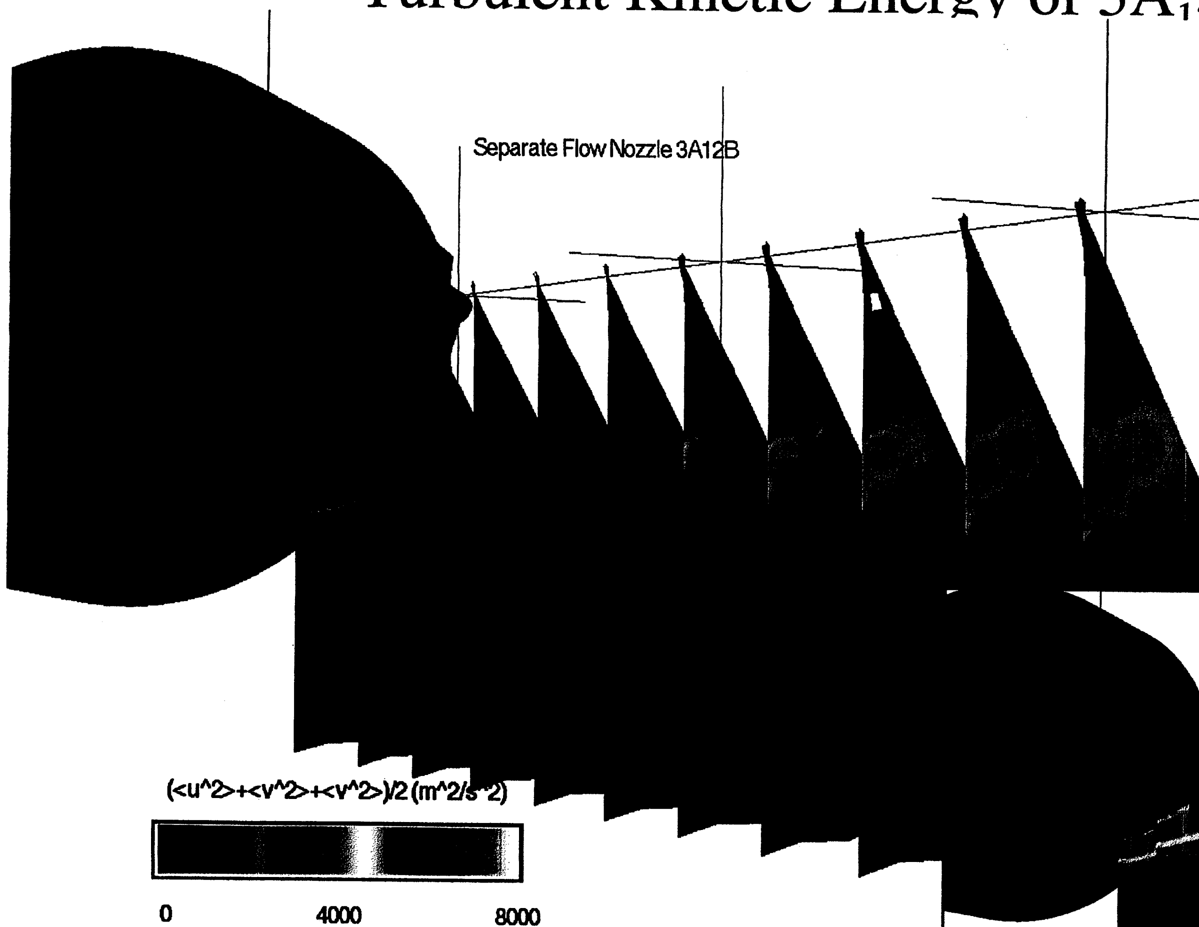
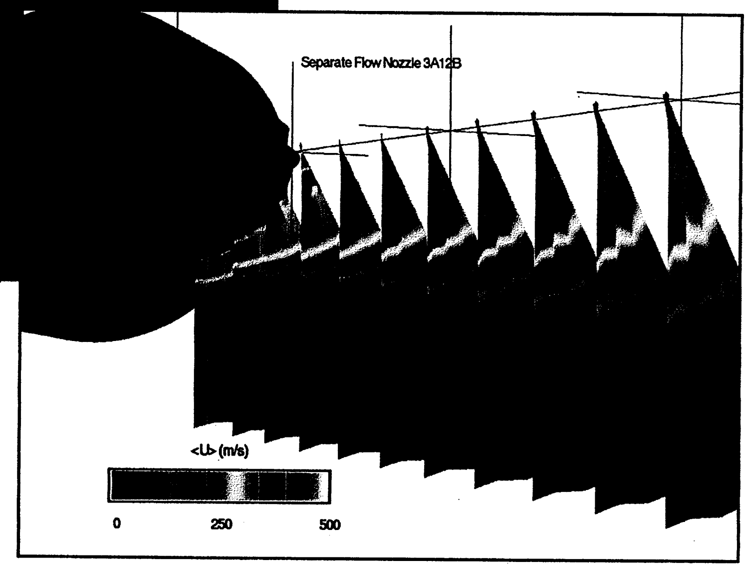
Turbulent Kinetic Energy of 3BB

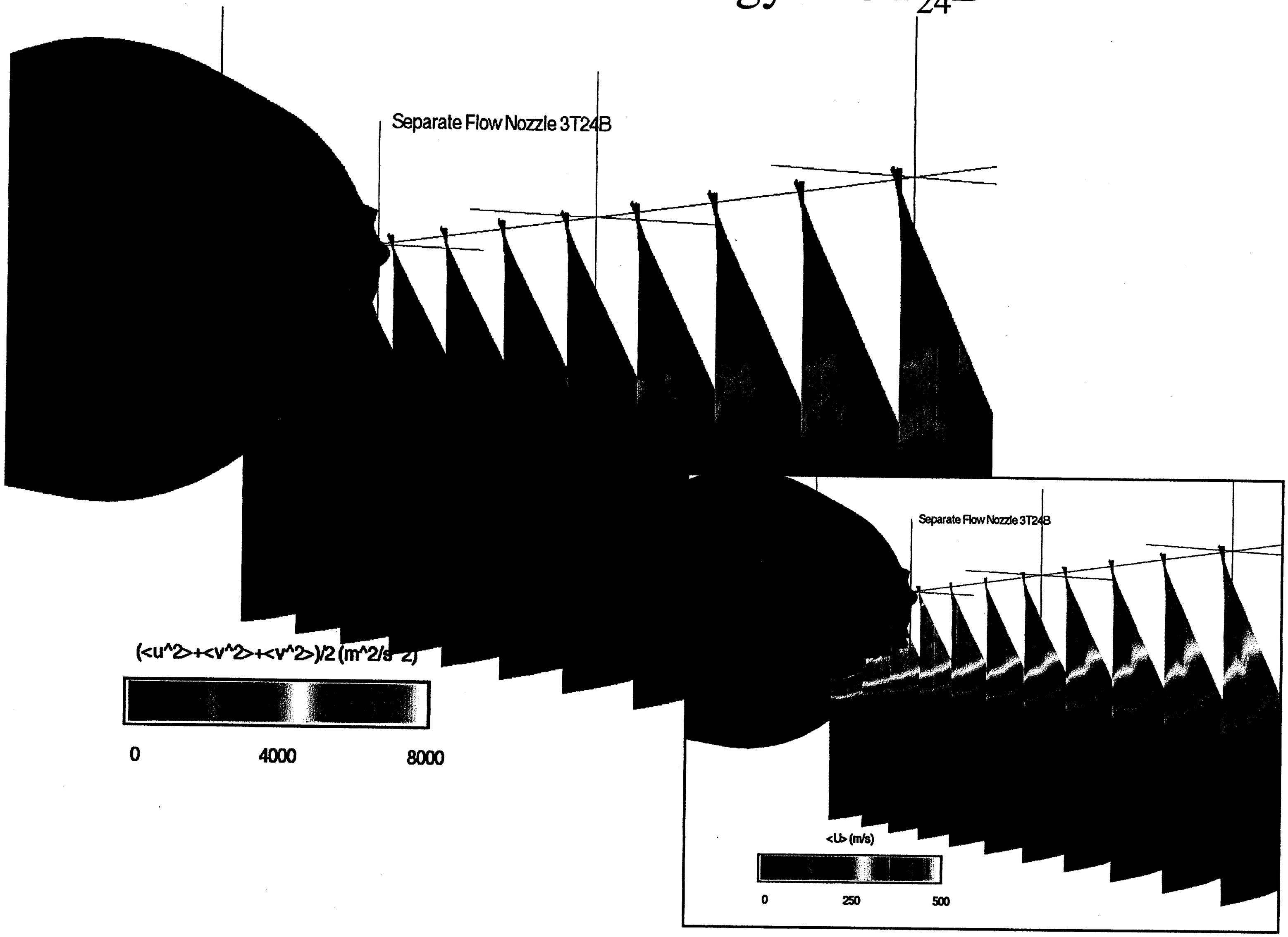


Turbulent Kinetic Energy of $3A_{12}B$





Turbulent Kinetic Energy of $3T_{24}B$



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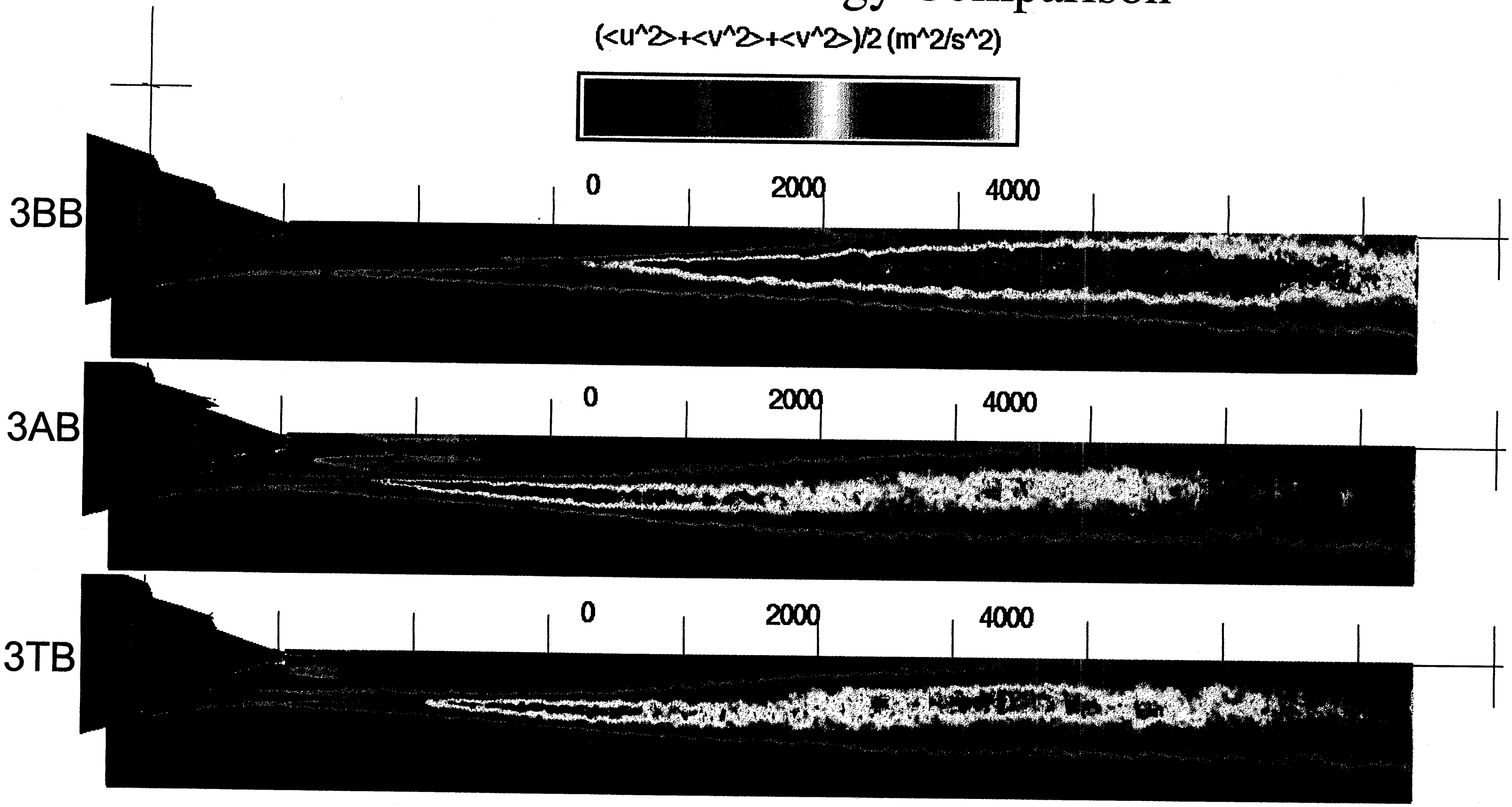
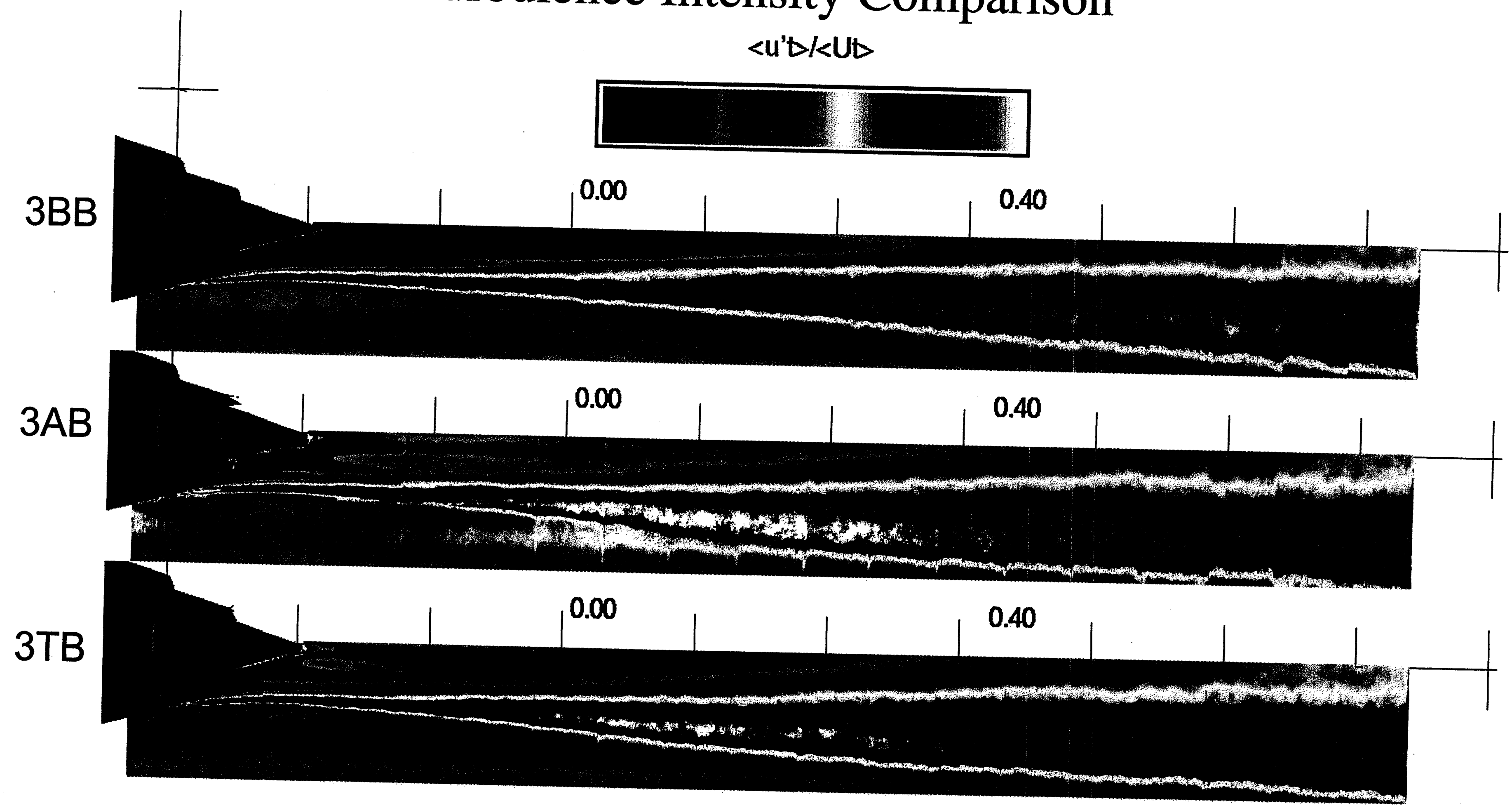
Turbulent Kinetic Energy Comparison



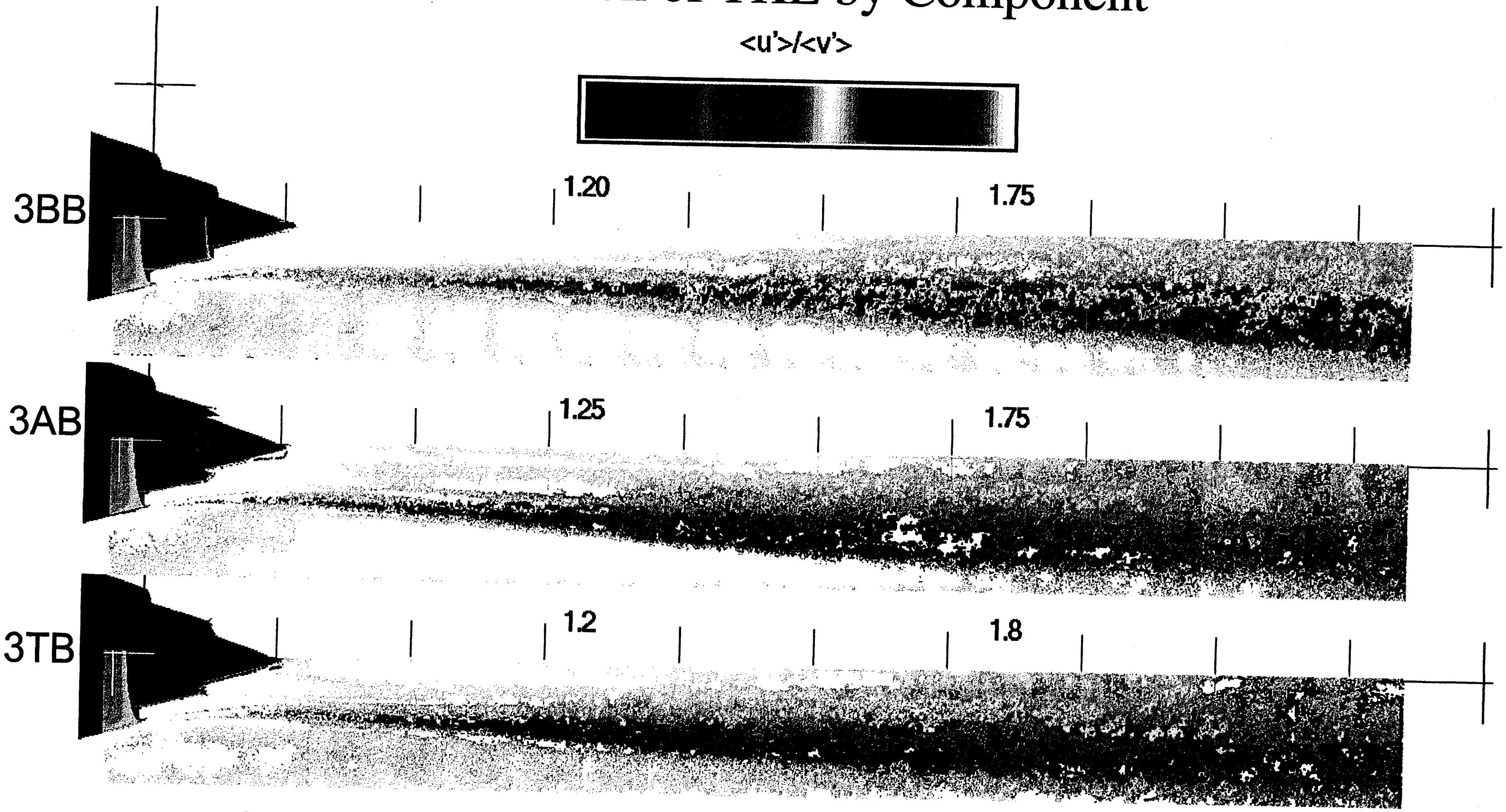
Large reductions, especially in fully mixed region

Turbulence Intensity Comparison



No reduction in intensity; if anything an increase upstream

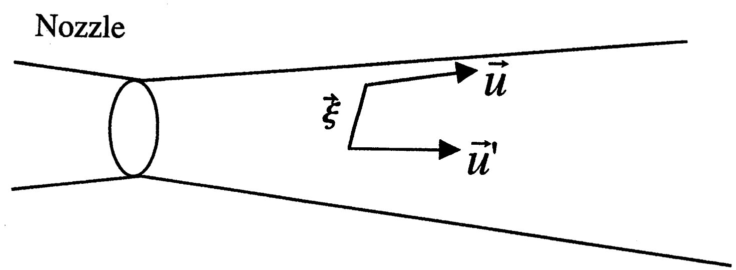
Distribution of TKE by Component



Higher value ⇒ more efficient sound conversion

Spatial Correlations of velocity

- Spatial correlations needed to model turbulence beyond turbulent kinetic energy, a one-point measure.
- PIV ideally suited for this measurement, capturing instantaneous velocity fields over a region chosen to be larger than the correlation size.



$$\tilde{\mathbf{R}}_{ij}(\xi_k,\vec{x}) = \frac{\overline{u_i(\vec{x}+\xi_k/2)\quad u_j'(\vec{x}-\xi_k/2)}}{\sqrt{\overline{u_i^2(\vec{x})}\quad \overline{u_j^2(\vec{x})}}}$$

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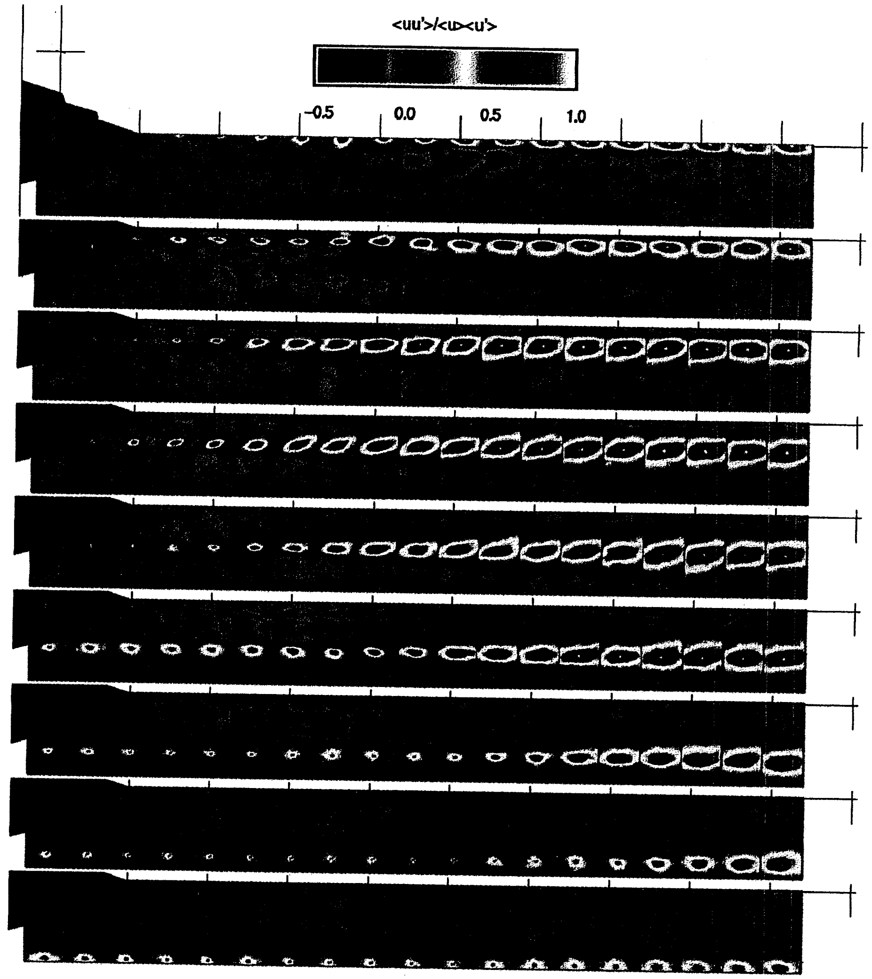
Two-Point Correlations of uu'
3BB

3BB



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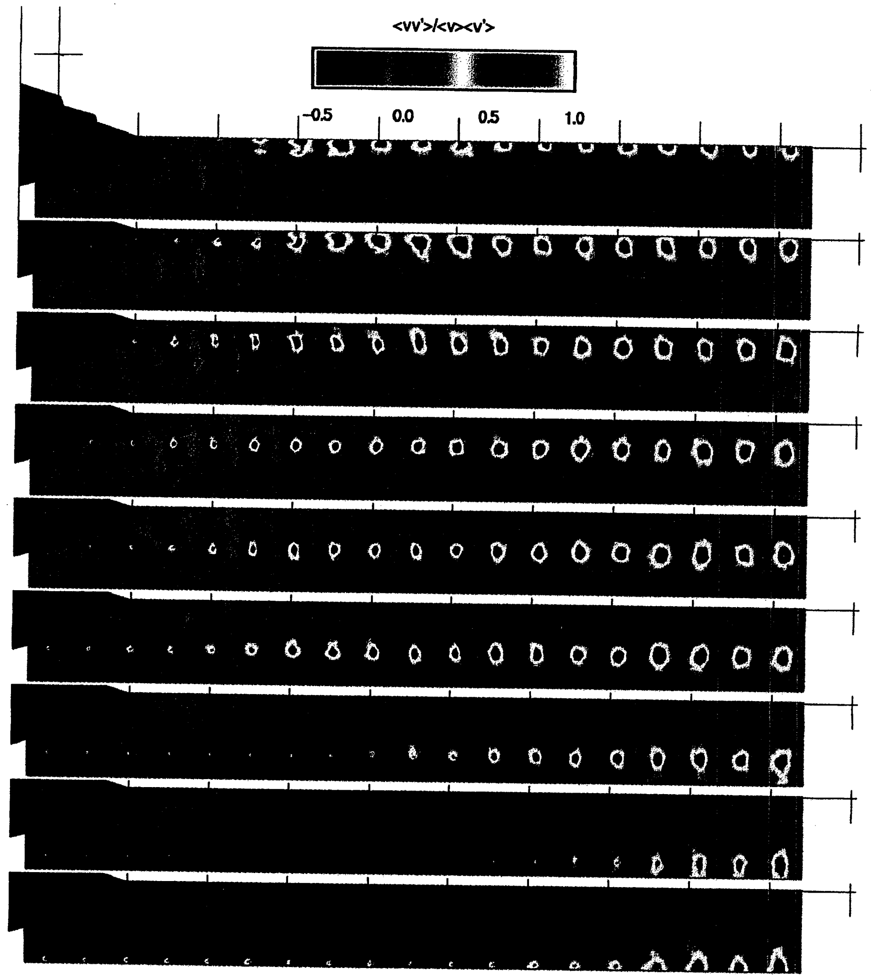
Two-Point Correlations of vv'
3BB

3BB



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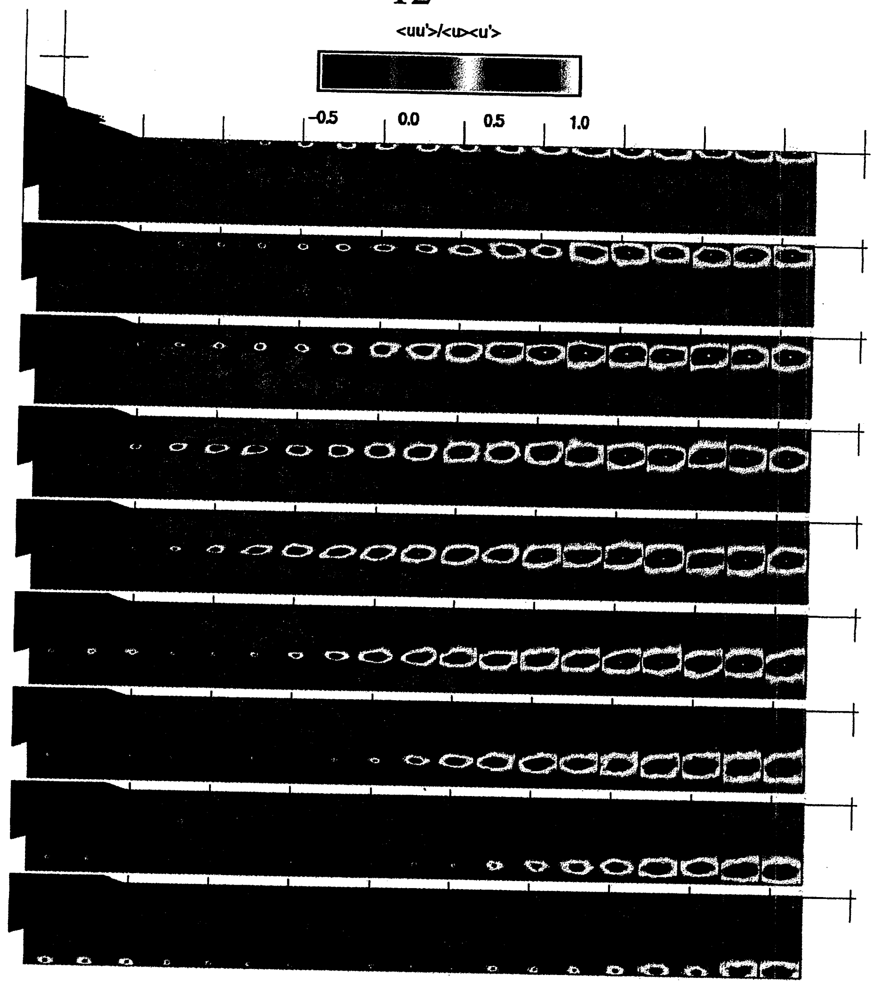
Two-Point Correlations of uu'

$3A_{12}B$



$3A_{12}B$

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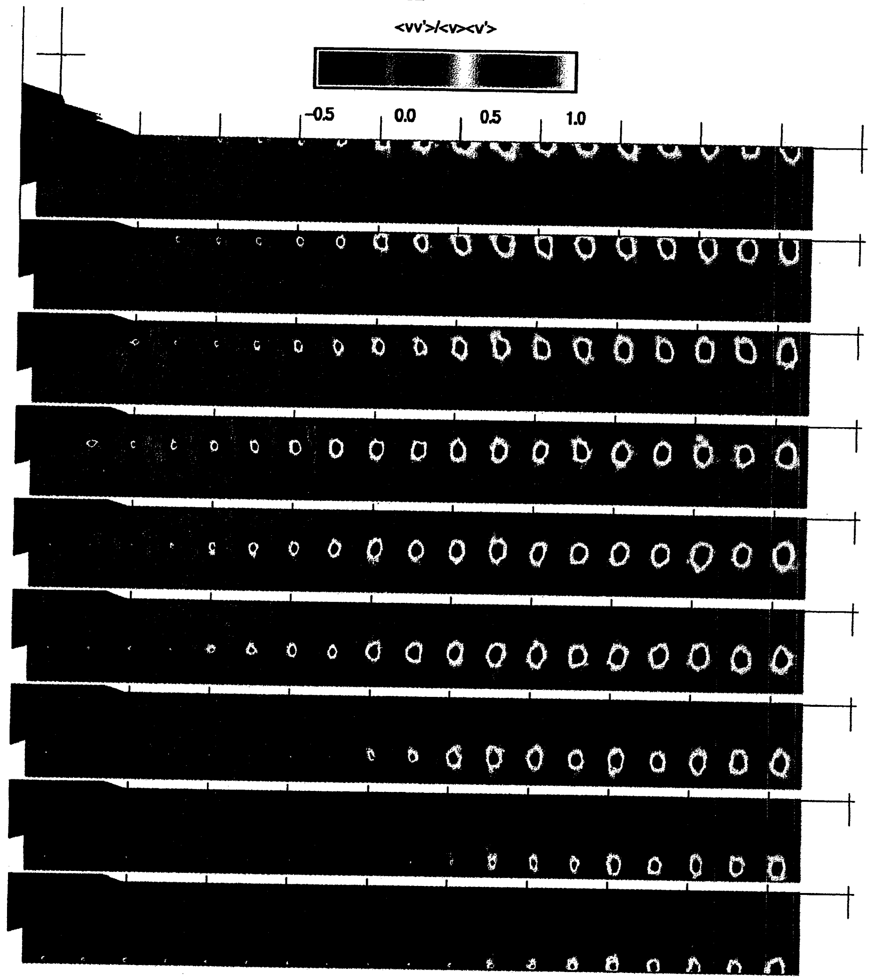
Two-Point Correlations of vv'

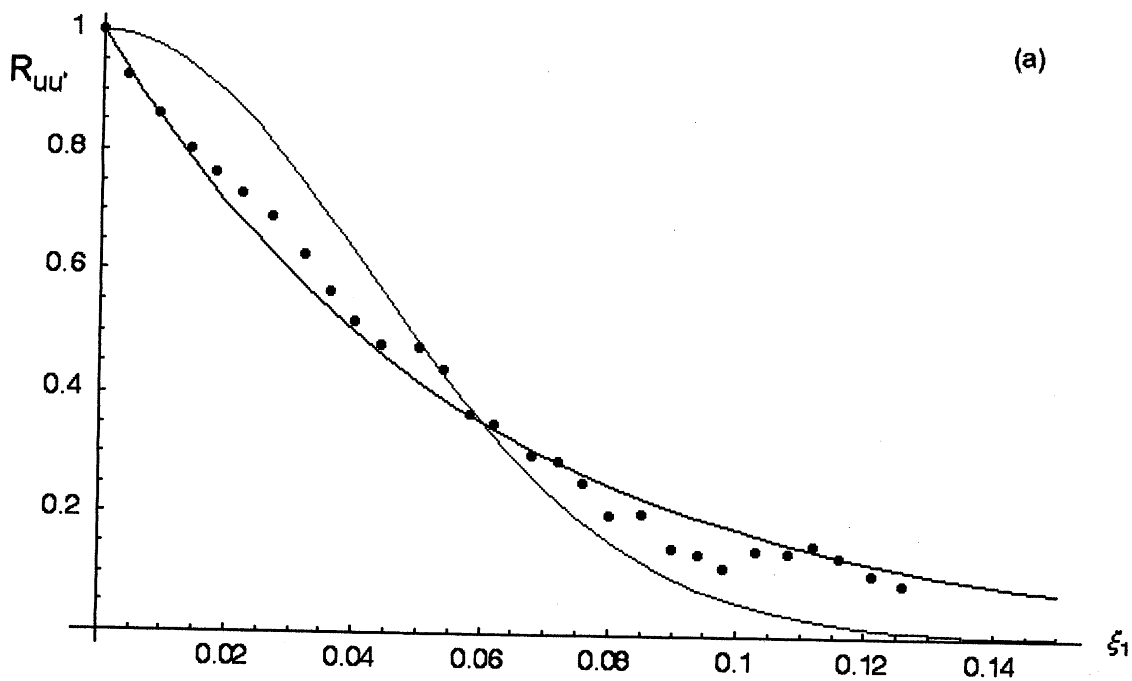
$3A_{12}B$

$3A_{12}B$



Fit of Spatial Correlation Data to Turbulence Models

- Modeling spatial correlations of velocity by form exp(-(ξ/L)^n).
- Usual model is Gaussian (n=2; in blue)
- Better fit for high Reynolds number is n=1 (black line)



Integral Lengthscales

- Integral lengthscales are a measure of largest scale of turbulence, measure of peak in turbulence wavenumber spectrum.
- Integral lengthscales are used in jet noise modeling to estimate frequency of sound being produced by kinetic energy in that region.
- Estimate integral lengthscales from integral of curve fitted to data.

$$Iu_i u_i, \xi_k(\vec{x}) = \int_0^\infty R_{ii}(\xi_k, \vec{x})\, d\xi_k$$

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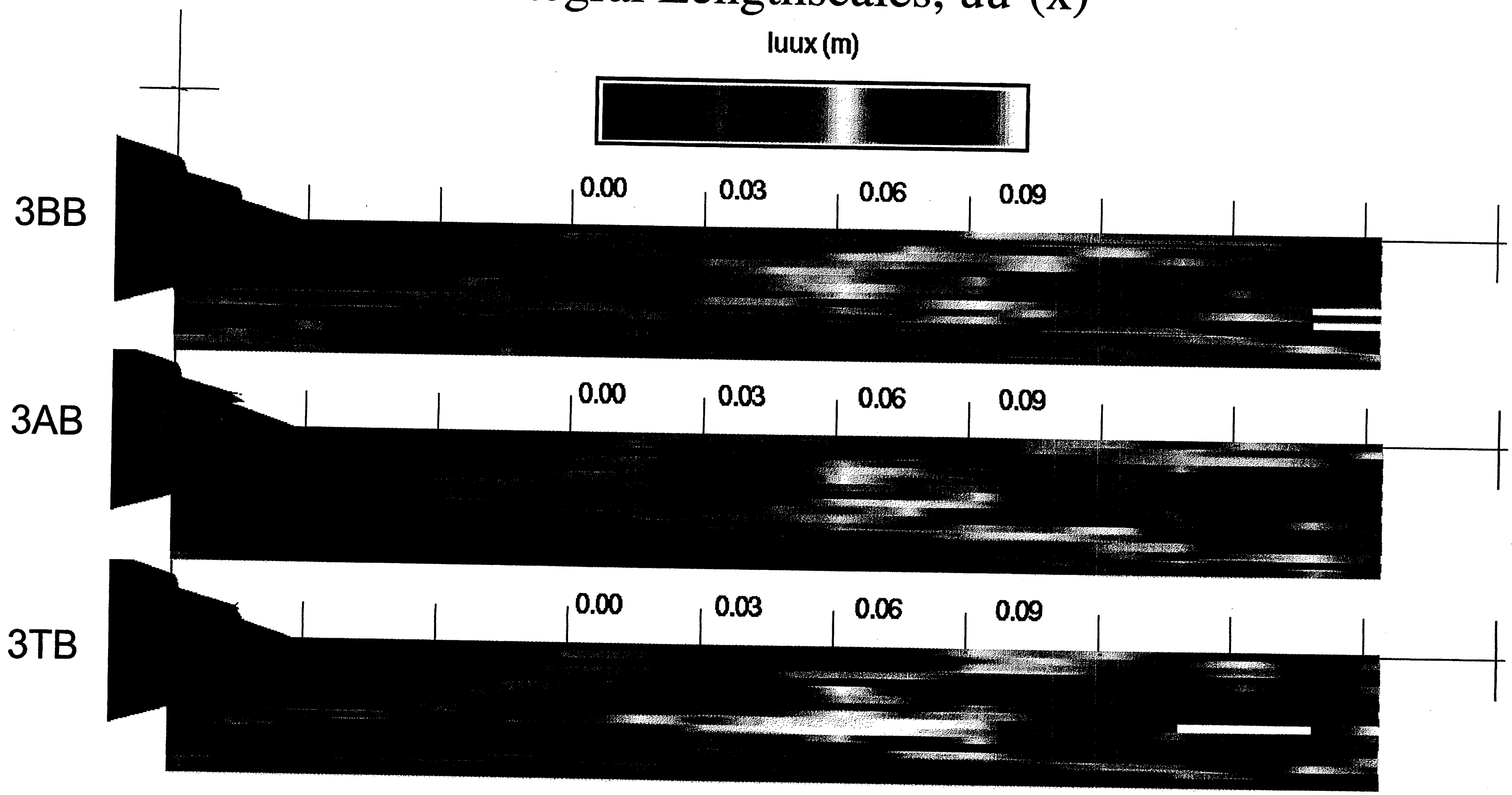
Integral Lengthscales, uu'(x)



Lengthscales relatively unaffected by mixing enhancement

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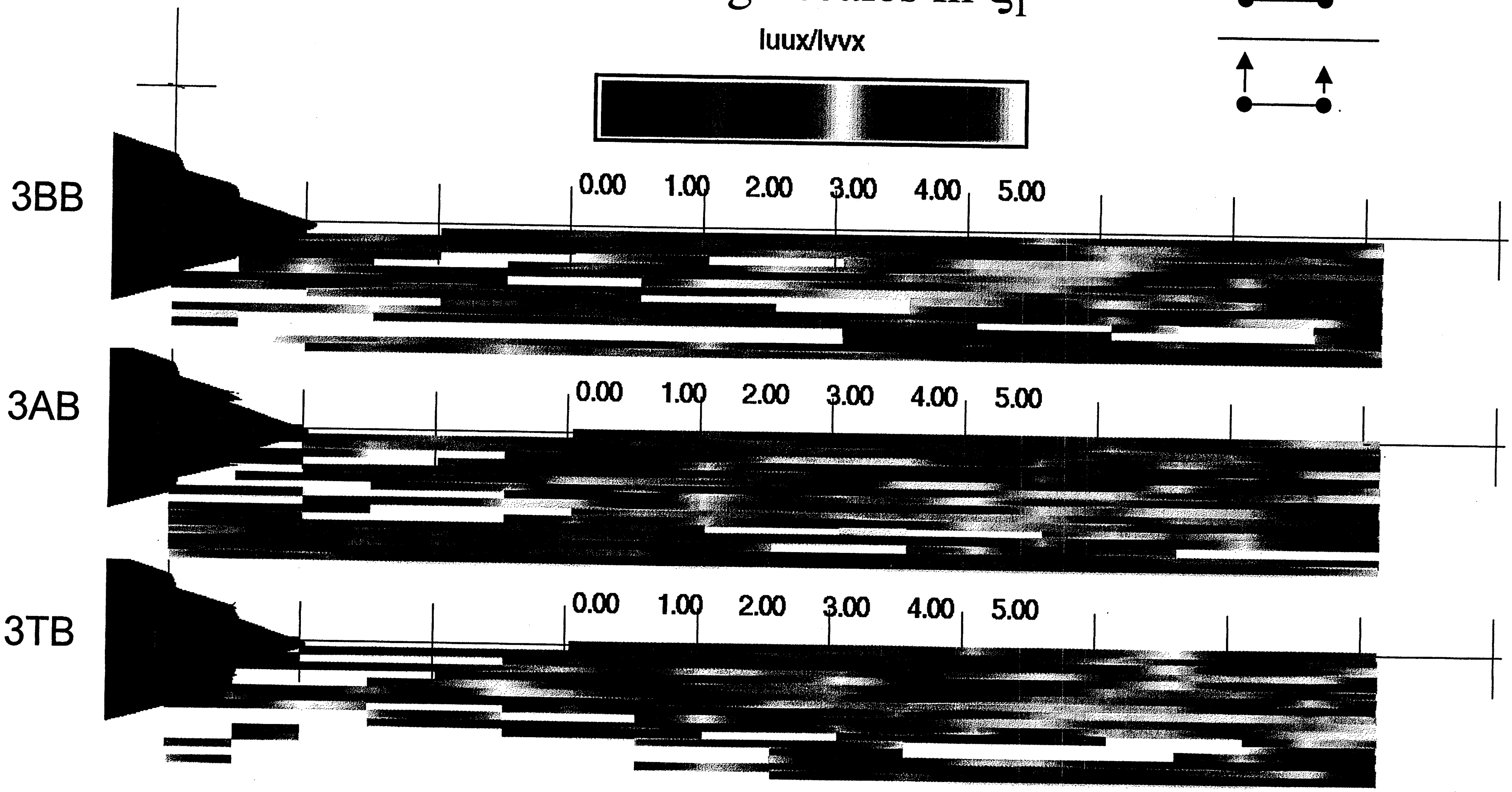
Ratio of Lengthscales in ξ_1



Equals 2 if isotropic; slightly more if axisymmetric

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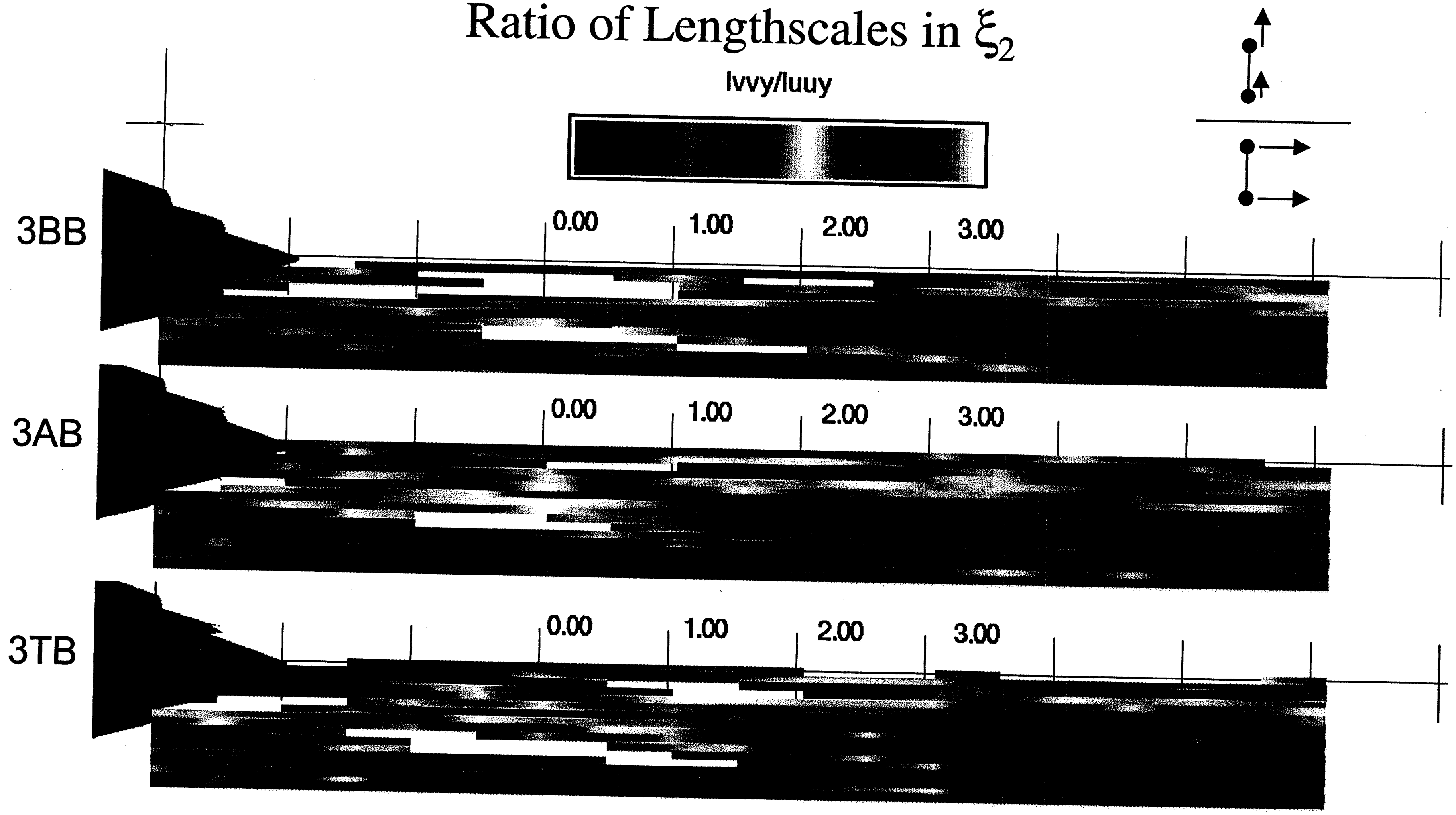
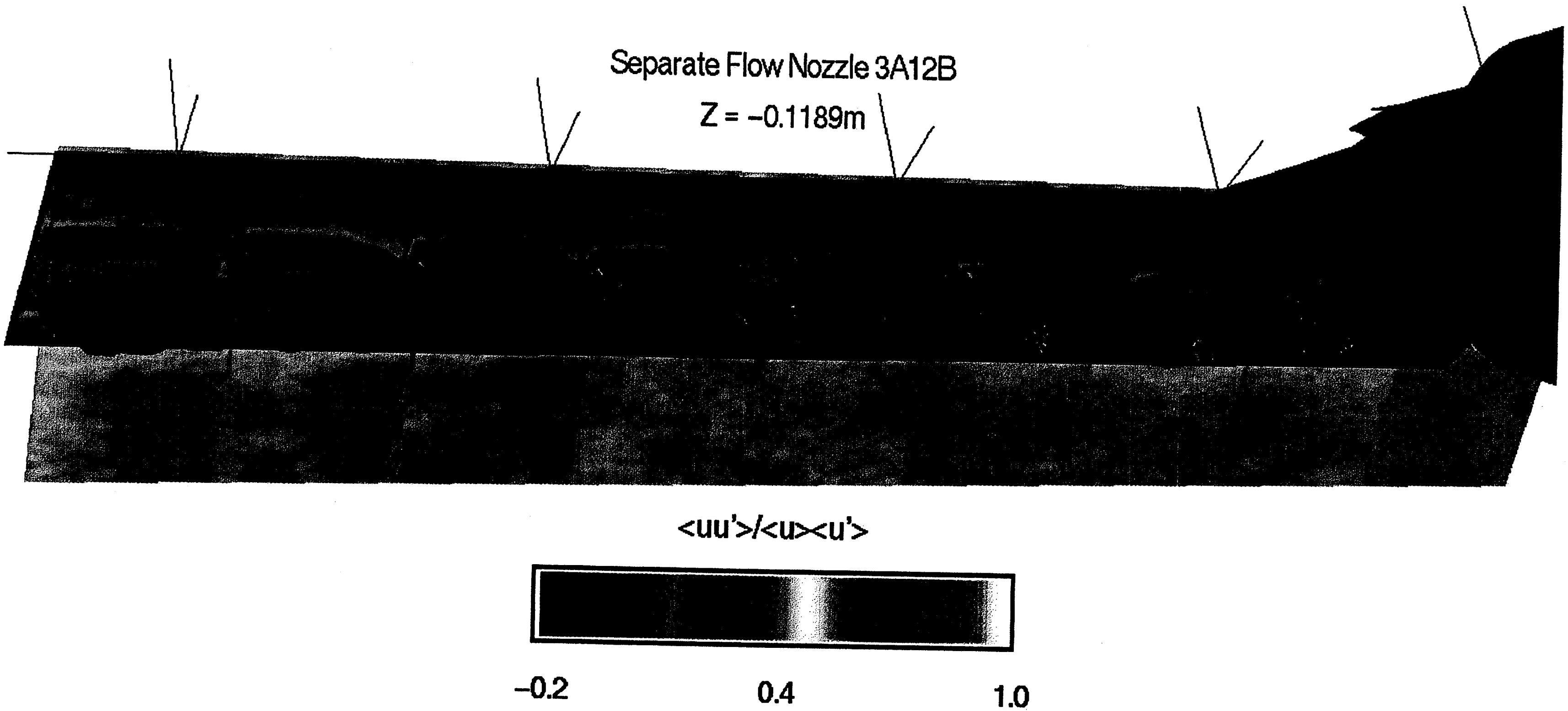
Ratio of Lengthscales in ξ_2

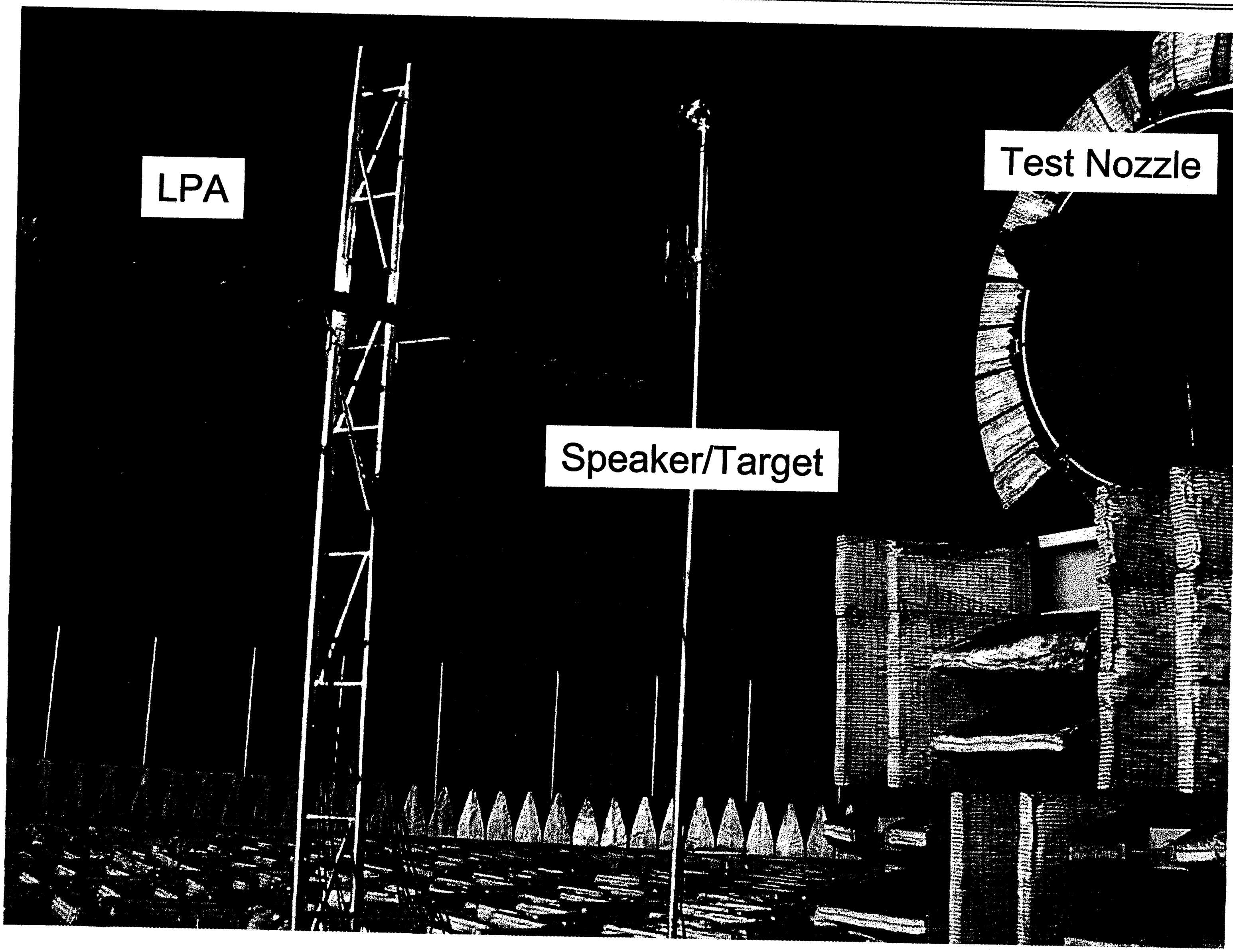


Expected to be 2 in either case, not nearly 1!

Two-Point Correlations



Spatial correlations are homogeneous, even in circumferential direction with chevrons


LPA
Speaker/Target
Test Nozzle

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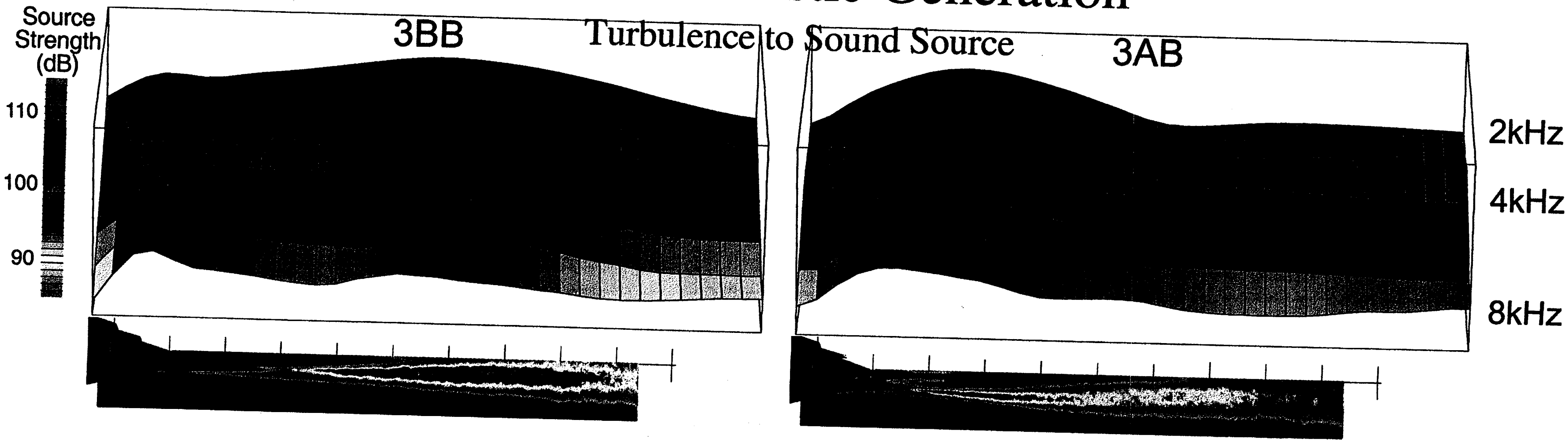
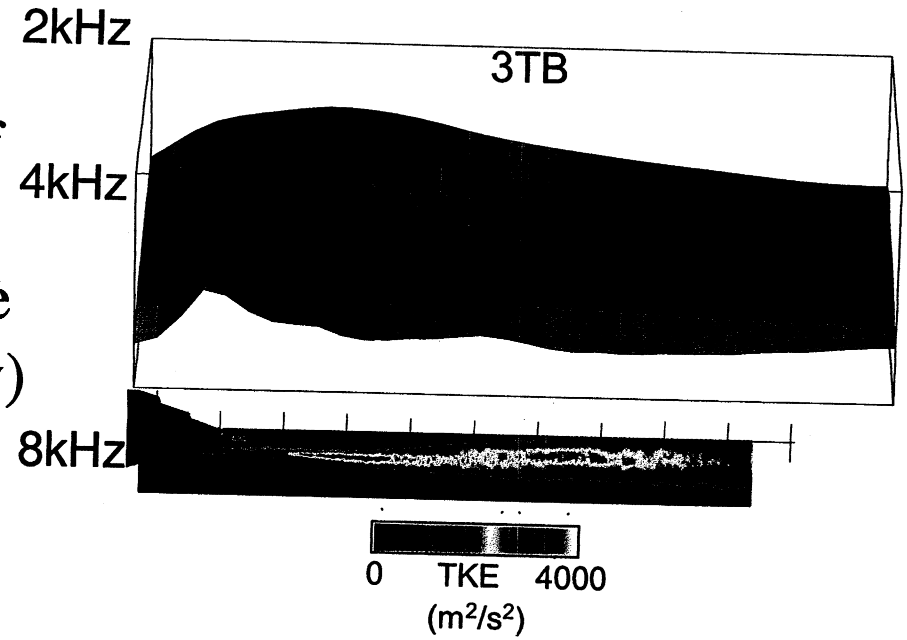
SFNT—Acoustic Generation

Turbulence to Sound Source



Fair spatial correlation of turbulence kinetic energy (PIV) and acoustic source distribution (phased array)



Conclusions

- Chevrons and tabs are effective mixing enhancement devices for jet nozzles.
- Thrust losses are small and noise modification is net reduction if done right.
- PIV allows measurement of turbulence quantities in hot, high-speed jets not available before.
- Mixing enhancement devices reduce mean velocity and turbulent kinetic energy in jet mixing region, cause some additional turbulence in first few diameters.
- Mixing enhancement devices change isotropy of turbulence (ratio of turbulence components)
- Mixing enhancement devices do not change lengthscales.
- Local homogeneity is good assumption, even in enhanced mixing nozzle flows.