Direct Numerical Simulations of Hypersonic Turbulent Boundary Layers

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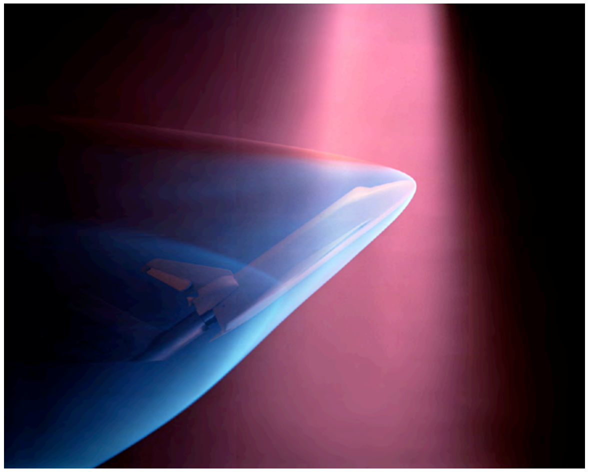
Examples

Space access and planetary entry

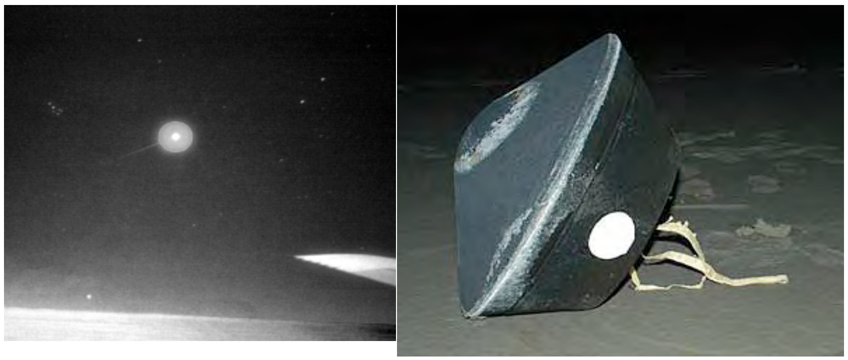
Shuttle – wind tunnel model

Wind Tunnels of NASA, NASA-SP-440 , JAN 1, 1981



NASA CEV

NASA Stardust
Comet Wild2

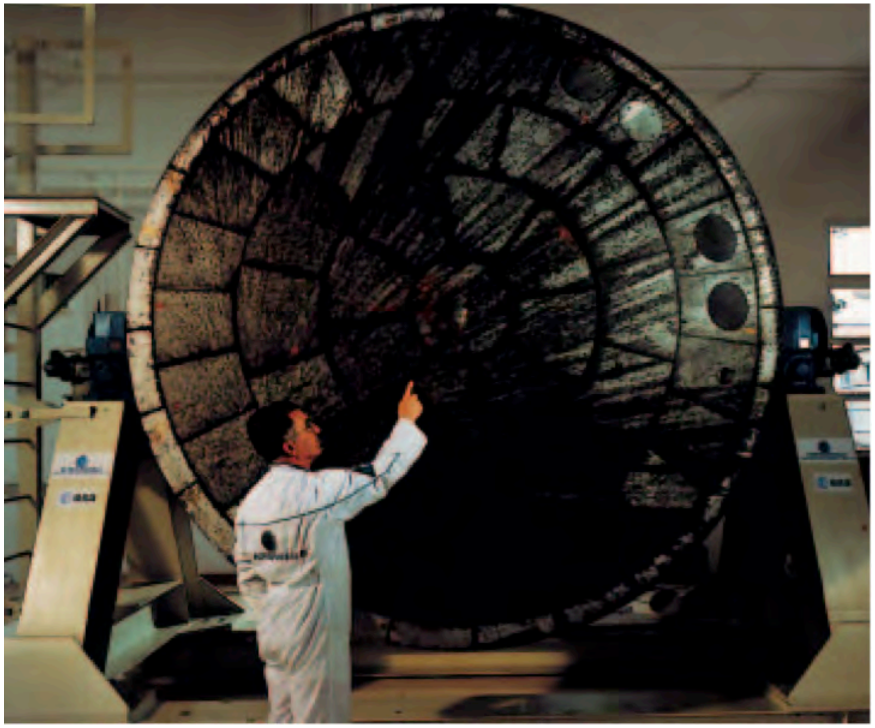


Key Physical Features

High Temperature phenomena dissociation/recombination, ionization, radiation surface catalysis and ablation

Pre-Flight

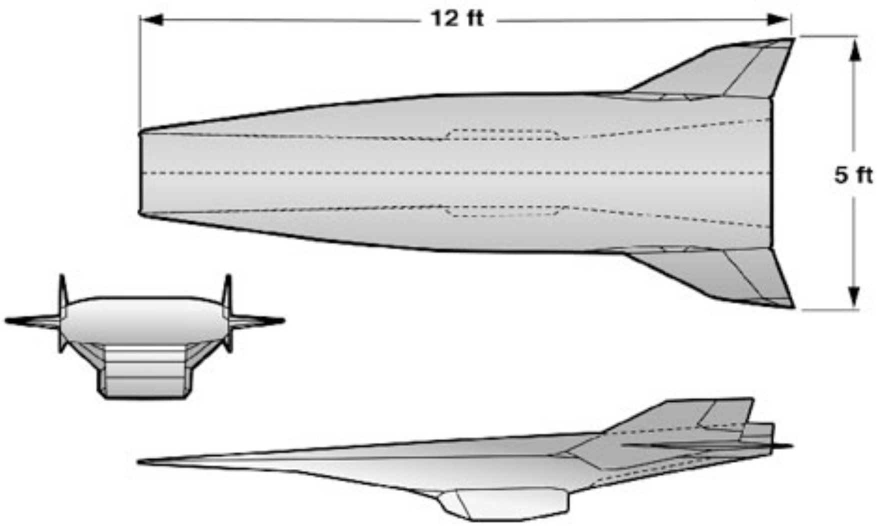
Post-Flight



ESA mission

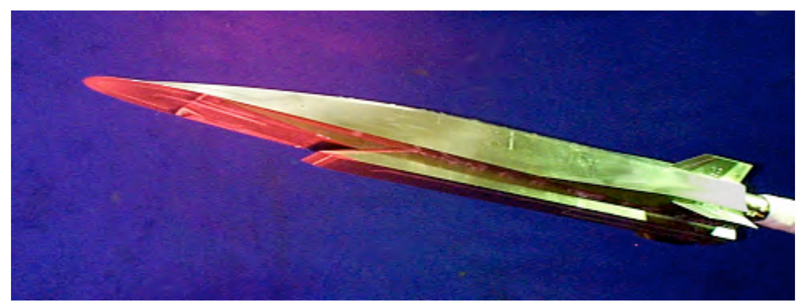
Examples

Atmospheric hypersonic flight external and internal flows



NASA X-43A
Reusable launch vehicle

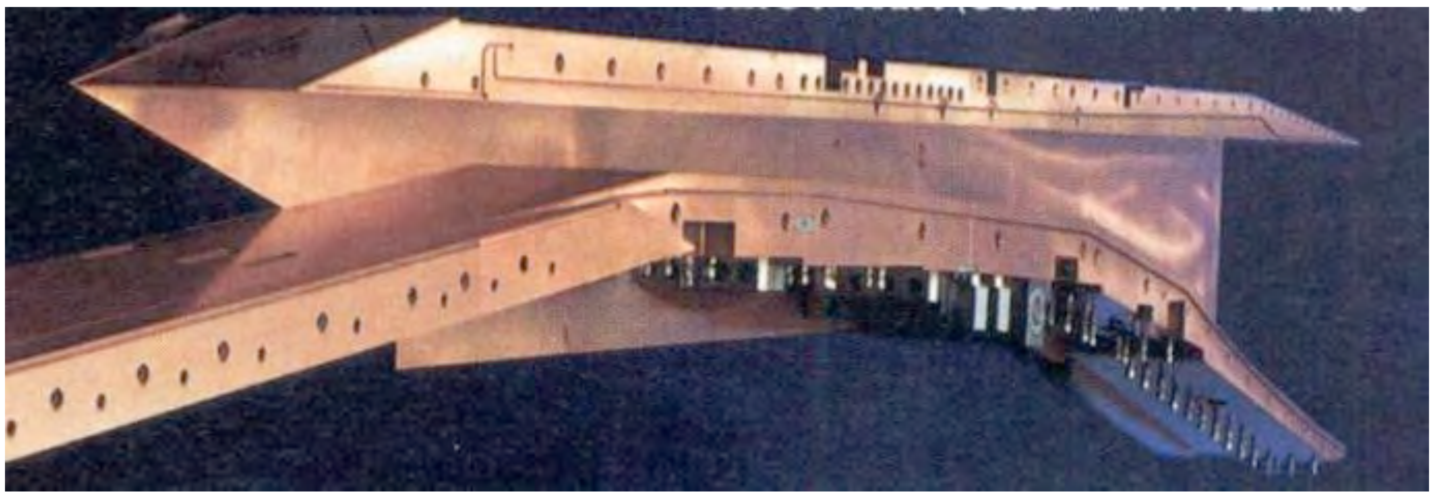
Boeing-AF X-51A
Reusable launch vehicle

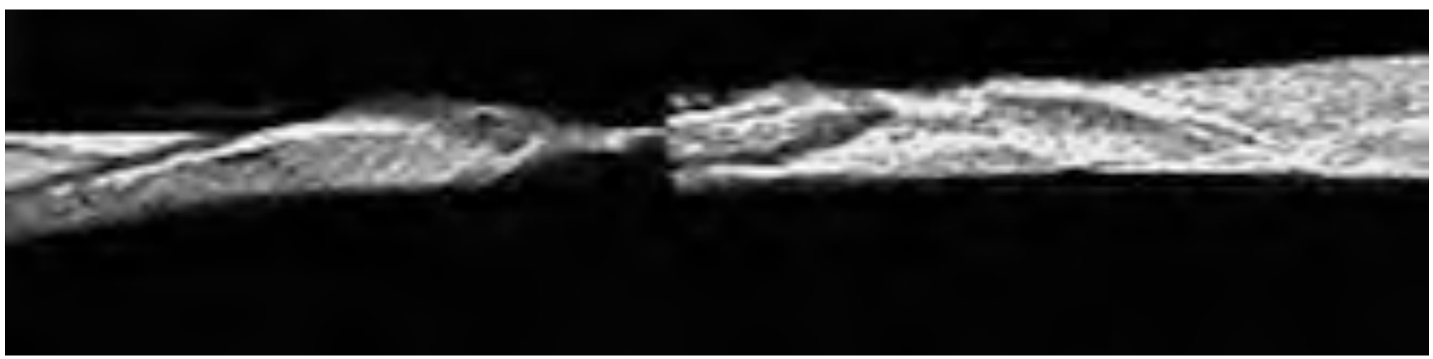


Key Physical Features

Shock wave and turbulence interaction

Pratt & Whitney Generic Scramjet Engine





Flow inside a generic scramjet engine, no combustion
Courtesy of Mike Holden, CUBRC

Research Approach and Objectives

Detailed Simulations of Hypersonic Turbulent Boundary Layers (HTBL)

- HTBL competing fundamental processes
  - Mach number, heat transfer, real gas, radiation, roughness effects
  - Transpiration, blowing, surface recession, surface reactions

- Approach
  - Decouple fundamental processes
  - Validate numerical data against experimental data, as much as possible
  - Enhance experimental data
  - Understand fundamental processes

- Objective
  - Understand the fundamental physics of fully coupled problem
  - Develop a detailed simulation capability (DNS/LES) for the coupled problem

Background: Key Relations

- Morkovin scaling:
  Any differences from incompressible turbulence can be accounted for by mean variations of fluid properties.
  Basis for the van Driest transformation and intensity scaling, which can be used to predict the mean and fluctuation velocities

- Strong Reynolds analogies:
  Relate fluctuating thermodynamic variables and velocity fluctuations
  Give basis for the evaluation of Pr_t

- Walz's equation:
  Analytical result from governing equations for zero-pressure-gradient BL under negligible wall pressure and total temperature fluctuations

$$\frac{\bar{T}}{\bar{T}_\delta} = \frac{\bar{T}_w}{\bar{T}_\delta} + \frac{\bar{T}_r - \bar{T}_w}{\bar{T}_\delta}\left(\frac{\bar{u}}{\bar{u}_\delta}\right) + \frac{\bar{T}_\delta - \bar{T}_r}{\bar{T}_\delta}\left(\frac{\bar{u}}{\bar{u}_\delta}\right)^2$$

- Effects of energetically dominant turbulence structure
  Direct connect between local flow physics and impact on the wall pressure and heat transfer

Background: Other Key Concepts

- Intermittency
  Gives a measure of the interaction between the irrotational fluid outside of the boundary layer and the viscous fluid within

- Skin friction
  Gives a measure of the viscous drag

- Wall pressure and thermodynamic fluctuations
  Relevant to gauge the structural and thermal design requirements

- A priori assessment of turbulence-chemistry interaction (TCI)
  Informs on the necessity to employ turbulence models to obtain accurate product formation and wall heating loads in design calculations

- Accurate product formation
  Pertains to the development of accurate scaling laws for temperature fluctuations

Mach Number Effects

Background

- Limited number of studies for boundary layers at high Mach numbers
  - Mikulla & Horstman AIAA J 1976
  - Owen & Horstman JFM 1972
  - Owen & Horstman AIAAJ 1972
  - Owen, Horstman & Kussoy JFM 1975
  - Baumgartner PhD Thesis Princeton University 1997
  - McGinley, Spina & Sheplak AIAA Paper 1994-2364
  - Sahoo & Smits AIAA Paper 2010-4471
  - Guarini, Moser, Shariff & Wray JFM 2001
  - Maeder, Adams & Kleiser JFM 2001
  - Martín AIAA 2004–2337
- Hot wire anemometry data: turbulent intensities below those in incompressible flow, not scaling according to Morkovin's scaling
  Owen & Horstman JFM 1972; McGinley et al 1994 (possible poor frequency response)
- PIV data gave much larger turbulence intensities
  Sahoo & Smits AIAA 2010-1559 (possibly low seeding particle densities)
- Maeder et al (2001) DNS data show Reynolds stress profiles that are fuller than those for incompressible flow but computational domain sizes were suspect
- Comparisons between DNS and experiments have been at moderate Mach numbers

Mach Number Effects

Martín 2004-2337, Beekman et al AIAA-2009-1328

Duan, Beekman & Martín AIAA 2010-0353

Case	M_δ	ρ_δ(kg/m^3)	T_δ(K)	T_w/T_δ	Re_θ	Re_τ	$Re_{\delta 2}$
M3	2.99	0.0891	218.2	2.60	2606	413	1361
M4	3.98	0.0914	219.2	3.83	3407	406	1367
M5	4.97	0.0910	221.8	5.37	4086	425	1386
M6	5.93	0.0942	221.9	7.30	5163	387	1365
M7	6.94	0.0922	221.1	9.62	5574	358	1336
M8	7.80	0.0948	227.7	11.9	6817	345	1360
M12	11.93	0.0921	228.0	27.6	9842	328	1384

$$\mathrm{Re}_\theta = \frac{\rho_\delta u_\delta \theta}{\mu_\delta} \qquad \mathrm{Re}_\tau = \frac{\rho_w u_\tau \theta}{\mu_w} \qquad \mathrm{Re}_{\delta 2} = \frac{\rho_\delta u_\delta \theta}{\mu_w}$$

Wall Temperature Effects
Background

- Limited number of detailed studies of heat transfer in HTBL
  - Gaviglio IJHMT 1987
  - Rubesin NASA CR 177556 1990
  - Huang, Coleman & Bradshaw JFM 1995
  - Maeder, Adams & Kleiser JFM 2001
  - Morinishi, Tamano & Nakabayashi JFM 2004

- Most of the work focused on the validity of the SRA

Wall Temperature Effects

Martín 2004-2337, Beekman et al AIAA-2009-1328

Duan, Beekman & Martín JFM 2010

Case	M_δ	$\rho_\delta(kg/m^3)$	$T_\delta(K)$	T_w/T_δ	Re_θ	Re_τ	$Re_{\delta 2}$
M5T1	4.97	0.0890	228.1	1.00	1280	798	1538
M5T2	4.97	0.0890	228.1	1.90	2300	625	1521
M5T3	4.97	0.0908	224.1	2.89	3010	522	1524
M5T4	4.97	0.0889	231.7	3.74	3820	434	1526
M5T5	4.97	0.0937	221.0	5.40	4840	386	1536

T_w /T_r varies from 1 to 0.1 with decreasing T_w

Turbulence Chemistry Interaction (TCI)

Background

- Limited number of studies for hypersonic boundary layer applications on single binary reaction mechanisms
  - Eschenroeder Phy Flu 1964
  - Martín & Candler Phys Flu 1998
  - Martín & Candler Phys Flu 1999
  - Martín & Candler AIAA 2001-2717
  - Martín AIAA 2003-4045

- Following Martín and Candler (1998), the turbulence/chemistry interaction depends on
  - The relative time scales of turbulence and chemical production, or turbulent Damköhler number
  - The relative heat release, the ratio of energy added to the system, relative to the energy that is present locally in the flow

- When the Damköhler number approaches one, there is interaction, which is modulated by the relative heat release.

- If the relative heat release is small, the interaction is insignificant

Real Gas Effects (RGE)

Half-cone angle 32º at 24 km, 100 nose radii downstream and free stream Mach number of 21

Duan & Martín AIAAJ 2009

Case	M_δ	ρ_δ(kg/m³)	T_δ(K)	T_w/T_r	Re_θ	Re_τ	$Re_{\delta 2}$
RGE	4.26	0.0468	3408.6	0.1	510	649	312
No RGE	4.26	0.0468	3408.6	0.1	510	649	312

- Five reaction mechanism for air
- Arrhenius parameters
- Equilibrium constant from Gibbs free energy functions of temperature fitted to Park (1990) expressions
- Thermal equilibrium using NASA LeRC curvefirts Gordon & McBride (1994)
- Gupta et al (1990)-Yos (1963) mixing rule for transport properties
- Multicomponent diffusion model Ramshaw (1990)
- Equilibrium catalytic binary condition
- Roe's matrix extended for multi-species calculations
- Direct measure of TCI by comparing $\overline{w(T,cs)}$ and $w(\overline{T},\overline{cs})$

Summary of Results

	Mach trend with Ma ↑	T_w trend with T_w ↓	RGE Trend with RGE
Morkovin	✓	✓	✓
SRA Huan et al JFM 1995	✓	✓	✓
Walz equation	✓	departure ↑ up to 10%	departure T_w effect
Inttermitency	↓	↑	T_w effect ↑
Skin Friction	↓	↑	T_w effect ↑
U_{packet}	↑	↓	↓ T_w effect
Packet coherence	↓	↑	↓ RGE
$P'_{w,rms}$	↑ <1% to 9%	↑ up to 15%	↑ Twofold
Thermodynamic fluctuations	↑ Up to 40%	↓	↓ RGE

Background on Performing DNS

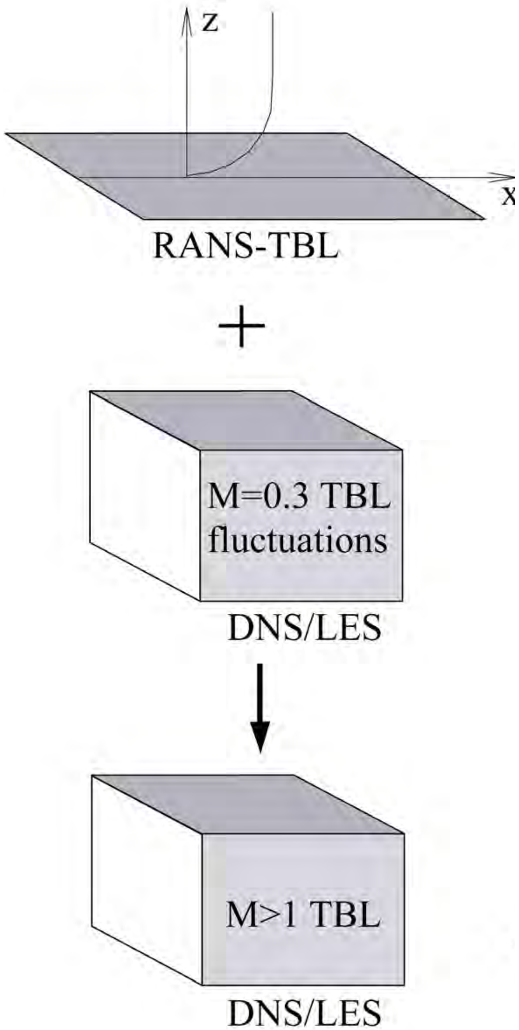
Direct and Large Eddy Simulations (DNS and LES) for Compressible Turbulence

- DNS/LES were well-developed for incompressible flows
  - **NOT** for compressible flow
- Require **high bandwidth** resolving efficiency and **shock capturing**
  - Attention to numerical dissipation
- **Implicit time integration** to alleviate stringent stability criteria
  - small wall-normal spacing and large speed of sound
- Starting a simulation from a laminar/random **initial condition**
  - Attention to cost
  - Control of flow conditions
- Require continuous **inflow conditions**

Initialization Procedure Development

Initial flow field resembles true flow mean, statistics, structure and spectra

Initial transient less than 10% of time required for gathering statistics



- Mean flow: Baldwin-Lomax RANS calculation (DPLR Code, NASA Ames)
  - Prescribe Mach and Reynolds numbers

- *Locally* transform velocity fluctuations using Morkovin's scaling

$$\left(\sqrt{\bar{\rho}/\bar{\rho}_w}\,\frac{u_i'}{u_\tau}\right)_{M>1} = \left(\sqrt{\bar{\rho}/\bar{\rho}_w}\,\frac{u_i'}{u_\tau}\right)_{M<1(Spalart\,1998)}$$

- Locally compute thermodynamic fluctuations from SRA analogy

$$T' = -(\gamma-1)M^2\frac{u'}{\bar{u}}\bar{T}$$

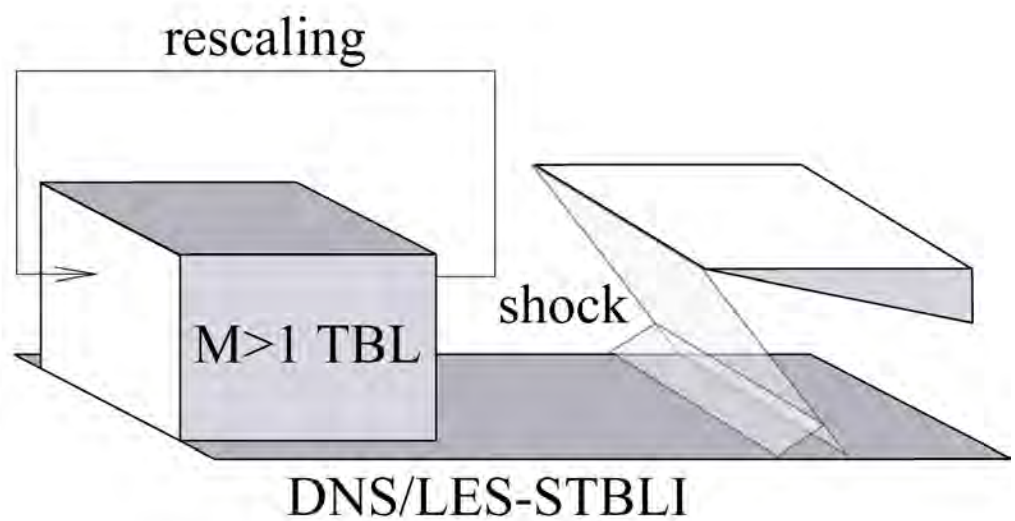
$$\frac{\rho'}{\bar{\rho}} = -\frac{T'}{\bar{T}}$$

Inflow Condition Development

Origin Lund et al. (1998) for incompressible flows

Xu & Martin Phys. Flu 2004

- Generalized rescaling relations
  - Velocity
  - Thermodynamic variables
  - Mean
  - Fluctuations

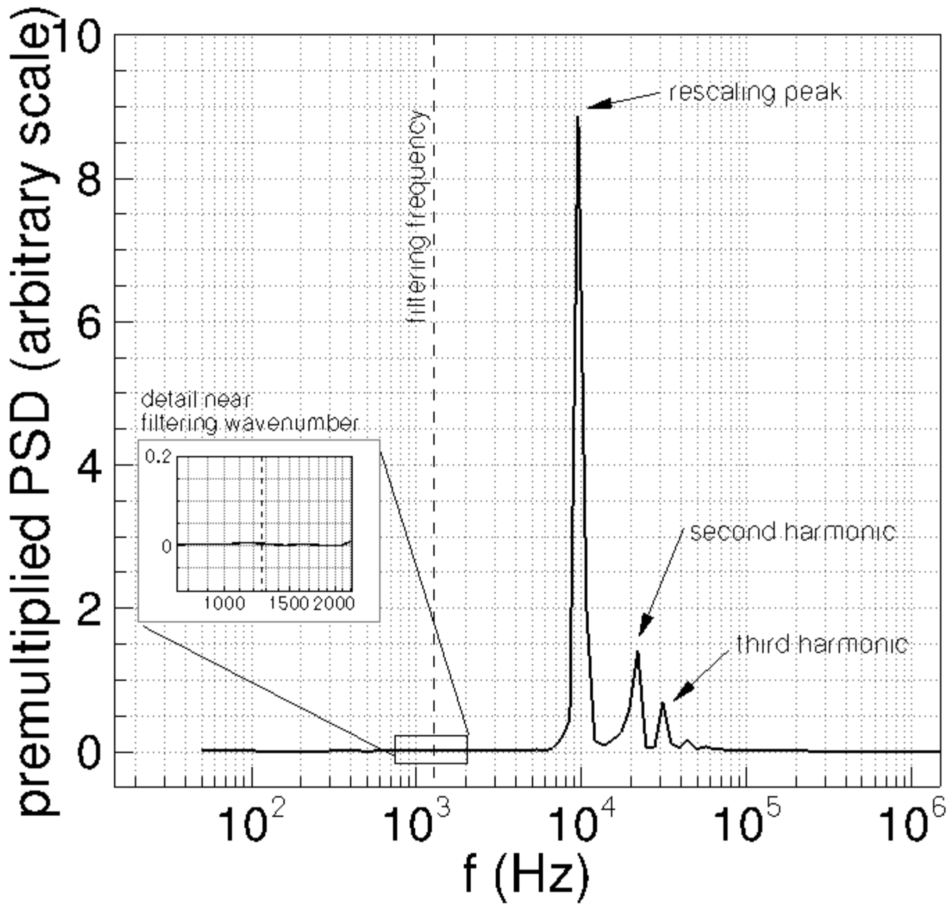


Inflow Condition Development

Origin Lund et al. (1998) for incompressible flows

Xu & Martin Phys. Flu 2004

Pre-multiplied velocity energy spectrum in the freestream (z=1.8δ)



The filtering does not introduce any forcing in the flow.

Developed Numerical Methods and Simulations Methodologies
for Detailed Simulations of HTBL

- Shock capturing, implicit time integration and continuous turbulence inflow data

  1. Xu & Martín **Phys Flu 2004**
  2. Martín & Candler **JCP 2006**
  3. Martín , Taylor, Wu & Weirs **JCP 2007**
  4. Taylor & Martín **JCP 2007**
  5. Taylor, Wu, & Martín **JCP 2007**
  6. Wu & Martín **AIAAJ 2007**
  7. Taylor & Martín **CiCP 2008**

- So far, satisfactory results for DNS and LES over flat plates

Validated Detailed Simulations

- For high-temperature phenomena
  8. Duan & Martín **AIAA J 2009**

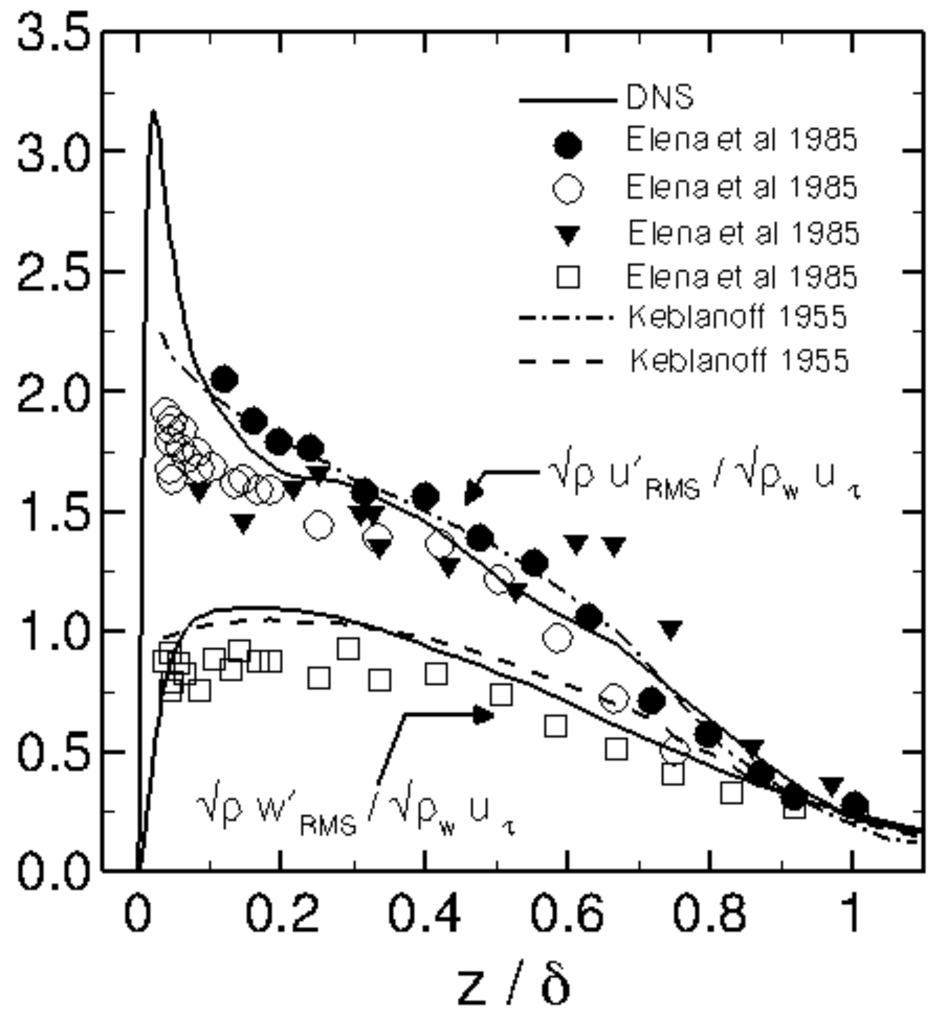
- For turbulent boundary layers against experiments at the same conditions
  9. Martín **JFM 2007**
  10. Wu & Martín **AIAAJ 2007**
  11. Ringuette, Wu & Martín **JFM 2008**

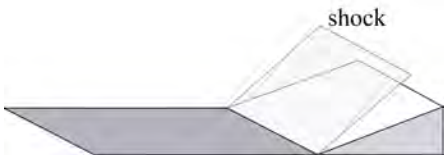
- In the presence of shock waves against experiments and grid convergence
  10. Wu & Martín **AIAAJ 2007**
  11. Ringuette, Wu & Martín **JFM 2008**
  12. Duan & Martín **accepted JFM 2010**
  13. Ringuette, Wu & Martín **AIAAJ 2008**
  14. Duan, Beekman, & Martín **under consideration for publication in JFM**
  15. Duan Beekman, Martín **AIAA 2010-0353**
  16. Beekman, Priebe, Ringuette & Martín **AIAA 2009-1328**

Validated DNS Data

Magnitude of Velocity Fluctuations in a Turbulent Boundary Layer

Ma_e =2.32, Re_θ=4450 from Martín JFM 2007



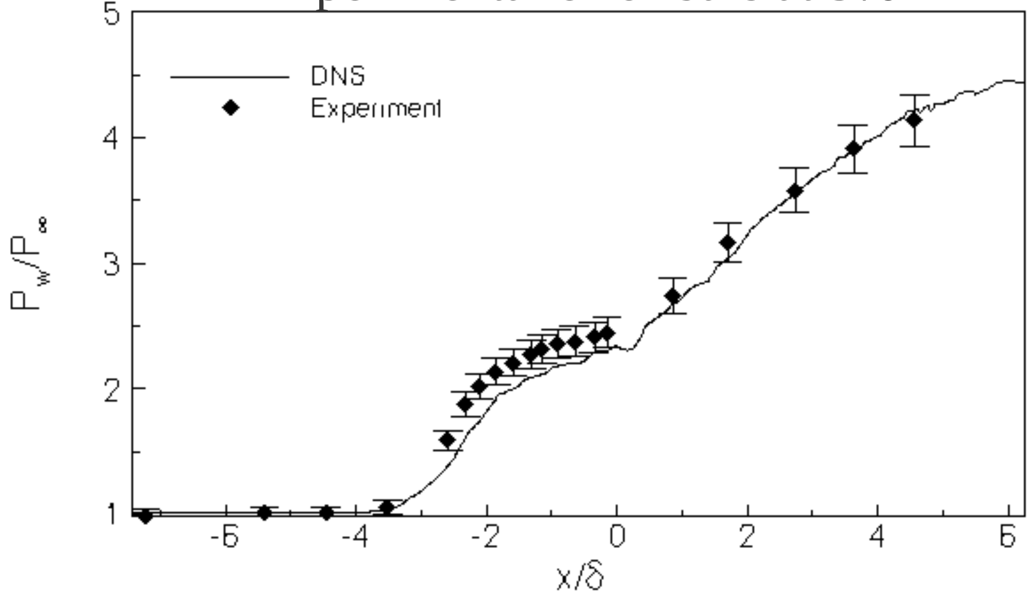


Validated DNS Data

Mach 2.9, Re_θ=2300 and 24º compression corner

Wu & Martin AIAAJ (2007)

Mean wall-pressure distribution
Experimental error bars at 5%



DNS data predicts experiment:

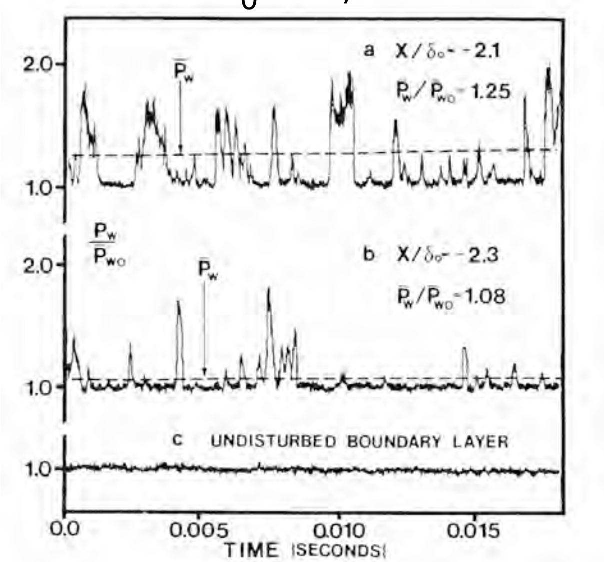
- Upstream boundary layer
- **Mean and RMS wall pressure**
- Size of separation bubble
- Velocity profile downstream of interaction
- Mass flux turbulent intensity
- **Characteristic low and high frequencies**

Low-Reynolds Number Effects

Mach 2.9, Re_θ=2300 and 24^o compression corner

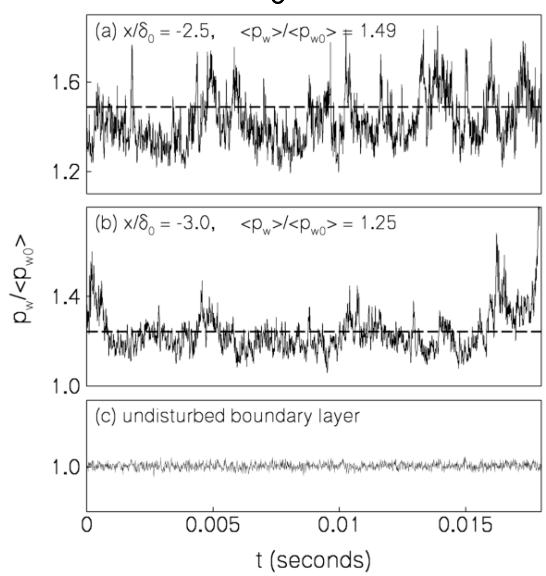
low-pass filtered at experimental resolution, 50kHz

Re_θ=69,000



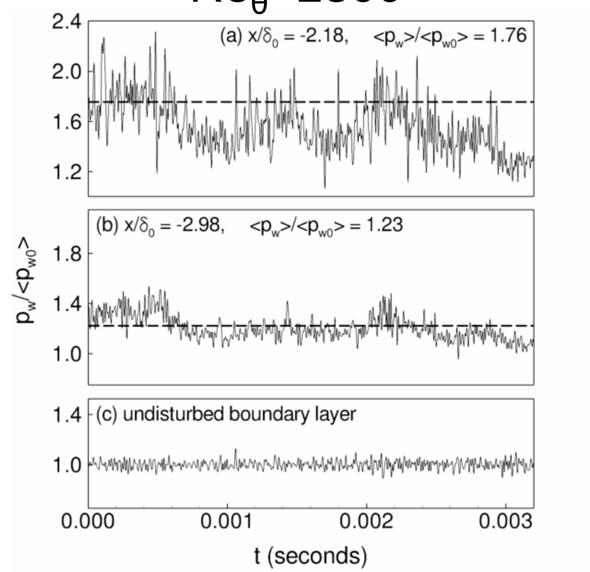
Dolling & Murphy AIAA J 1983
experiment
Frequencies from Selig et al., AIAAJ 1989

Re_θ=2400

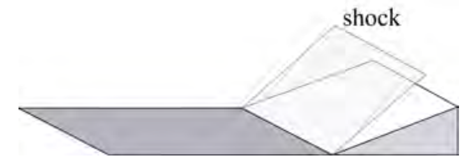


Ringuette & Smits AIAA 2007-4113
experiment

Re_θ=2300



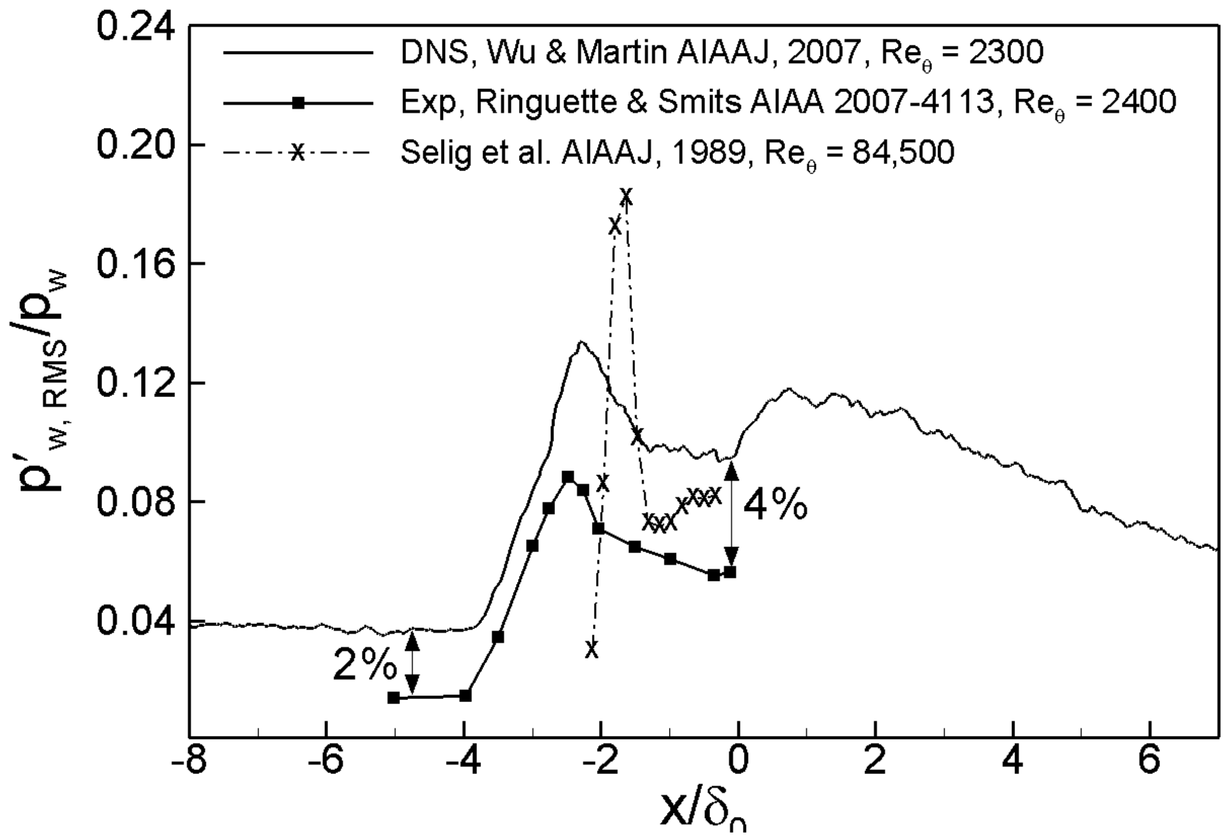
Wu & Martín AIAA J 2007
DNS



Validated DNS Data

Mach 2.9, Re_θ=2300 and 24º compression corner

Ringuette & Martín AIAAJ 2008



$$\left(p'_{\text{wall}} + p'_{\text{noise}}\right)^2 \approx p'^2_{\text{wall}} + p'^2_{\text{noise}}$$

$$p'^2_{\text{noise}} = \text{free stream value}$$

$$p'^2_{\text{noise}} / p'^2_{wall} = \text{ 4\% upstream of shock}$$

$$\text{16\% downstream}$$

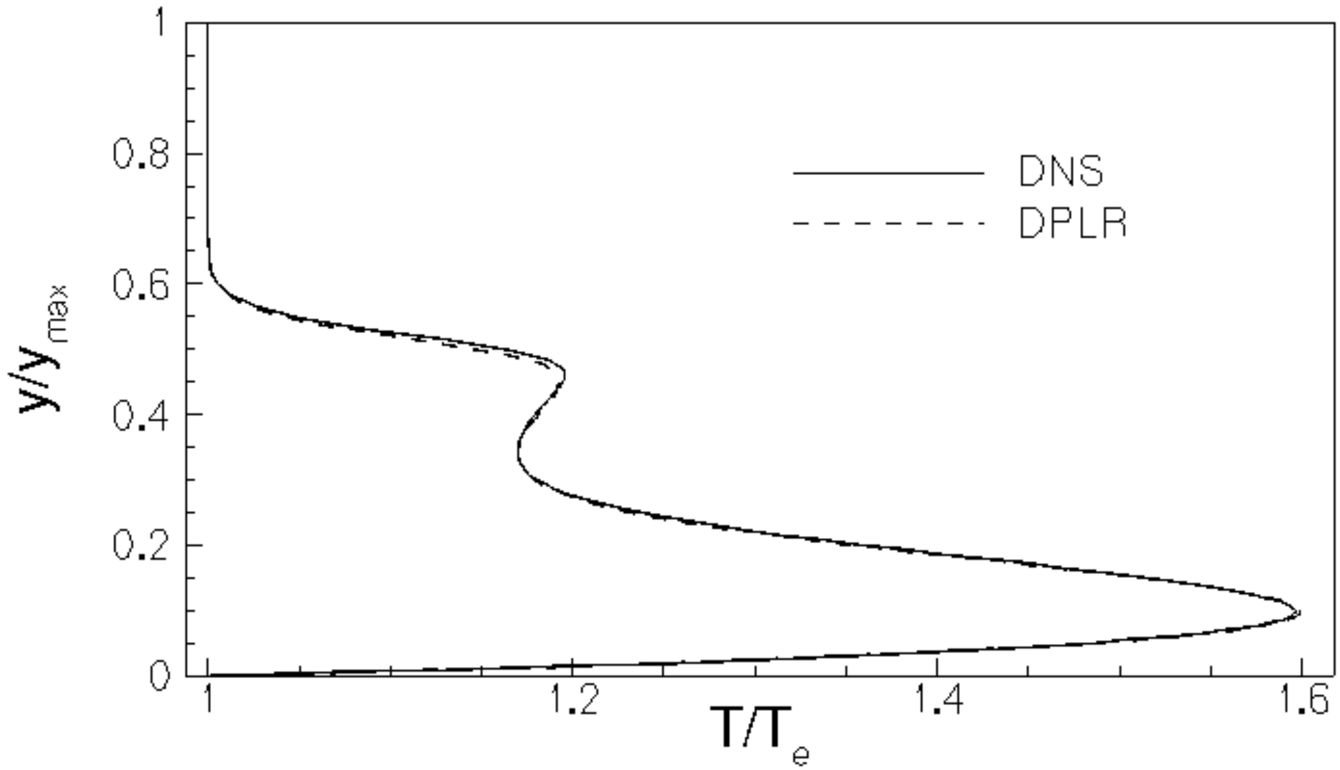
Validated DNS Data

Temperature Profile in a Laminar Hypersonic Boundary Layer

Ma_e = 4.0, Le =1, non-catalytic isothermal wall with $T_e = T_w$ =1, Re_l=1000

$N_2 + M \rightleftarrows 2N + M$

from Duan & Martín AIAA J 2008



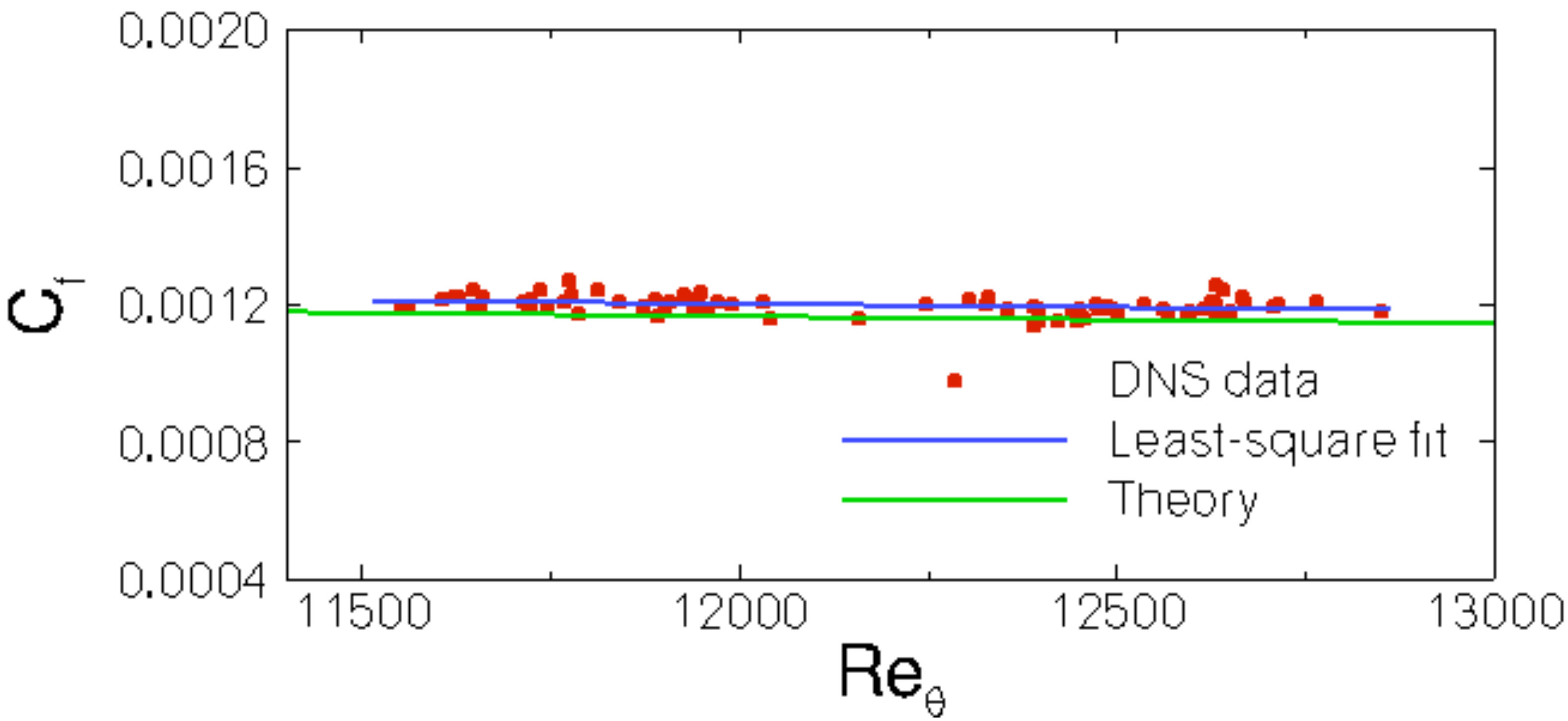
Validating real gas implementation and constitutive relations

Validated DNS Data

Local Skin Friction in a Spatially Evolving Turbulent Hypersonic Boundary Layer

SDNS compared with semi-empirical prediction and LS minimization data reduction

Ma_e = 4.0 from Xu & Martín Phys. Flu. 2004

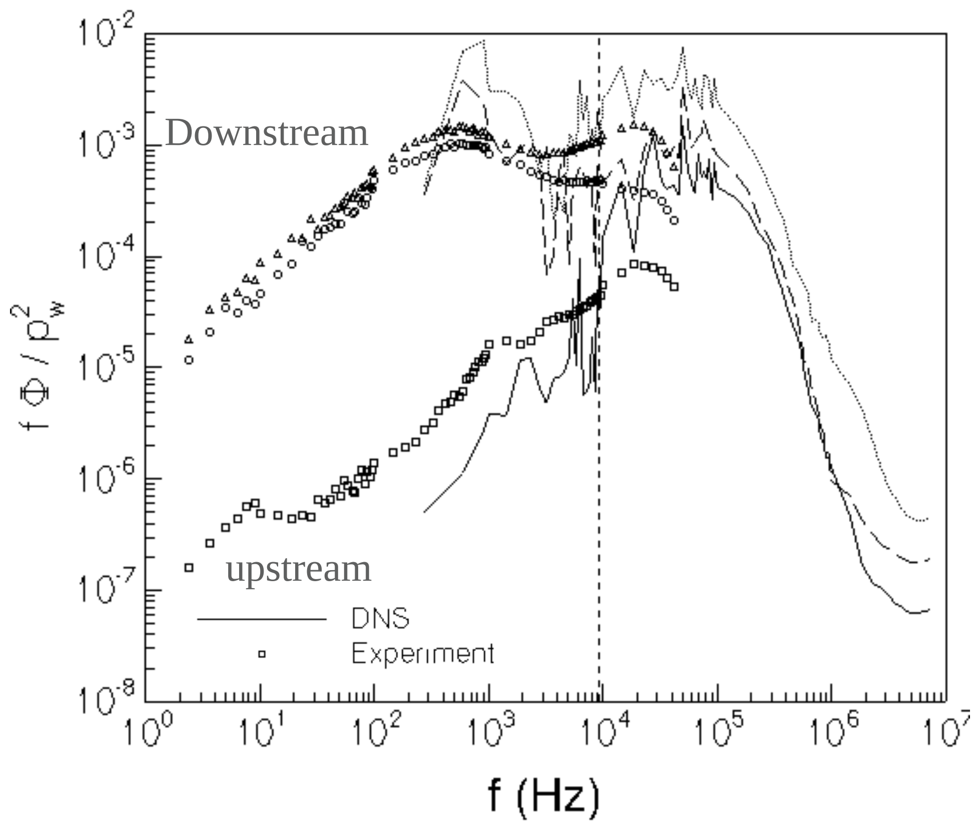


Validated DNS Data

Wall-Pressure Signal in Frequency Space from Experiments and DNS

Mach 2.9, Re_θ=2300 and 24º compression corner

Ringuette, Wu & Martín AIAAJ 2008



	Exp	DNS
U_∞/δ	90kHz	95kHz
f_{low}	**(0.6 – 0.8) kHz**	**(0.6 – 1.2) kHz**
F_{high}	**(20 – 30) kHz**	**(17 – 95) kHz**
High frequency Resolution	50kHz	950kHz

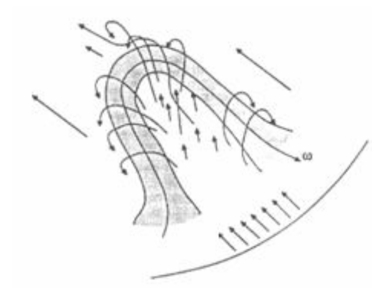
DNS data for 304 δ/U∞

Learning from DNS data

Coherent Structures in Turbulent Boundary Layers

Background

- Hairpin vortices (horseshoes, canes, etc)

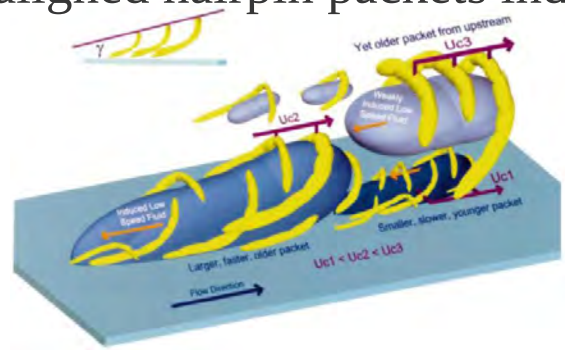


Ideal hairpin vortex (Theodorsen 1952)

- Hairpin vortices are organized into **‘packets’**
    - Adrian, Meinhart & Tomkins (JFM 2000)
    - Ganapathisubramani, Longmire & Marusic (JFM 2003)

- Very long (>10δ in the streamwise direction) **low-momentum regions** exists in the log layer
    - Very-large-scale motions or VSLM (Kim & Adrian, PoF 1999)
    - Superstructures (Hutchins & Marusic JFM 2007)

- It has been proposed that groups of streamwise-aligned hairpin packets induced the low-momentum regions beneath them
    - VLSM model of Kim & Adrian (PoF 1999)



Adrian et al. JFM 2000

Coherent Structures in Turbulent Boundary Layers

Background

- There is relatively very little data on compressible wall-bounded flows

  - Ganapathisubramani et al. (JFM 2006) observed superstructures in a Mach 2 boundary layer using PIV

  - Ringuette, Wu & Martin (JFM 2008) investigated the outer layer structure in DNS data of a Mach 3, Re_θ=2300 boundary layer
    - Observed hairpin packets
    - Observed superstructures
    - Showed that packets cluster above superstructures as hypothesized by Kim & Adrian (PoF 1999)

  - Van Oudheusden, Delf University of Technology, PIV studies of supersonic boundary layers

Boundary Layer Structure Analysis

Motivation

- Motivation: Hairpin packets and superstructures carry a significant fraction of the Reynolds shear stress and TKE
  - Ringuette, Wu & Martin (JFM 2008) find one third of TKE in the log-layer is in the superstructures

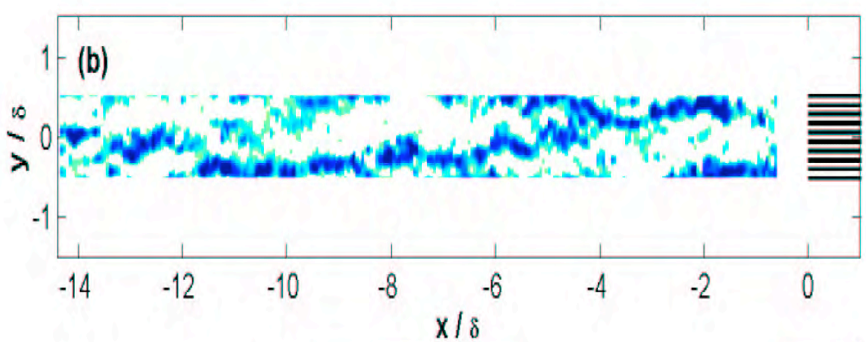
- Aims:
  - Identify ‘strong’ packets in DNS data
  - Track the hairpin packets over time
  - Develop physics-based identification and tracking technique using
    - geometric packet algorithms (Ringuette, Wu & Martin, JFM 2008)
    - enhanced correlation analyses (Brown & Thomas, PoF 1974)
    - O’Farrell & Martin JoT 2009

  - Characterize packet properties, wall signatures and the relevant frequencies
    - Priebe, Beekman, Ringuette & Martin (APS DFD 2008)
    - Beekman, Priebe & Martin (APS DFD 2008, AIAA 2009-1328)

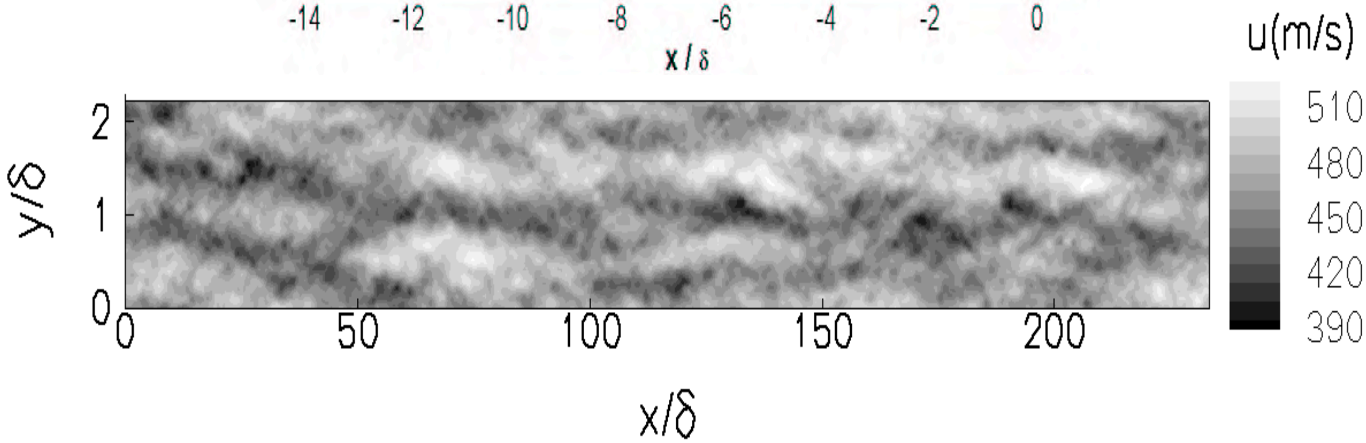
Characteristics of upstream boundary layer

Superstructures exist in DNS data

Wu & Martin AIAAJ 2007 and Ringuette, Wu & Martin JFM 2008



Atmospheric boundary layer experiments
Hutchins & Marusic JFM 2004



DNS data of boundary layer
Mach 3 Re_θ 2300
Wu & Martin AIAAJ 2007

Rake signal from DNS data at z_n=0.2δ
Contours of velocity on streamwise-spanwise planes
x-axis reconstruction using Taylor's hypothesis with convection velocity of 0.76U_∞
Data are averaged in x=4δ intervals

Packet Identification

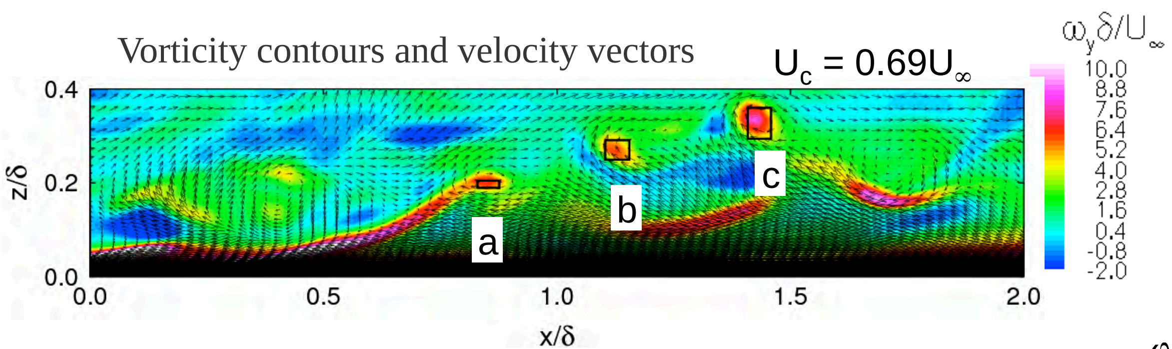
Part I: Geometric Analysis

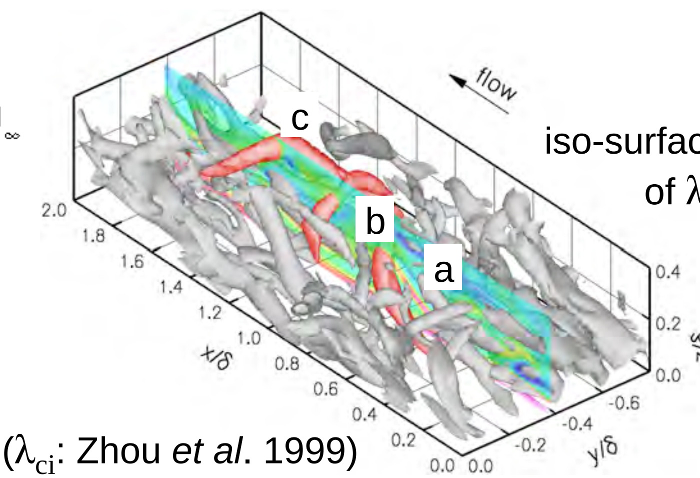
- Geometric packet finding algorithm of Ringuette, Wu & Martin (JFM 2008)

  - Identifies hairpin heads using two thresholds
    - Swirling strength : $\lambda_{ci} \geq 4.5\overline{\lambda_{ci}}$
    - Vorticity: $\omega_y \geq \overline{\omega_y} + 2\sigma(\omega_y)$

  - Finds Ideal packets conforming to a set of geometric characteristics (following the hairpin packet of Adrian et al. JFM 2000)
    - Hairpin heads are closely spaced in the streamwise direction
    - Heads belonging to a packet are arranged at an acute angle to the wall (≤45°)

Vorticity contours and velocity vectors





iso-surface of λ_{ci}

(λ_{ci}: Zhou *et al*. 1999)

Analytic Tools

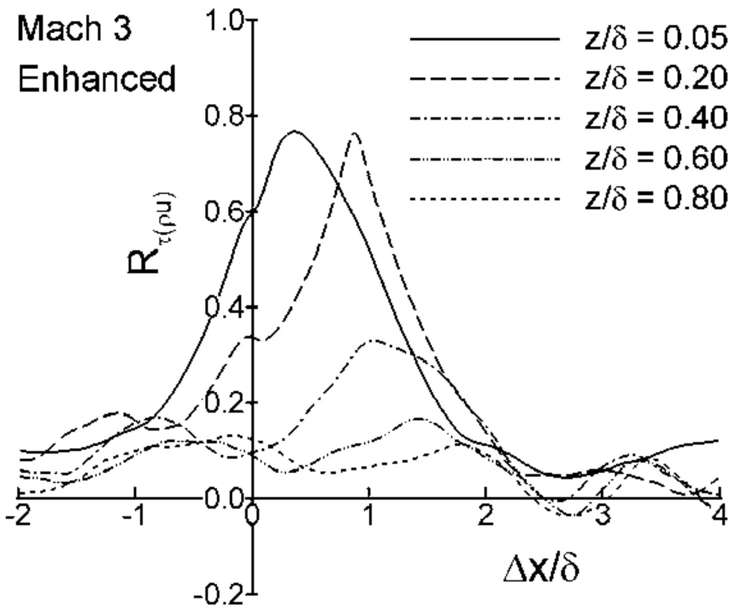
Part II: Statistical Analysis

- Correlate the shear stress at the wall with the streamwise mass flux at various wall-normal locations (following Brown & Thomas PoF 1977)

$$R_{\tau_w(\rho u)}(\Delta x) = 1/(x_2 - x_1)\left\langle \overline{\int_{x_1}^{x_2} \tau'_w(x)(\rho u)'(x+\Delta x)dx} \right\rangle / \tau'_{w,RMS}(\rho u)'_{RMS}$$

- Correlation profiles peak at increasing streamwise separation, indicating the presence of a downstream-leaning coherent structure

- If, at a specified wall-normal distance, the instantaneous peak correlation exceeds the average peak value by a factor of 5, a **`strong' event** is present



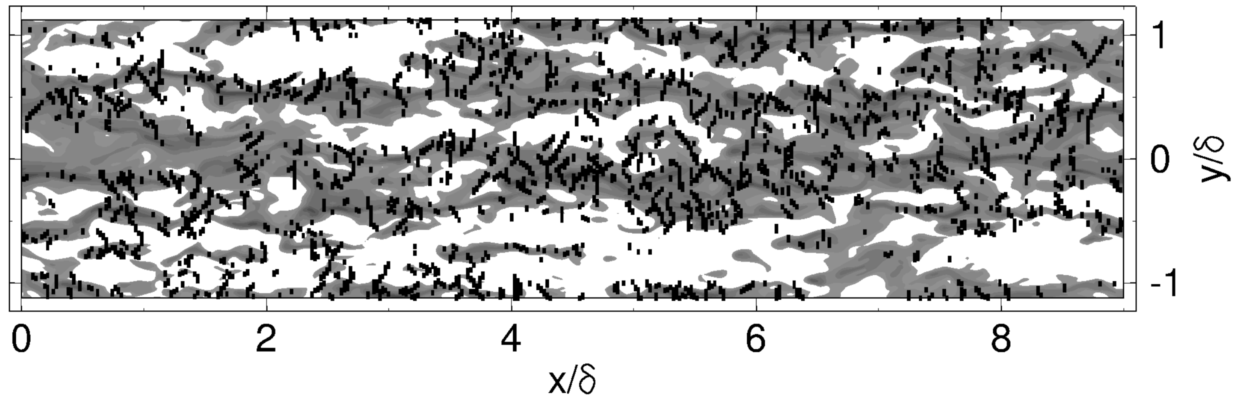
Correlation profiles for DNS data of a Mach 3 turbulent boundary layer, following Brown and Thomas PoF 1977

Packet Identification

Part III: Interpretation of Geometric Analysis

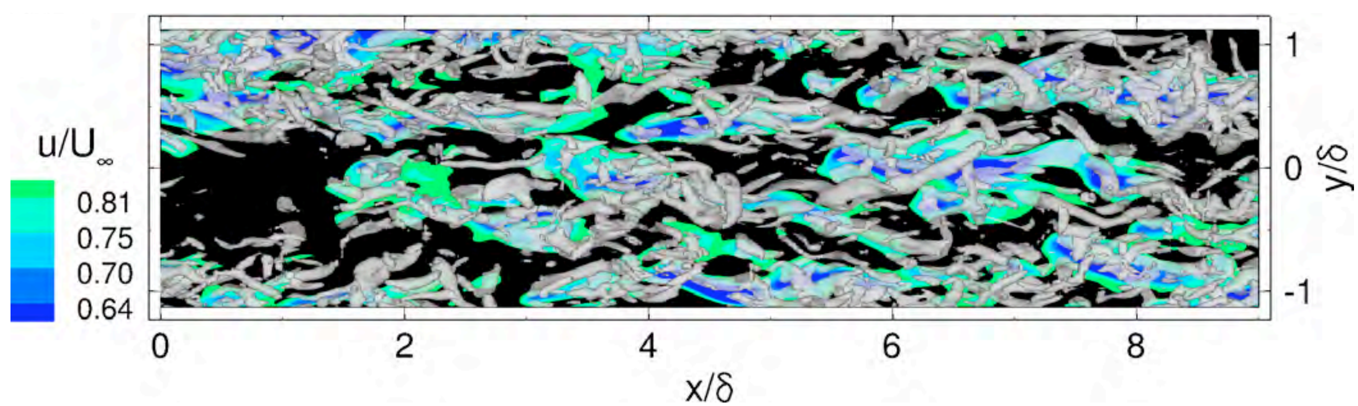
Instantaneous volume visualization connecting low-speed superstructures with "geometric" hairpin packets
Contours of velocity (for $u < \overline{U}_{\text{packet}}$)
Ticks mark location of hairpin vortices belonging to "geometric" packets

Mach 4
Re_θ=3400



Similar to above with color contours and
iso-surface of swirling strength at 3.5 times the time and volume averaged

Mach 8
Re_θ=5700



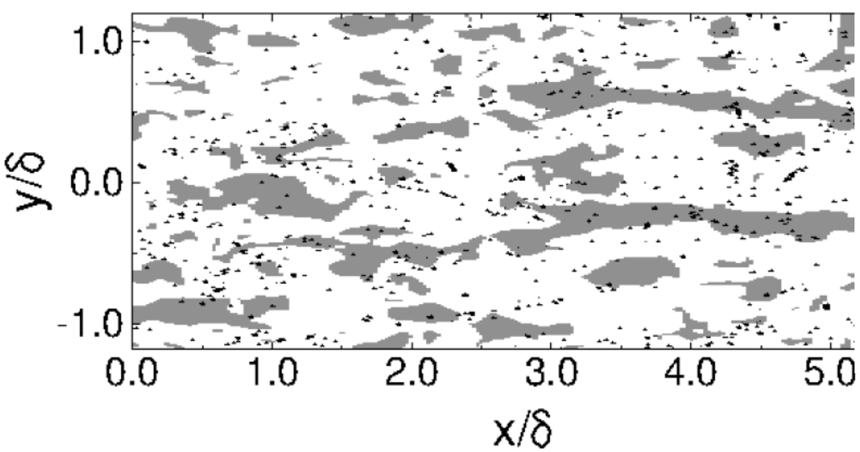
Analytic Tools

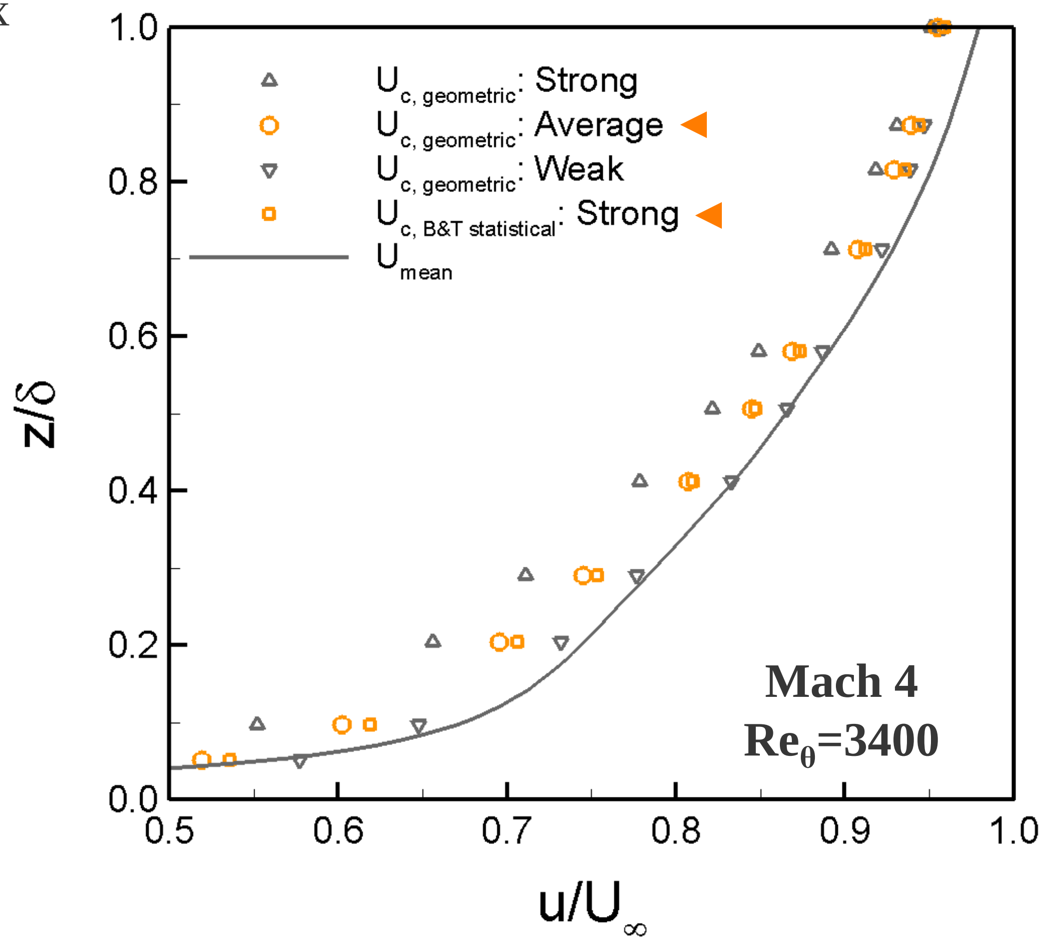
Part III: Relationship between geometric and correlation analysis

O'Farrell & Martin, JoT 2009

Right: Strong, average, and weak vortex convection velocity profiles for geometrically ideal packets, vortex convection velocity profile for all statistically strong events, and mean flow velocity profile.

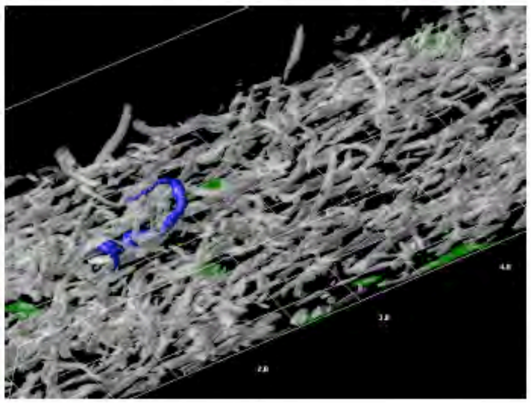
Below: Regions of elevated Brown and Thomas correlations (gray) and 'geometric' events at the wall



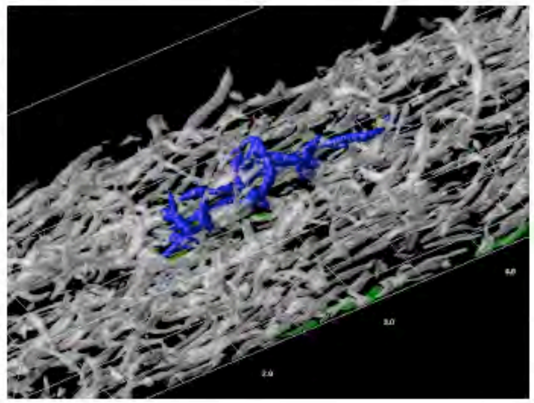


Analytic Tools

Part IV: Packet Tracking



1



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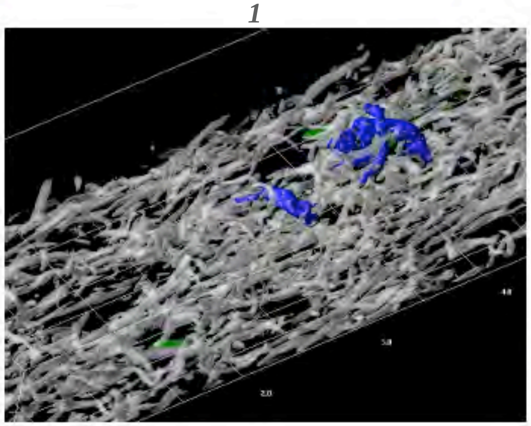

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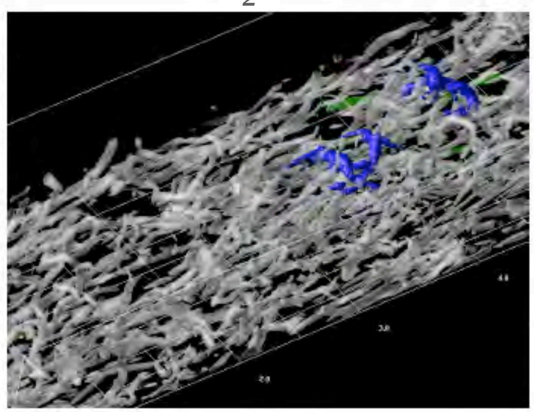
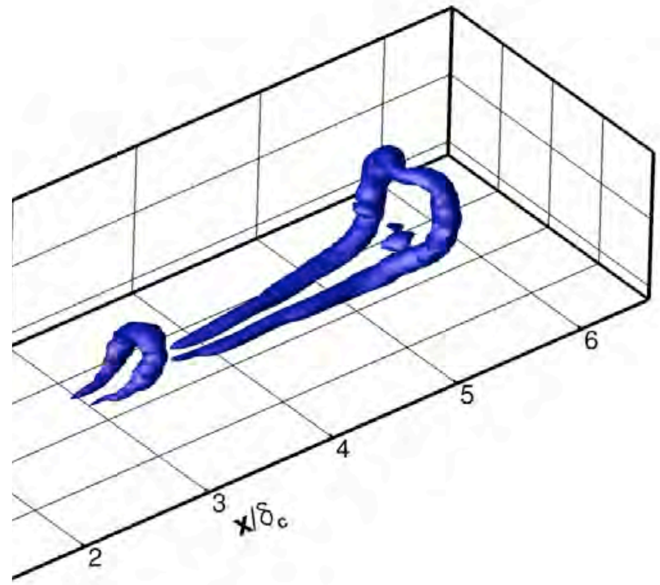


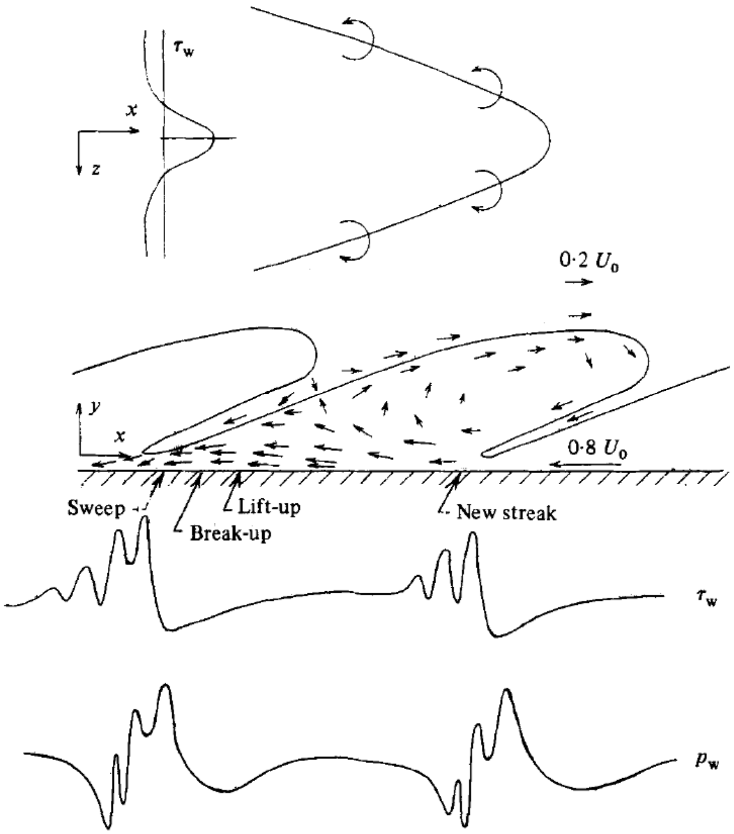
4

Tracking a hairpin packet in a mach 3 turbulent boundary layer. (Using Ostrck 2.0 software, c.f. Wang, X. and Silver, D., "Tracking and Visualizing Turbulent 3D Features," IEEE, 1997)
O'Farrell & Martin, JoT 2009

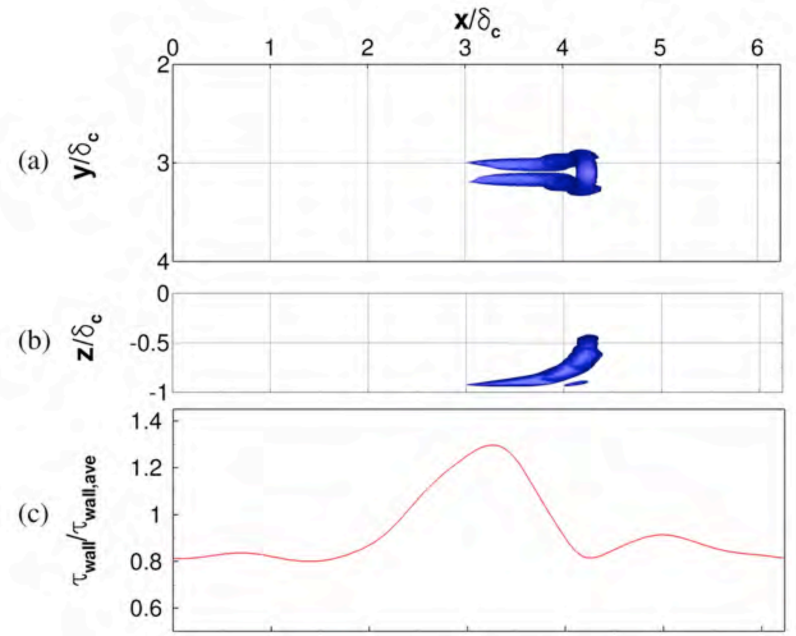


Tracking a lone hairpin and the hairpins it spawns to form a packet in an incompressible channel flow (DNS). (After O'Farrell senior thesis, 2008, Princeton University; data courtesy of Green, Rowley & Haller, JFM 2007)

Analytic Tools
Part V: Packet Wall Signatures



Hairpin packet model and wall associated signatures theorized by Thomas and Bull.after Brown and Thomas (Thomas & Bull, JFM 1983, Brown & Thomas PoF 1977)



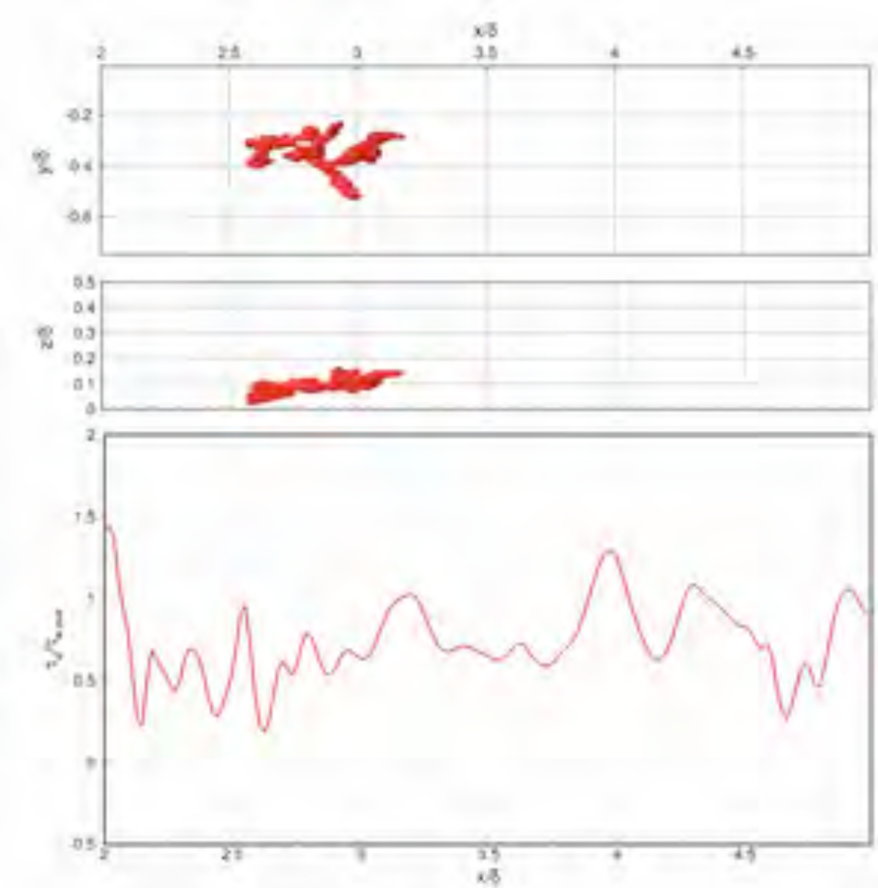
A lone, synthetically generated hairpin vortex and associated wall signature in incompressible channel flow. (After O'Farrell senior thesis, Princeton University, 2008; data courtesy of Green, Rowley & Haller, JFM 2007)

Identification and Tracking of Hairpin Packets

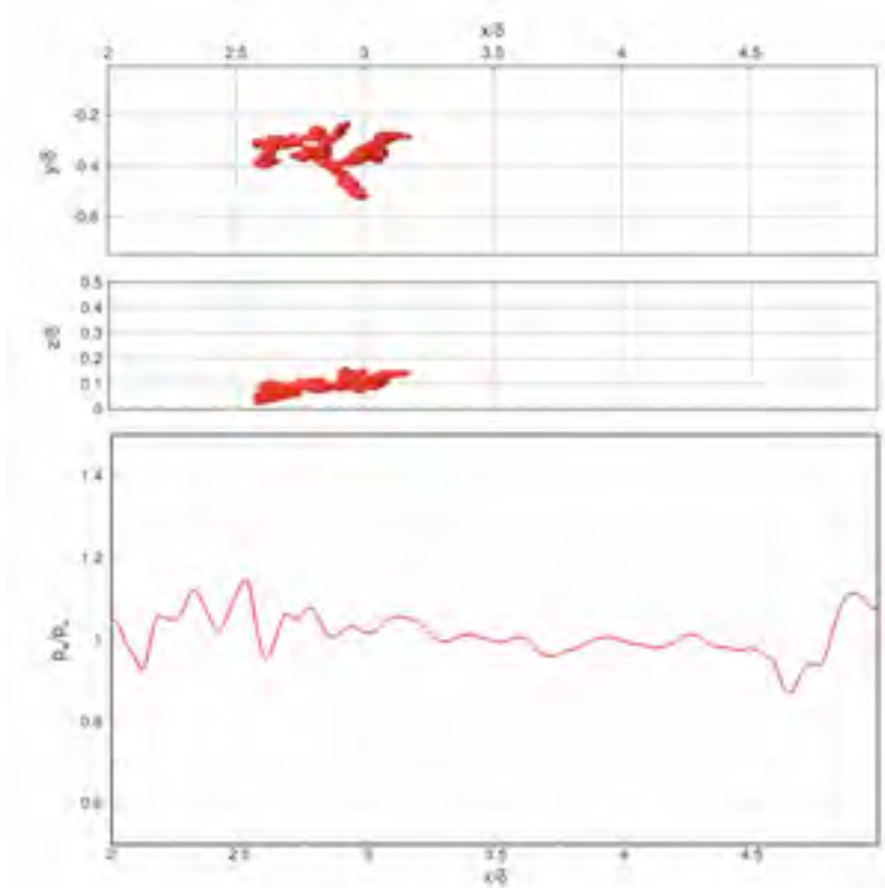
DNS of Mach 4 turbulent boundary layer

Wall signatures

Shear stress



Pressure



Signals taken at y/δ = -0.35

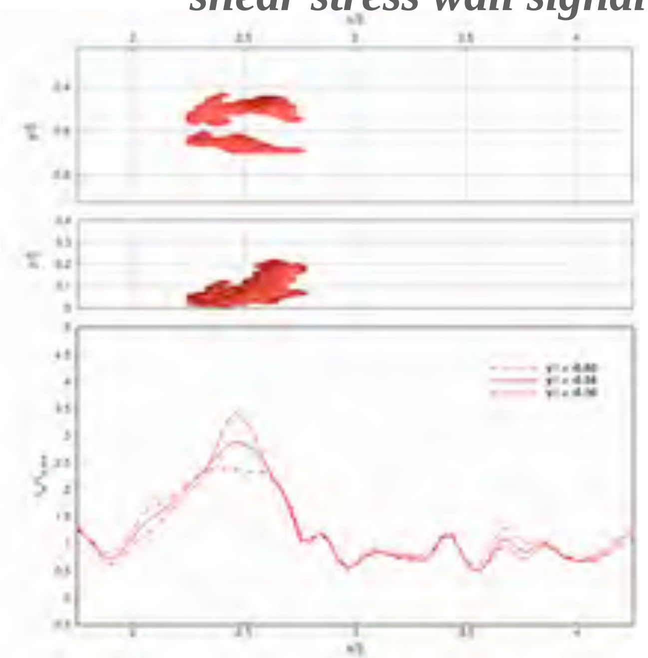
Identification and Tracking of Hairpin Packets

DNS of Mach 8 turbulent boundary layer

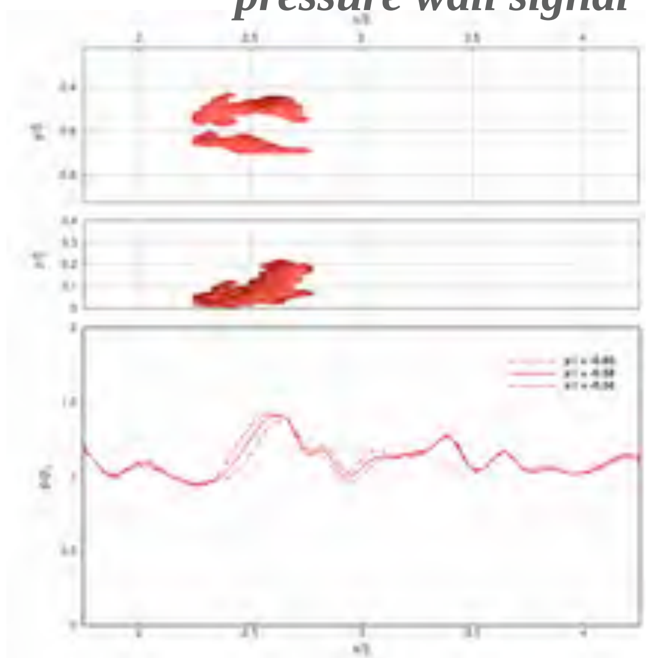
Wall signatures

Mach 8 Re_θ 5400

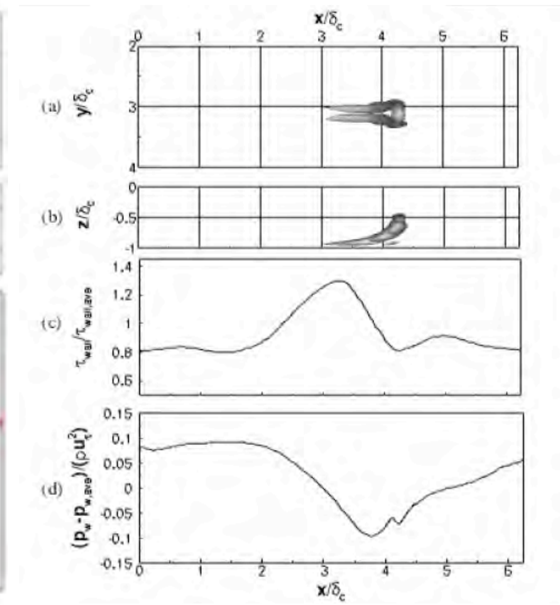
shear stress wall signal



pressure wall signal



Synthetically generated hairpin in incompressible channel flow



Taken from O'Farrell, Senior Thesis, Princeton Univ. 2008

Other On-Going Work

Flow physics

- Completed reports on statistics
  - PART I: Initialization and validation, JFM 2007
  - PART II: Heat Transfer Effects, JFM 2009 with Duan & Beekman
  - PART III: March Number Effects, under consideration JFM, with Duan & Beekman
- Reporting:
  - Real gas effects, wall catalytic effects, with Duan
  - Radiation emission effects, under consideration AIAAJ, with Duan, Levin and Modest
- Studying turbulence structure origins and evolution

  Heat transfer effects, Mach number effects, with Beekman & Priebe
- Roughness and transpiration studies, joined experiments and simulations with Beekman

  experimental collaboration with A.J. Smits at Princeton
- Robust/validated large-eddy simulation methodologies for high Mach number and high temperature flow physics, with Grube

Conclusion

Turbulent hypersonic flows

- There are abundant physical phenomena that remain unexplored

- Developed numerical methods and methodologies
  - Accurate numerical solutions are possible
  - Parametric studies are feasible
  - Developing analytical tools for data interpretation

- Numerical error is within experimental uncertainty

- Simulation run time is of the order of the experiment turn-around time

- Detailed data is a terrific playground for developing ***understanding*** and ***predictive capabilities for large-scale calculations***

Timely opportunity to make significant advances in this area