Reducing Turbulence- and Transition-Driven Uncertainty in Aerothermodynamic Heating Predictions for Blunt-Bodied Reentry Vehicles

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Thank you

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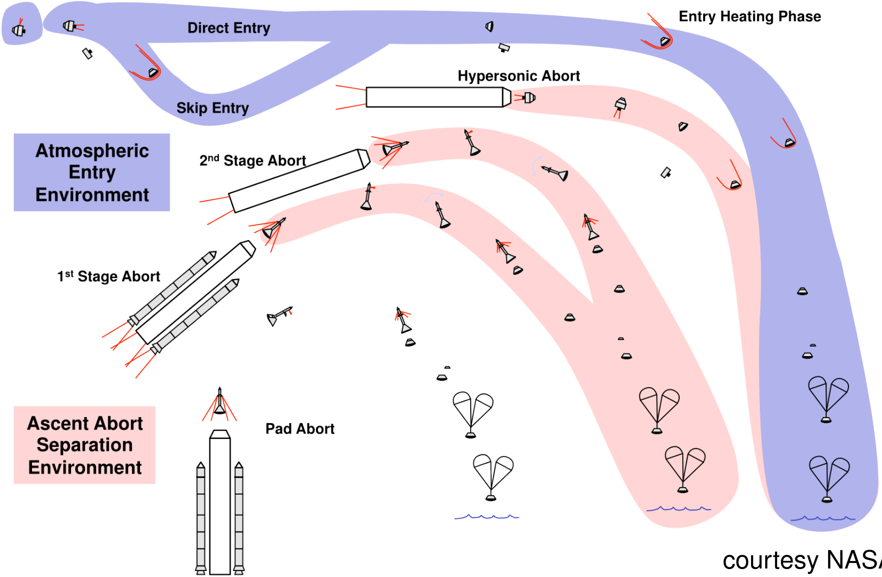
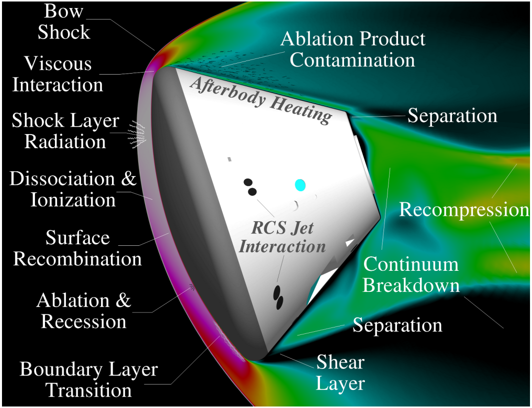
Michelle, Ozark, & Oxford

Outline

NASA Orion Multi-Purpose Crew Vehicle (MPCV)

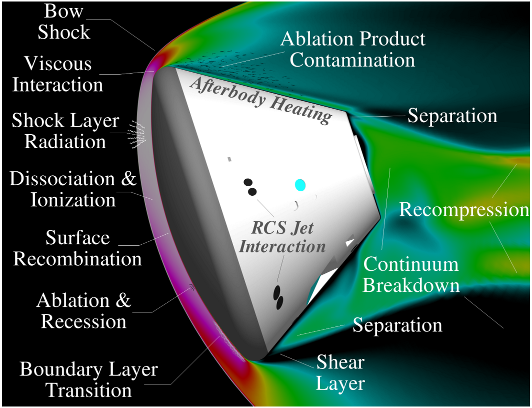


courtesy NASA



Survival of a blunt-bodied reentry vehicle depends upon

- Recession rate of ablative thermal protection system (throughout peak heating regime of flight trajectory)
- Local peak heat flux to after-body



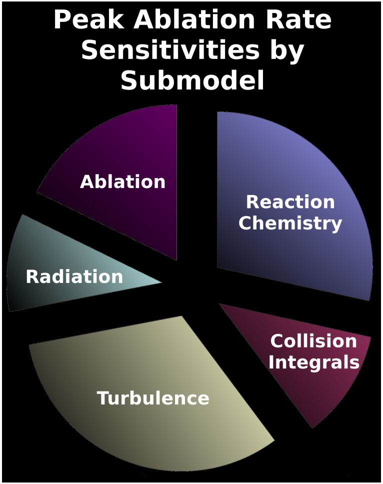
Among other things, ablation rate depends upon

Turbulence Relative to laminar behavior, turbulent mixing intensifies heating by enhancing momentum, energy, and chemical species transport

Transition Transition from laminar-to-turbulent flow determines where exactly this intensified heating occurs on the ablative heat shield

Outline

Ablation rate predictions highly sensitive to turbulence and therefore highly dependent on calibration data



from Stogner et al. [2011]

Eddy viscosity-based turbulence models widely used in engineering:

- Models well-known to be imperfect and unreliable
- Higher-fidelity approaches computationally intractable

Turbulence models contain imperfectly known parameters

- Must be calibrated using relevant, trusted data
- Prediction uncertainty limited by effectiveness of calibration

Effective calibration demands high-quality data but data relevant to blunt-bodied vehicle reentry is scarce

High-quality data from the heating prediction scenario is nonexistent

Seek boundary layer data from conditions representative of reentry and use surface heat flux as a surrogate for ablation rate:

1. Cold wall
2. Wall blowing
3. Favorable pressure gradients
4. Chemically reacting species under high-enthalpy conditions
5. Convex surface curvature
6. Surface roughness

High-quality, Ma > 1 turbulent boundary layer data generally scarce
Scarcity compounded by adding any one of the above conditions

Direct numerical simulation (DNS)

DNS solves the complete Navier–Stokes equations:

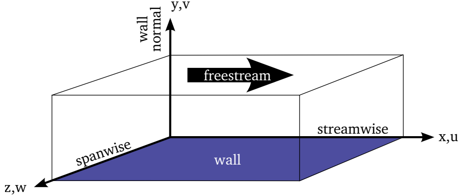
- Must resolve all scales of motion
- Becomes painfully expensive as Reynolds number increases
- Expense mainly comes from resolving small, dissipative scales

Isotropic DNS expense

L	Macro length scale
$\eta \equiv \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$	Kolmogorov scale
$N \sim \frac{L}{\eta} \sim \mathrm{Re}_L{}^{3/4}$	1D resolution
$N^3 \sim \mathrm{Re}_L{}^{9/4}$	3D resolution
$\mathrm{Re}_L{}^4$	3D w/ CFL

Reentry scenario is accessible by DNS: $\mathrm{Re}_\theta \lesssim 700$

Spatially evolving boundary layer simulations are difficult



- One must somehow specify inflow behavior:
  - Tripping a laminar profile to force transition (e.g. Wu et al. [1999])
  - Generate an approximately turbulent profile (e.g. Lund et al. [1998])
  - Recycle from elsewhere in the simulation (e.g. Simens et al. [2009])
  - Perform an auxiliary simulation to obtain an inflow profile
- All choices require time before the profile “relaxes” to the right state
- Schlatter and Örlü [2010] assessed low-Re simulations[1] finding “. . . surprisingly inconsistent predictions. . . ”

[1] Ferrante and Elghobashi [2005], Khujadze and Oberlack [2004, 2007], Komminaho and Skote [2002], Schlatter et al. [2009a,b], Simens et al. [2009], Spalart [1988], Wu and Moin [2009]

Research Objective

Reduce turbulence-driven uncertainty by generating high-quality turbulent boundary layer calibration data for

- Cold wall
- Wall blowing
- Favorable pressure gradients

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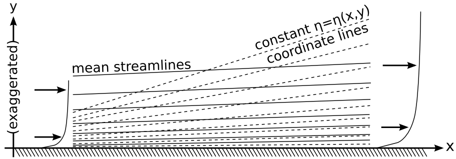
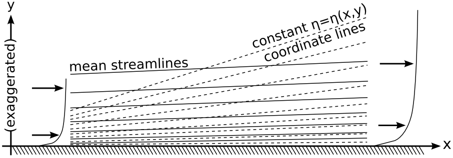
Outline

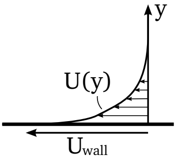
Homogenized boundary layer simulations are less difficult



- Spalart [1988] observed layer thickness and energy vary slowly in x
  - Separated “slow” and “fast” spatial evolution
  - Fast evolution assumed periodic— no need to specify inflow behavior
  - Modeled impact of resulting “slow growth” terms on a “fast” simulation
  - Guarini [1998] extended technique to compressible case
- Two periodic directions entirely sidesteps subtle inflow conditions
  $\Longrightarrow$ spectral techniques, smaller sampling error $\Longrightarrow$ reduced uncertainty
- Spatial homogenization not suited to calibrating off-the-shelf models

Homogenized boundary layer simulations are less difficult





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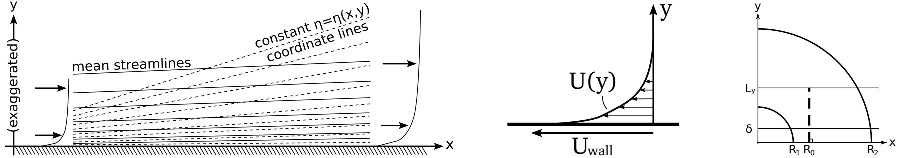

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- Topalian et al. [2011] temporally homogenized Rayleigh's problem
- Topalian et al. [2014a] spatiotemporal extension
  adds "inviscid base flow" terms permitting pressure gradients

Compressible Navier–Stokes formulation

$$
\begin{aligned}
\frac{\partial}{\partial t}\rho &= -\nabla\cdot\rho u + \mathcal{S}_{\rho} \\
\frac{\partial}{\partial t}\rho u &= -\nabla\cdot(u\otimes\rho u) - \frac{1}{\mathrm{Ma}^2}\nabla p + \frac{1}{\mathrm{Re}}\nabla\cdot\tau + f + \mathcal{S}_{\rho u} \\
\frac{\partial}{\partial t}\rho E &= -\nabla\cdot\rho E u + \frac{1}{\mathrm{Re}\,\mathrm{Pr}\,(\gamma-1)}\nabla\cdot\mu\nabla T \\
&\qquad - \nabla\cdot p u + \frac{\mathrm{Ma}^2}{\mathrm{Re}}\nabla\cdot\tau u + \mathrm{Ma}^2 f\cdot u + q_b + \mathcal{S}_{\rho E}
\end{aligned}
$$

$$p = (\gamma-1)\left(\rho E - \frac{\mathrm{Ma}^2}{2}\rho u^2\right) \qquad T = \gamma\frac{p}{\rho}$$

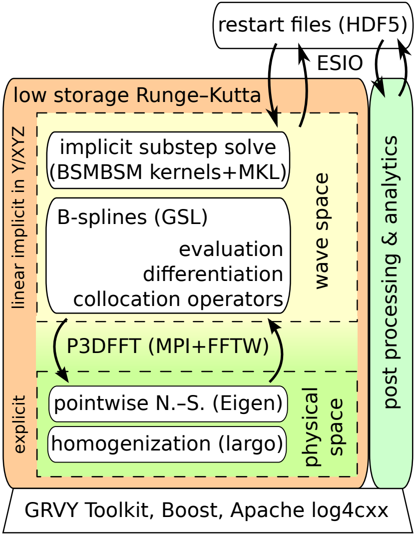
$$\mu = T^{\beta} \qquad \lambda = \left(\alpha - \frac{2}{3}\right)\mu \qquad \tau = \mu\left(\nabla u + \nabla u^{\mathsf{T}}\right) + \lambda\left(\nabla\cdot u\right) I$$

$$\mathrm{Re} = \frac{\rho_0 u_0 l_0}{\mu_0} \qquad \mathrm{Ma} = \frac{u_0}{a_0} \qquad \mathrm{Pr} = \frac{\mu_0 C_p}{\kappa_0} \qquad \mathrm{Kn} = \frac{\mathrm{Ma}}{\mathrm{Re}}\sqrt{\frac{\gamma\pi}{2}}$$

Suzerain: a new spectral, compressible DNS framework

http://github.com/RhysU/suzerain

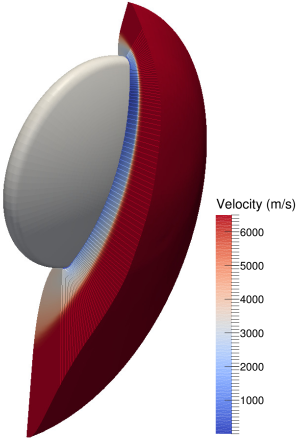
- “Clean room” C99/C++03 implementation built as long-lived, extensible research platform
- Fourier–Galerkin, B-spline collocation spatial scheme
- Hybrid implicit/explicit, low-storage temporal scheme [Spalart et al., 1991]
- Automated test suite and MMS-based verification [Ulerich et al., 2012]
- *In situ* statistics collection and post-processing
- Autoregressive-based uncertainty estimation per Oliver et al. [2014]



Outline

Fully turbulent Orion MPCV from Bauman et al. [2011]

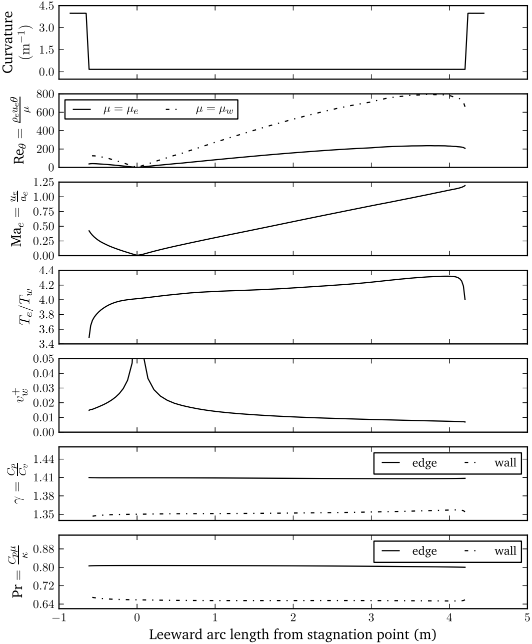
Translated to $\gamma = 1.4$ air holding Ma_e constant. Reduction by O. Sahni & V. Topalian.



$\mathrm{Re}_\theta = \frac{\rho_e u_e \theta}{\mu_e}$	$\mathrm{Ma}_e = \frac{u_e}{a_e}$	$\beta = \frac{\delta^*}{\tau_w}\left(\frac{\partial p}{\partial \xi}\right)_e$
391	0.88	-0.81
440	0.99	-0.81
511	1.09	-0.93
520	1.15	-0.92
526	1.19	-0.94

Fully laminar Orion MPCV

Data courtesy of P. Bauman
Reduction in present work



New Direct Numerical Simulations

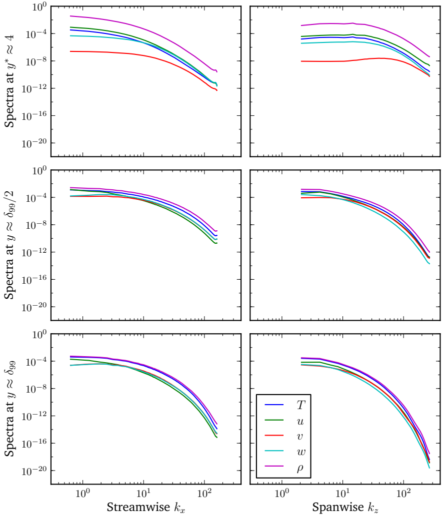
Domain is $10\delta \times 2.5\delta \times 3\delta$ with $512 \times 256 \times 256$ expansion coefficients for 168M DOF

Case	Re_θ	Ma_{99}	T_{99}/T_w	$v_w^+ = v_w/u_\tau$	$p^*_{99,\xi} = \frac{\delta_{99}(\partial_x p)_{99}}{\rho_{99} u_{99}^2}$
t3.199	382	0.904	4.13	$8.52\mathrm{e}{-3}$	-0.010
t4.134	531	1.152	4.20	$7.18\mathrm{e}{-3}$	-0.012

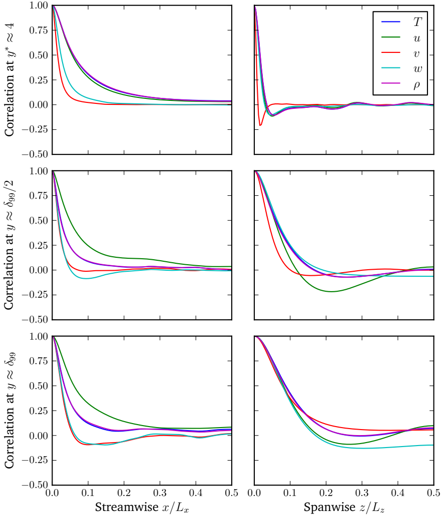
Case	Δx^+	y_1^+	y_{10}^+	Δz^+	Eddy Turnovers
t3.199	13.9	0.14	6.1	8.4	6.4
t4.134	19.0	0.17	7.2	11.4	6.9
Coleman et al. [1995]	17	0.1	8	10	—

Resolution assessment for simulation t3.199

Compares favorably with Coleman et al. [1995] and Guarini et al. [2000]



Spectra

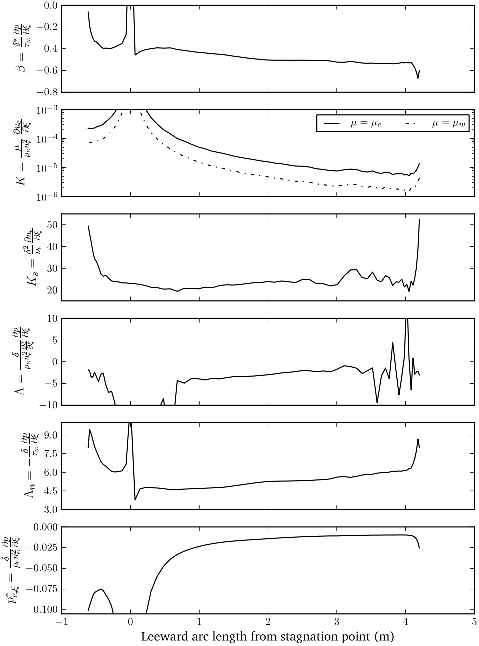


Two-point correlations

Fully laminar Orion MPCV

Pressure gradient characterization

- β Clauser [1954]
- K Launder [1964]
- K_s Pohlhausen [1921]
- Λ Cal and Castillo [2008]
- Λ_n Narasimha and Sreenivasan [1979]
- $p^*_{e,\xi}$ New parameter in present work



Functionals of Interest from the New Simulations

Case	$K, \mu = \mu_{99}$	$K, \mu = \mu_w$	K_s	Λ_n
t3.199	$4.18\mathrm{e}{-6}$	$1.62\mathrm{e}{-6}$	25.4	3.35
Laminar MPCV	$8.84\mathrm{e}{-6}$	$2.64\mathrm{e}{-6}$	29.3	5.60
t4.134	$3.73\mathrm{e}{-6}$	$1.43\mathrm{e}{-6}$	41.8	4.11
Laminar MPCV	$6.95\mathrm{e}{-6}$	$2.08\mathrm{e}{-6}$	25.7	7.12

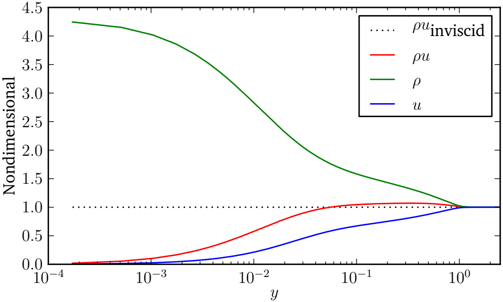
Case	Re_{99}	Re_τ	Ma_τ	c_f	$-B_q$	Nu_{99}
t3.199	2468	714	0.0501	$6.13\mathrm{e}{-3}$	0.0977	15.6
t4.134	3346	976	0.0631	$5.99\mathrm{e}{-3}$	0.102	21.7

$$c_f = \frac{2\tau_w}{\rho_{99} u_{99}^2} \qquad B_q = -\frac{\mu_w \left(\partial_y T\right)_w}{\mathrm{Pr}\,\rho_w u_\tau T_w} \qquad \mathrm{Nu}_{99} = \frac{\delta_{99}\left(\partial_y T\right)_w}{T_{99} - T_w}$$

Integral Thicknesses and the Clauser Parameter

Case	δ^*/δ_{99}	Re_{δ^*}	θ/δ_{99}	$H = \delta^*/\theta$	β
t3.199	0.00643	15.8	0.156	0.0413	-0.0215
t4.134	-0.0392	-129	0.161	-0.243	0.161
Turbulent MPCV	0.113	406	0.134	0.847	-0.88

$$\delta^* = \int_0^{L_y} \frac{\rho u_{\text{inviscid}} - \rho u}{\rho u_{\text{inviscid}}} \,\mathrm{d}y$$

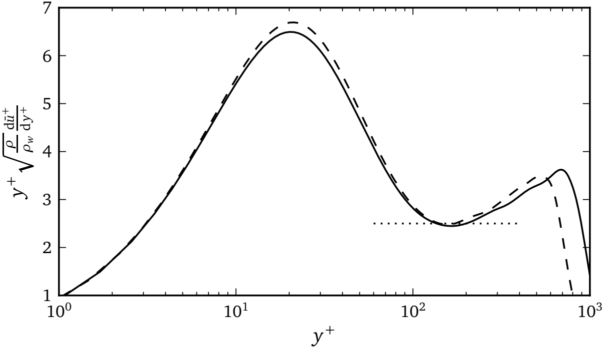


Case t4.134

Outline

Inner scaling for simulations t3.199 and t4.134

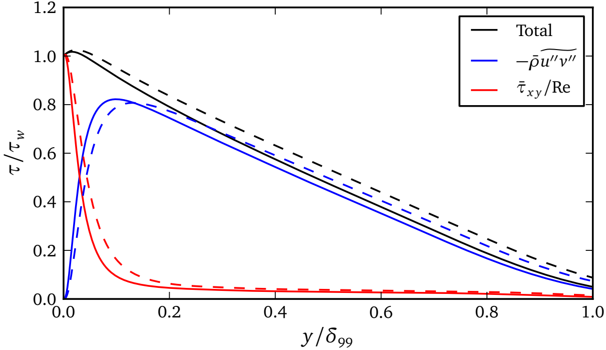
Viscous sublayer and buffer layer but no logarithmic region due to low Re_θ



Case t3.199 (dashed) and t4.134 (solid)

Stress contributions to the streamwise momentum

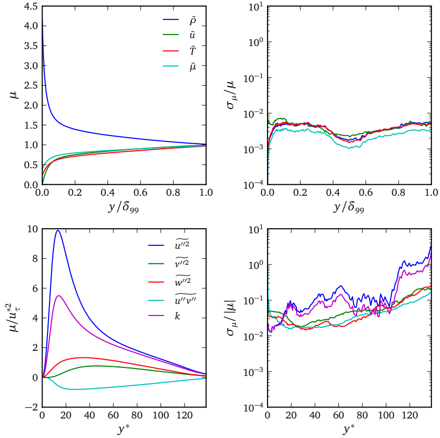
Reduced maximum relative to Topalian et al. [2014b] due to favorable pressure gradient



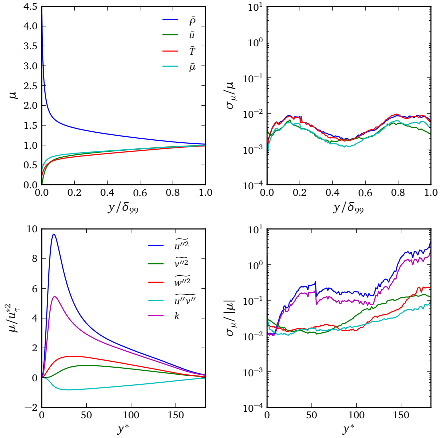
Case t3.199 (dashed) and t4.134 (solid)

Primitive and Reynolds stress profiles with uncertainty

Maximum $\widetilde{u''^2}$ higher than Coleman et al. [1995], Guarini et al. [2000] consistent with wall blowing [Sumitani and Kasagi, 1995]



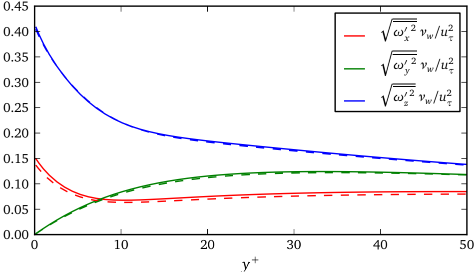
Case t3.199

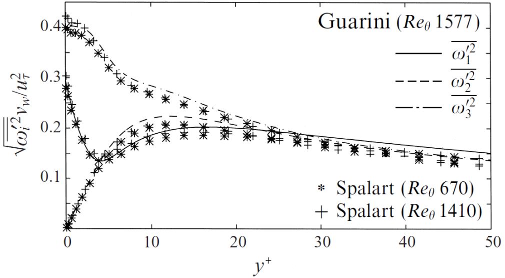


Case t4.134

Near-wall, root-mean-squared vorticity fluctuations

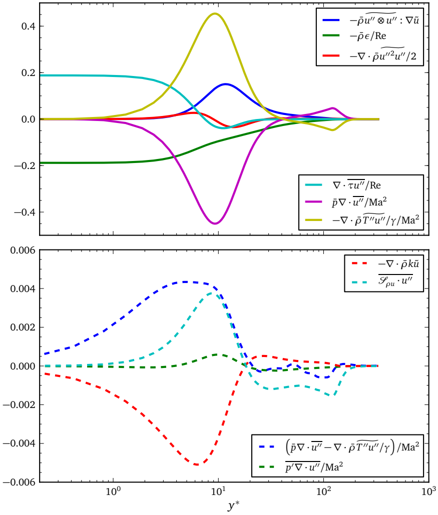
Vs adiabatic-wall, Ma $= 2.5$ by Guarini et al. [2000] and incompressible by Spalart [1988]





Turbulent kinetic energy budgets

Peak production lower than 0.25 found by Schlatter et al. [2009b] from ZPG at $\mathrm{Re}_\theta = 670$



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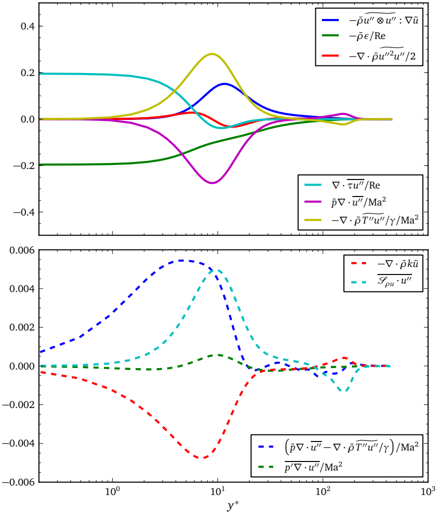


Case t4.134

Conclusions

1. Created a new, well-verified, openly available Fourier/B-spline DNS framework already reused, in part or in full, by Lee and Moser, Lee et al. [2013, 2014], Malaya et al. [2012], Oliver et al. [2014], Topalian et al. [2013, 2014a,b]
2. Generated new, openly available DNS data with well-quantified certainties suitable for modeling and calibration purposes
3. Simulations show significant cold wall, wall blowing, and favorable pressure gradient effects
4. Near-wall vorticity fluctuations exhibit qualitatively different behavior than observed by Guarini et al. [2000] or Spalart [1988]
5. Small or negative displacement thicknesses present because of the cold wall
6. Turbulent kinetic energy budget supports notion that spatiotemporally homogenized flows can serve as a convenient model problem for calibration

Outline

Ablation rate predictions are sensitive to transition and transition is sensitive to upstream environment

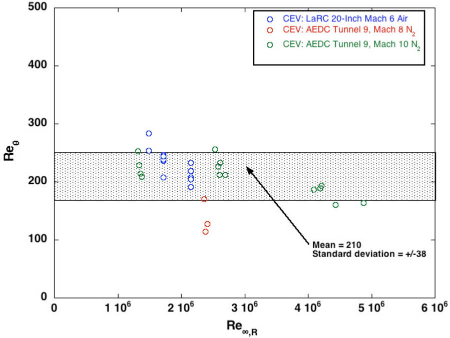
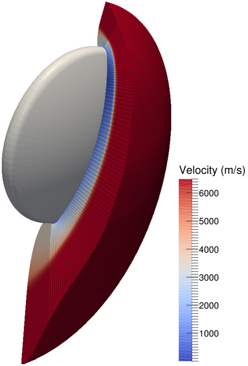


Figure 22. Transition onset values of Re_θ

"Because of the challenges associated with analysis of all the possible transition mechanisms, it is the defined policy of the [Orion MPCV] program to make a conservative assumption that the vehicle will experience turbulent flow throughout its trajectory."

from Hollis et al. [2008]



Q Where has transition occurred?

A It depends. . .

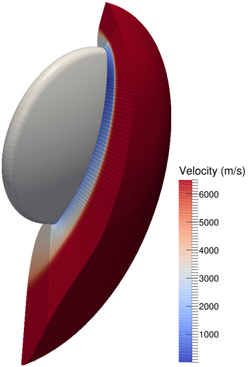
- Freestream perturbation level
- Details of the bow shock
- Aerothermochemistry
- Outgassing of ablation products
- Ablator roughness due to fibrosity, spallation

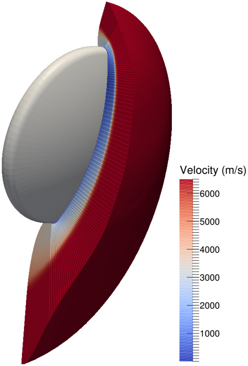
The heat shield is an incredibly noisy environment

The unknowable details of that noise thwart answering this question well, let alone with much certainty

For this reason, Orion MPCV project takes a conservative, assumed-turbulent approach

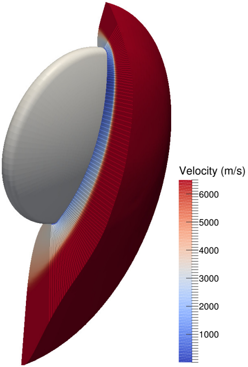
Q Where hasn't transition occurred?





Q Where hasn’t transition occurred?

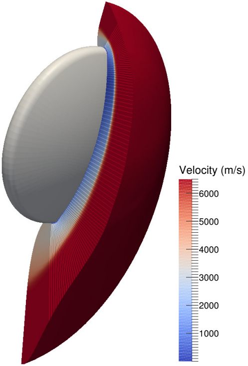
A The neighborhood of the stagnation point



Q Where hasn't transition occurred?

A The neighborhood of the stagnation point

A Wherever local conditions can't sustain turbulence



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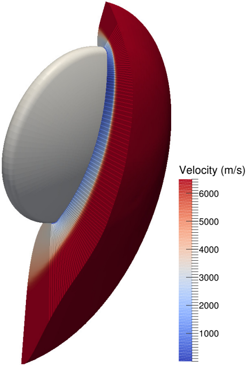
1. Turbulent boundary layer relaminarizes

   Schraub and Kline [1965], Blackwelder and Kovasznay [1972], Narasimha and Sreenivasan [1973], Narasimha and Sreenivasan [1979], Sreenivasan [1982], Iida and Nagano [1998], Ichimiya et al. [1998], Talamelli et al. [2002], Mukund et al. [2006], Cal and Castillo [2008], Bourassa and Thomas [2009]



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2. Self-sustaining, nontrivial fluctuations can be found

   Akin to being unstable per energy perturbation arguments

Stability of fluids to arbitrary disturbances (Serrin [1959])

Incompressible Navier–Stokes equations with prescribed boundary

$$\begin{aligned} \partial_t v + \nabla \cdot v \otimes v &= -\rho^{-1} \nabla p + \nu \Delta v + f & p, v &\in \Omega, \\ v &= v_0 & v &\in \partial\Omega \end{aligned}$$

For any admissible v', the perturbation $u = v' - v$ satisfies

$$\begin{aligned} \partial_t u &= \partial_t v' - \partial_t v & u &\in \Omega, \\ u &= 0 & u &\in \partial\Omega \end{aligned}$$

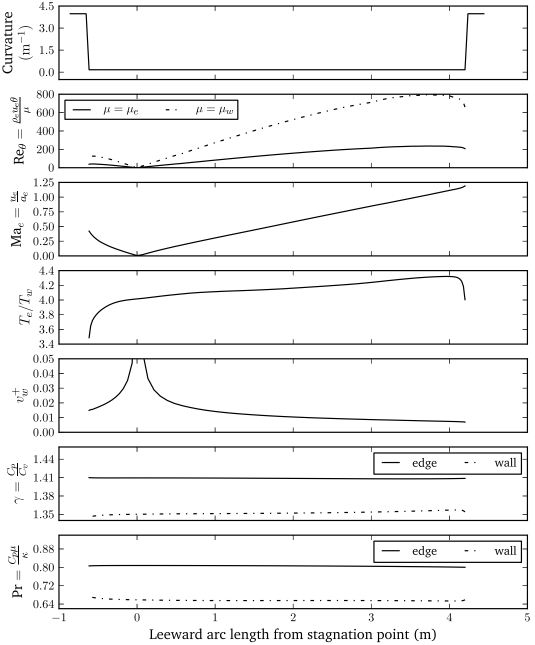
Smoothness and R.T.T. $\implies$ perturbation energy $E = u^2/2$ obeys

$$\frac{\mathrm{d}}{\mathrm{d}t} \int_\Omega E = \int_\Omega \left(u \cdot \left[\frac{1}{2} \left(\nabla v + \nabla v^{\mathsf{T}} \right) \right] \cdot u - \mathrm{Re}^{-1} \nabla u : \nabla u \right)$$

Theory extended by Joseph [1965, 1966], Dudis and Davis [1971a,b], Davis and Kerczek [1973], Galdi and Rionero [1983], Maremonti [1984], Galdi and Straughan [1985], Galdi and Padula [1990], Padula and Pileckas [1997], Padula [2000], Padula [2011]

Research Objective

Reduce transition-driven uncertainty by detecting the regions on an ablative heat shield that can sustain turbulence



Outline

Local conditions from the fully laminar Orion MPCV

Location	Re_θ	Ma_e	T_e/T_w	v_w^+	$p_{e,\xi}^*$
4.134 m	223	1.15	4.29	0.00718	-0.0123
3.199 m	225	0.899	4.26	0.00839	-0.0102
2.299 m	177	0.660	4.18	0.00977	-0.0127
1.389 m	114	0.411	4.13	0.0123	-0.0179

Coarse simulations ($\Delta x^+ \approx 30$) sustained fluctuations at each location:

- Coarse grids suppress proper dissipation of turbulent kinetic energy
- Stationary turbulent production, Reynolds stresses, skin friction, etc.
- Stationary boundary layer thickness such that domain was $10\delta \times 2.5\delta \times 3\delta$
- Long correlations relative to δ unlike real turbulent boundary layers
- These fields are "admissible v'" per the energy perturbation method

Location 4.134 m

$\Delta x^+ \approx 18.7$ and $\Delta z^+ \approx 11.2$

Refinement to production resolution at $t = 0$

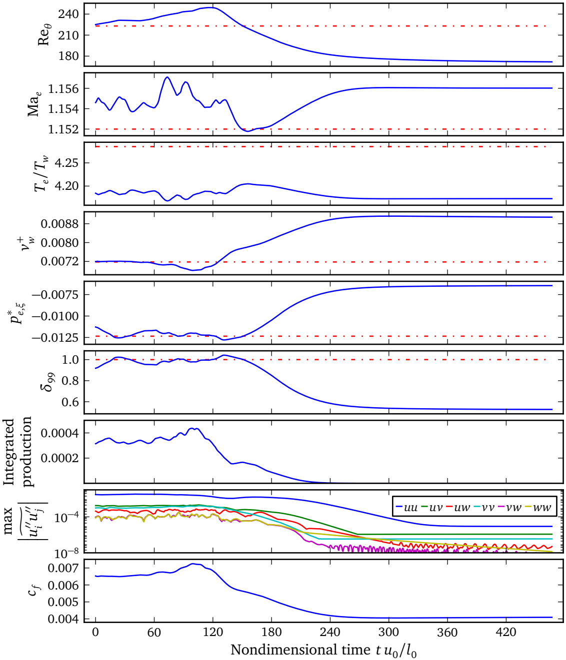
Mean freestream flow traverses L_x roughly every $\Delta t = 10$.

Relaminarizes like a spatially evolving boundary layer [Cal and Castillo, 2008] after O(6) eddy turnovers

Integrated production

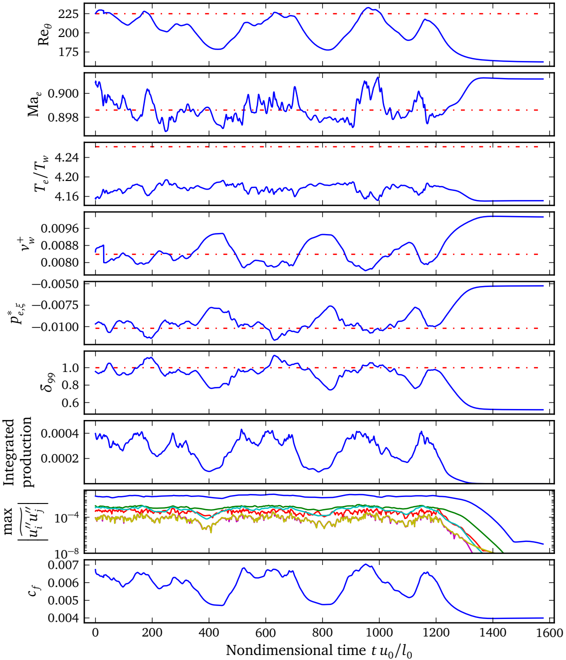
$$= \frac{1}{L_y} \int_0^{L_y} -\bar{\rho} \widetilde{u'' \otimes u''} : \nabla \tilde{u} \, dy$$

Reaches "quasi-laminar" state [Sreenivasan, 1982]



Location 3.199 m

$\Delta x^+ \approx 18.0$ and $\Delta z^+ \approx 10.8$

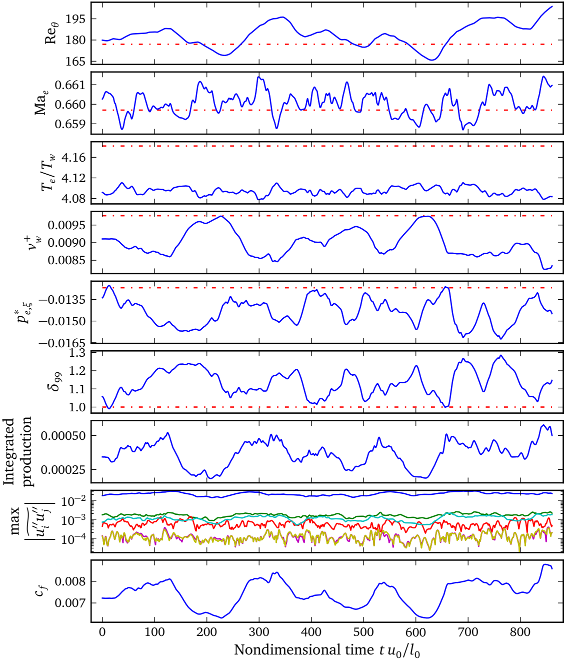


Several intermittent dips in production

Finally decays after O(36) eddy turnovers

Location 2.299 m

$\Delta x^+ \approx 14.1$ and $\Delta z^+ \approx 8.5$



Intermittent dips in production

Sustains fluctuations for O(23) eddy turnovers

v_w^+, $p^*_{e,\xi}$, and δ_{99} off target

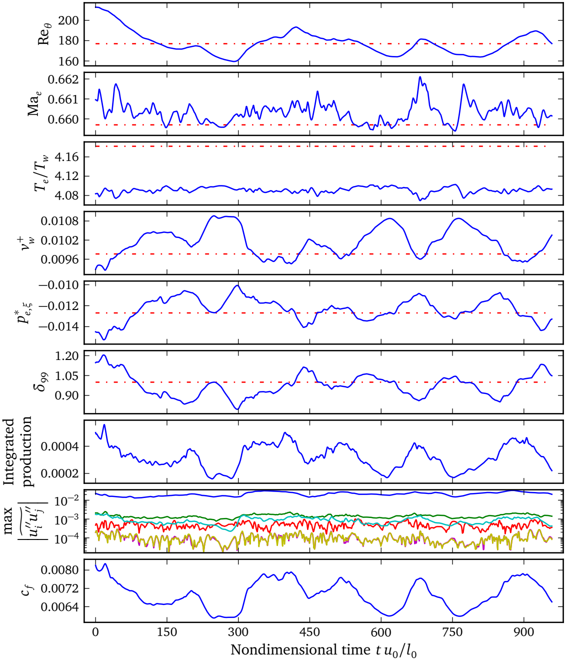
Location 2.299 m

$\Delta x^+ \approx 14.1$ and $\Delta z^+ \approx 8.5$ (Continued)

Corrected v_w^+, $p_{e,\xi}^*$, and δ_{99}

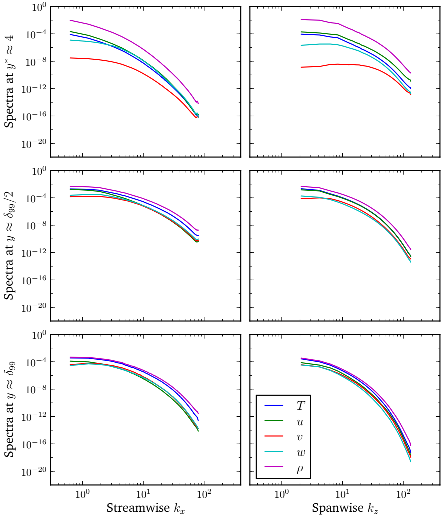
Sustains fluctuations for another O(23) eddy turnovers

What is this flow?

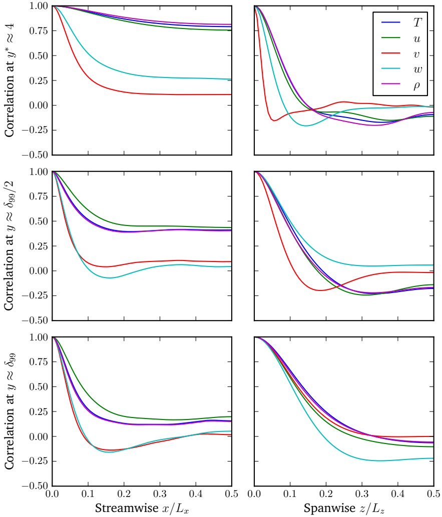


Assessing fluctuation-sustaining solution at 2.299 m

Well-resolved with large structures consistent w/ transitioning & marginally turbulent flows



Spectra

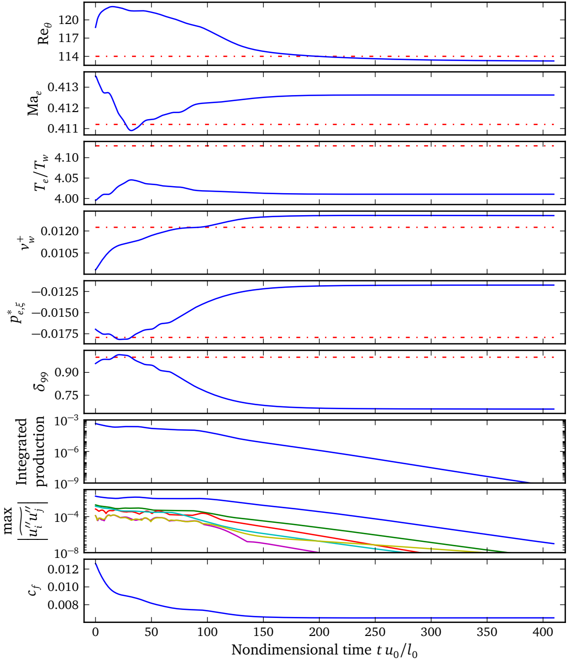


Two-point correlations

Location 1.389 m

$\Delta x^+ \approx 11.7$ and $\Delta z^+ \approx 7.0$

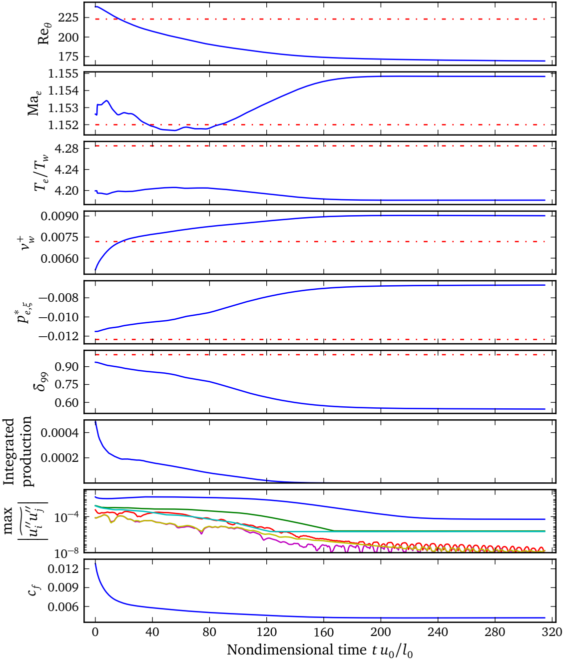
Fluctuations decay in under 3.6 turnovers



Outline

Location 4.134 m

$\Delta x^+ \approx 17.2$ and $\Delta z^+ \approx 10.3$



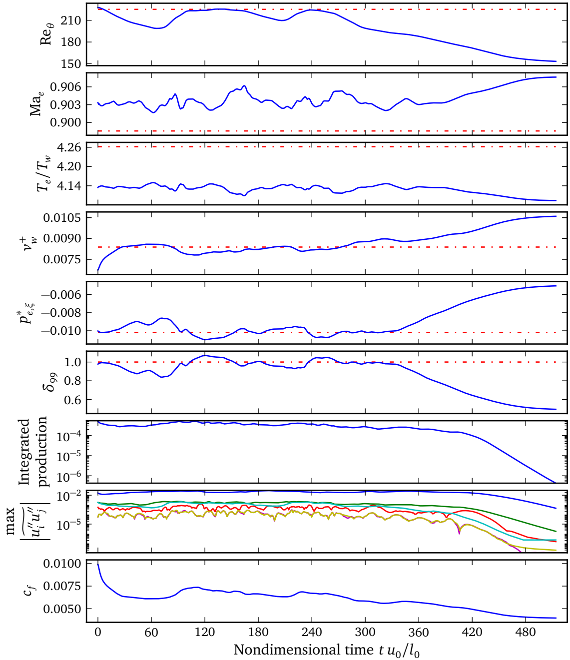
Initialized with fully turbulent field from prior study simulation t4.134

Changed Re at $t = 0$ so that Re_θ would be in vicinity of target value

Relaminarized in O(10) turnovers

Location 3.199 m

$\Delta x^+ \approx 13.2$ and $\Delta z^+ \approx 7.9$



Initialized with fully turbulent field from prior study simulation t3.199

Relaminarized in O(13) eddy turnovers

Longer “turbulent dwell” than 4.134 m, likely because of weaker pressure gradient

Outline

Recapping the observations:

- Locations 4.134 m and 3.199 m…
  - …relaminarized from "admissible v'" after 6 and 36 turnovers, respectively
  - …relaminarized from turbulent initial conditions after 10 and 13 turnovers
- Location 2.299 m sustained nontrivial fluctuations for 46 turnovers
- Location 1.389 m unable to sustain fluctuations

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- Simulations are periodic— perturbations never leave, only dissipate
- In flight, new perturbations continually arrive from upstream sources

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The turbulence-sustaining region is more than 1.389 m leeward of the Orion MPCV stagnation point during International Space Station return

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To conclude, a prediction:

The turbulence-sustaining region is more than 1.389 m leeward of the Orion MPCV stagnation point during International Space Station return[a]

[a] Assuming the present homogenized flows capture the turbulence-sustaining behavior of spatially evolving boundary layers (not validated in present work)

Research Summary

Reduced turbulence- and transition-driven uncertainty in aerothermodynamic heating predictions for blunt-bodied reentry vehicles. . .

1. Through direct numerical simulation, provided high-quality homogenized turbulent boundary layer data possessing
   - cold walls,
   - wall blowing, and
   - favorable pressure gradients

   which reduces turbulence-driven predictive uncertainty by allowing more effective model calibration.

2. Through examining a numerically accessible surrogate problem, reduced transition-driven uncertainty by providing new guidance about the regions on an ablative heat shield that should be modeled as turbulent— without requiring perturbations in the flight environment to be well-characterized.

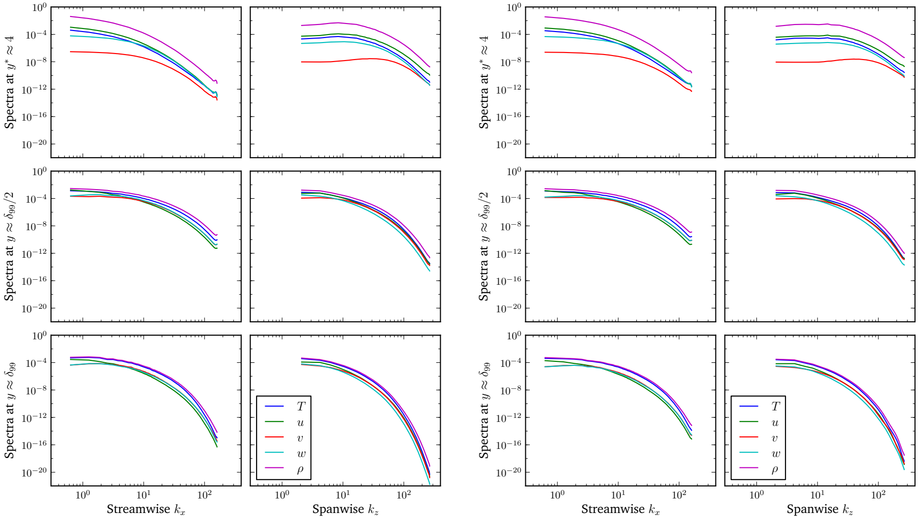
Future Work

1. Further investigate the basic character of boundary layers simulated using Topalian et al. [2014a]'s homogenization technique
    - Tease apart cold wall, transpiration, pressure gradient effects
    - Reduce homogenization to low Mach or incompressible limit
2. Recompute Orion MPCV solution tripping turbulence at location 1.389 m and compare predicted heat fluxes to measurements from NASA Exploration Flight Test 1 which launches in December 2014
3. Examine scenario variants which do sustain turbulence, given fully turbulent initial conditions, to interrogate flow physics and assess parameter sensitivity
4. Variety of DNS studies possible with current Suzerain capabilities, e.g.
    - Supersonic, isothermal wall homogenized boundary layers
    - Low Mach, homogenized boundary layers in adverse pressure gradients

Backup

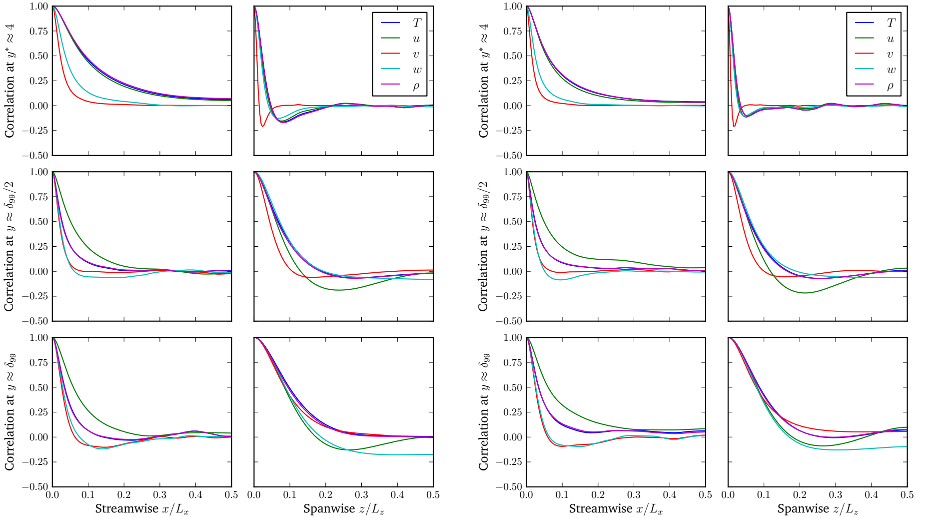
Spectra for simulations t3.199 and t4.134

Compares favorably with Coleman et al. [1995] and Guarini et al. [2000]

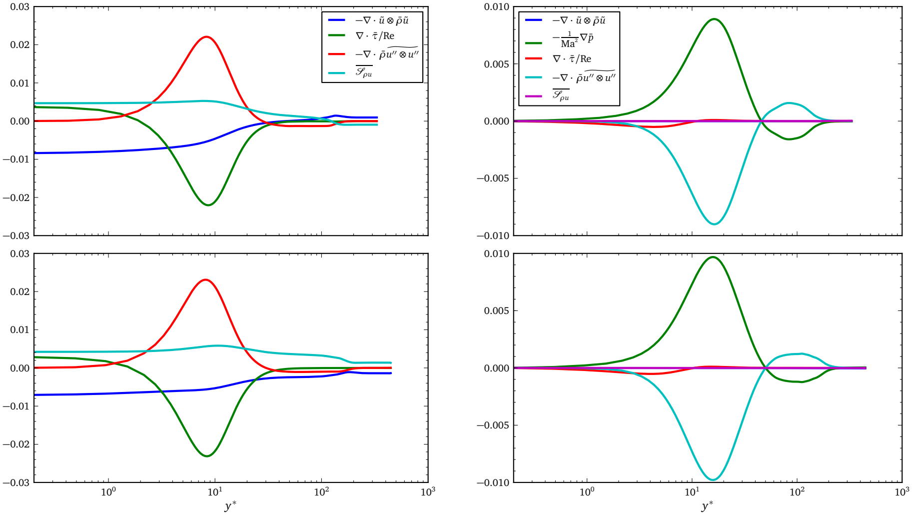


Two-point correlations for simulations t3.199 and t4.134

Compares favorably with Coleman et al. [1995] and Guarini et al. [2000]



Momentum budgets for t3.199 (upper) and t4.134 (lower)



Streamwise momentum, ρu

Wall-normal momentum, ρv

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