Numerical Challenges for DNS and LES of Highly Compressible Turbulence

M. Pino Martín

Princeton University
Mechanical and Aerospace Engineering Department

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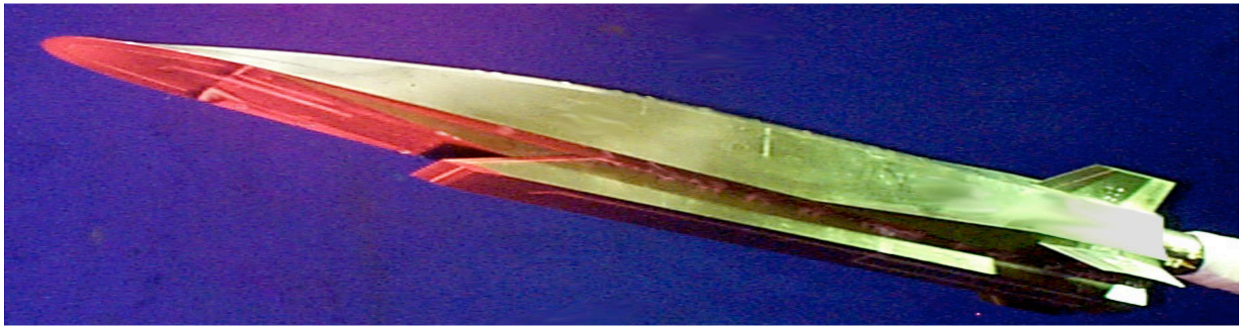
Foundational research issues

Enable the development of future hypersonic capabilities

Boeing-AF X-51A
Reusable launch vehicle



Research Approach and Goals

- Perform ***efficient*** 3D time/space accurate simulations including key physics
  - Unsteady shock wave phenomena
  - Finite-rate reactions
  - Gas-surface interactions
  - Radiation

- Collaborate with experimentalist for validation

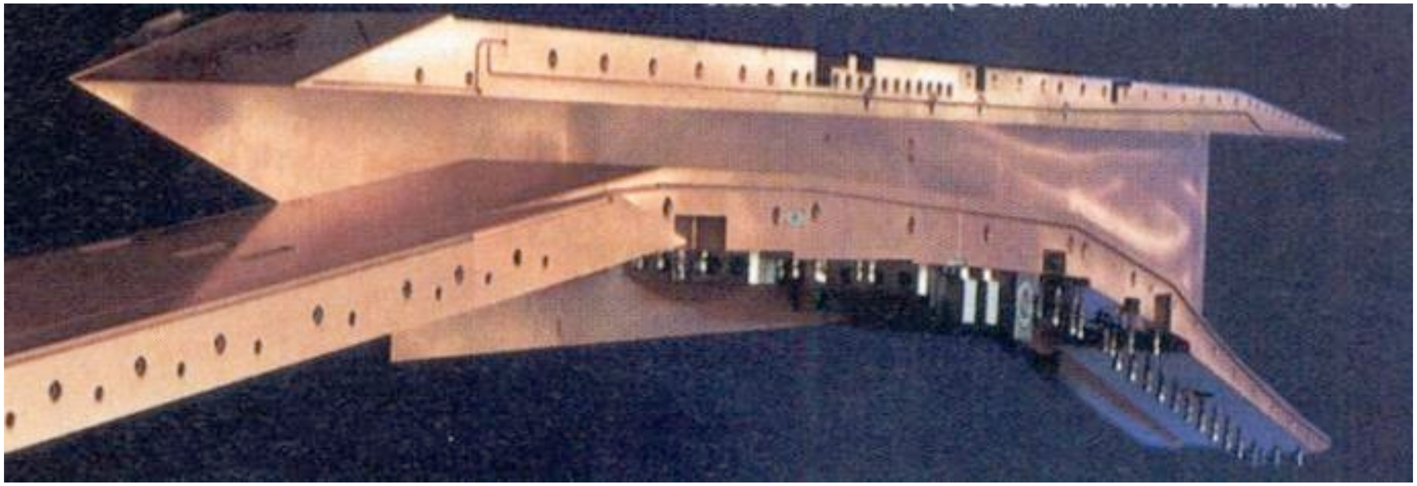
- Focus on canonical problems using DNS and LES
  - Predict the flow physics
  - Develop new scaling and turbulence models
  - Develop novel control strategies

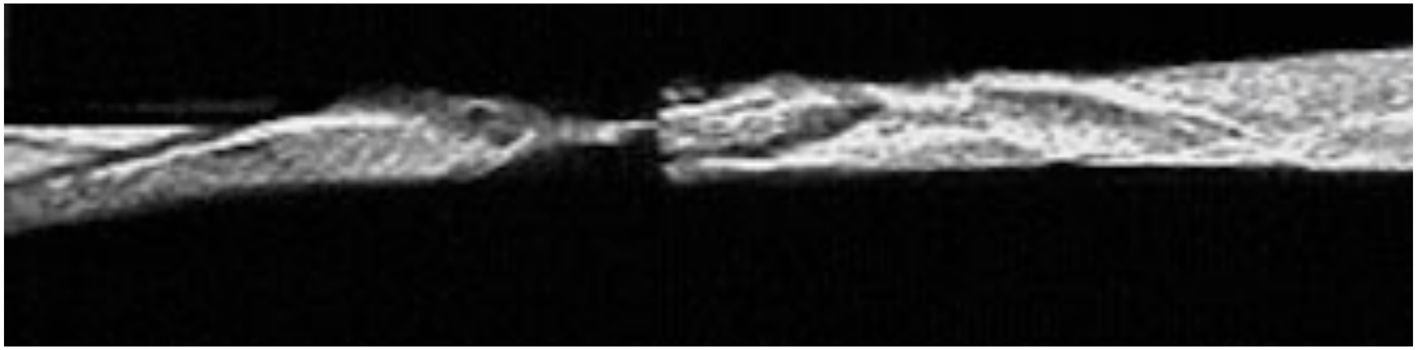
- Bridge the gap between fundamental research and large-scale calculations for engineering design

Key Physical Features

Shock wave and turbulence interaction

Pratt & Whitney Generic Scramjet Engine

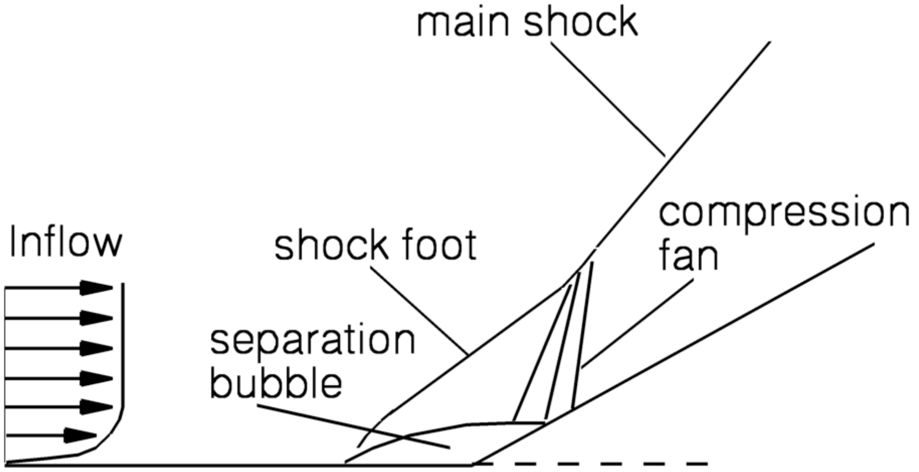




Flow inside a generic scramjet engine, no combustion
Courtesy of Mike Holden, CUBRC

Background

Shock unsteadiness in the context of a compression ramp configuration



Settles et al. 1979
Kunt et al. 1987
Smits and Muck 1987
Dolling and Murphy 1983
Andronceau 1984
Selig et al. 1989

Adams 2000
Loginov et al. 2004

Low frequency motion
with time scale: $10\frac{\delta}{U_\infty}$ to $100\frac{\delta}{U_\infty}$

Incoming boundary layer
time scale $\vartheta(\delta / U_\infty)$

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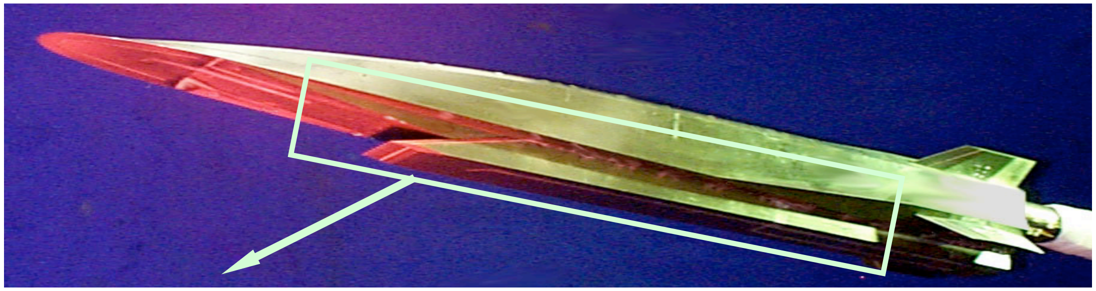
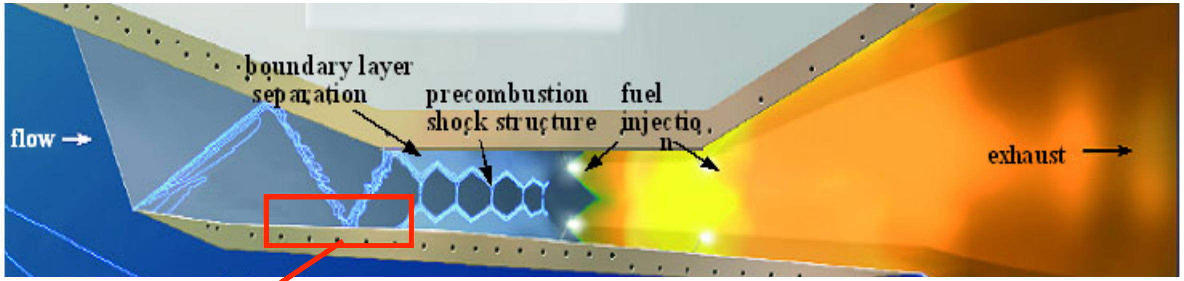
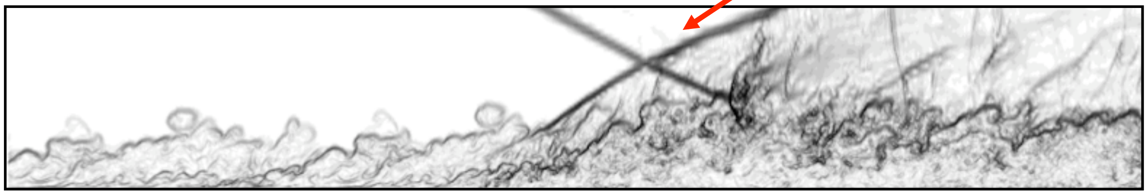




Courtsey: R. Baurle, NASA



DNS, CRoCCo Lab, Princeton University
Martín, Priebe & Wu AIAA 2008-0719

Direct and Large Eddy Simulations 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

Direct and Large Eddy Simulations for Compressible Turbulence

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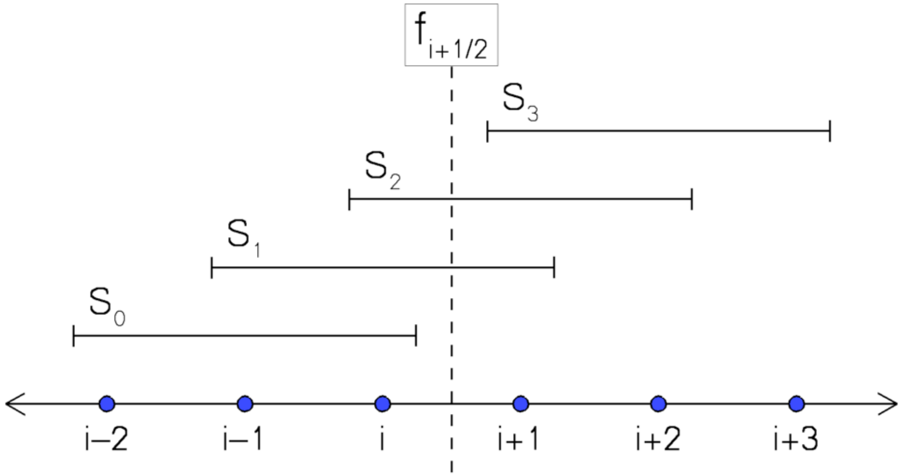
WENO Method Development for Finite Difference

Origin Jiang & Shu (1996) &Weirs (1997)

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x} f(u) = 0 \rightarrow \frac{d\hat{u}}{dt} = -\frac{1}{\Delta}\left(\hat{f}_{i+1/2} - \hat{f}_{i-1/2}\right)$$

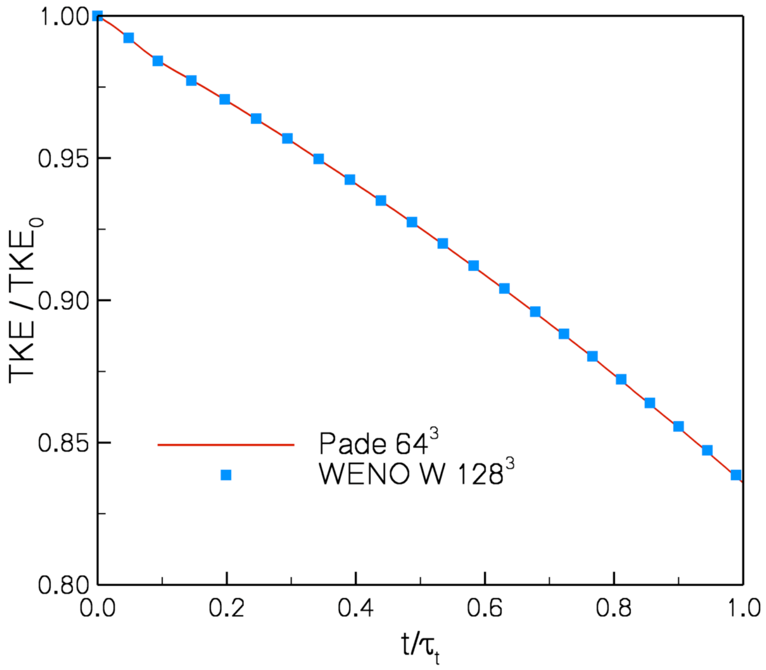


Flux: weighted sum of candidates
source of non-linearity

$$\hat{f}_{i+1/2} = \sum_{k=0}^{r} w_k q_k^r$$

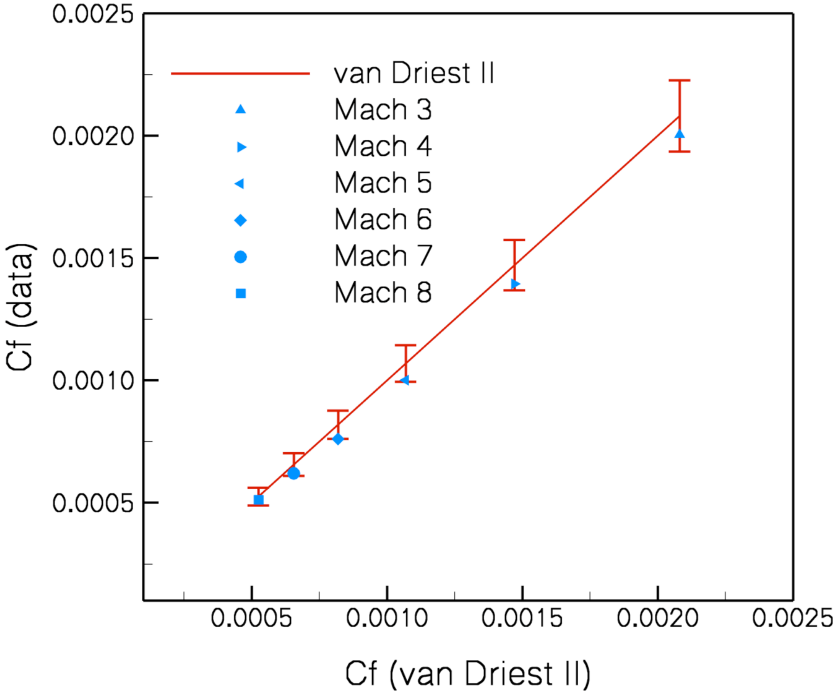
Bandwidth Optimized WENO Methods

Success



DNS data Isotropic turbulence

M_t=0.1 and Re_θ=35



DNS data Turbulent boundary layers

Re_θ=400 and Re_θ [4,500 : 13,000]

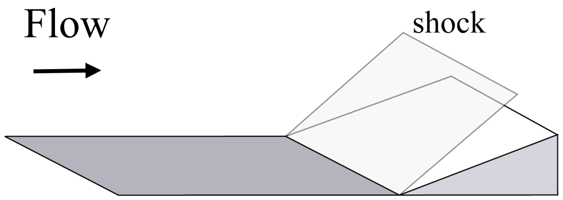
Grid size 11M grid points and error bars at 7%

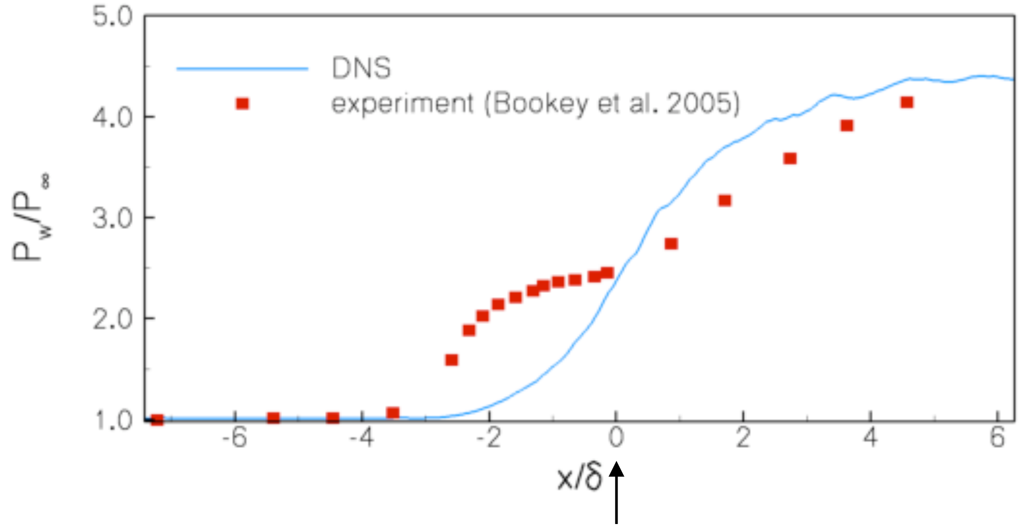
Bandwidth Optimized WENO Methods

Failure

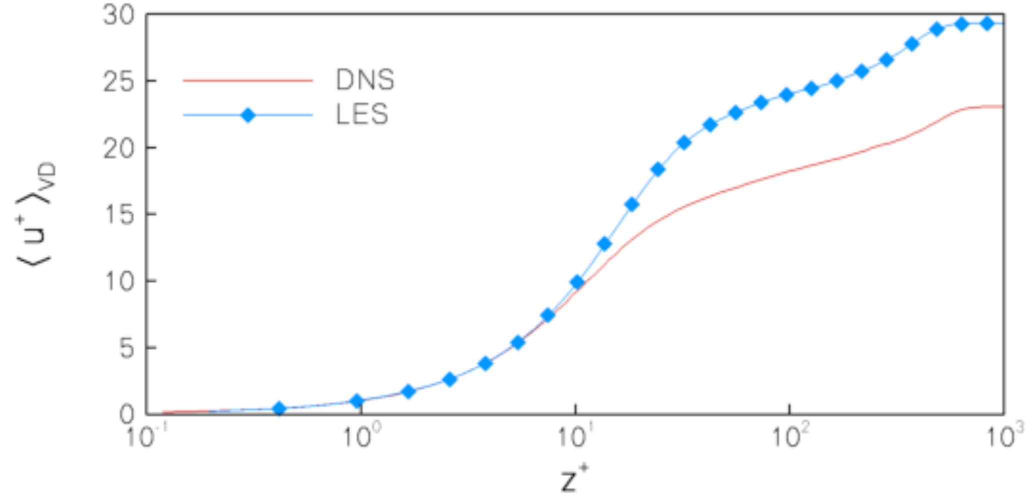
Shock wave and turbulence interaction

M=3 and Re_θ=2400





corner



Turbulent boundary layer

M=4 and Re_θ =9800

WENO Method Development

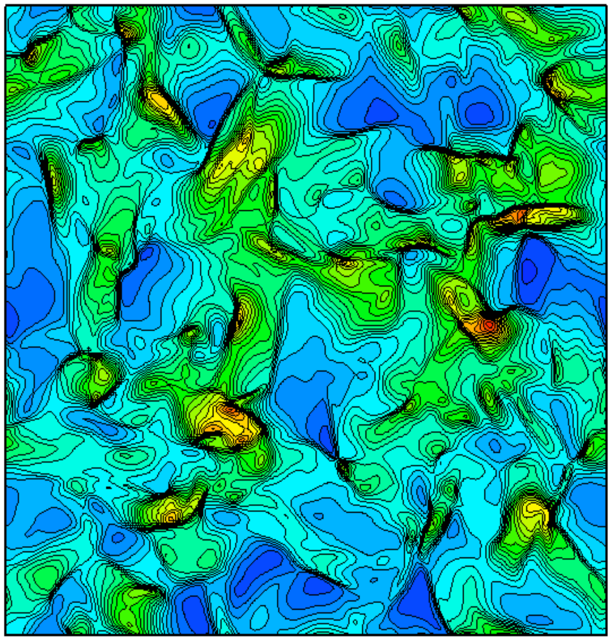
Sources of numerical dissipation

- Linear dissipation
  - Bandwidth properties of each candidate stencils
- Non-linear dissipation
  - Non-theoretical bandwidth properties of adapted stencils when deviation from optimal stencil is necessary
  - Unnecessary deviation from the optimal stencil due to smoothness measurement technique
- Non-linear dissipation can be significantly reduced using limiters
  - Calibration of limiters for particular flow condition and configuration is not feasible

Linear/Non-linear Optimization for Turbulence

Taylor, Wu & Martin JCP (2007) and Wu & Martin AIAAJ (2007)

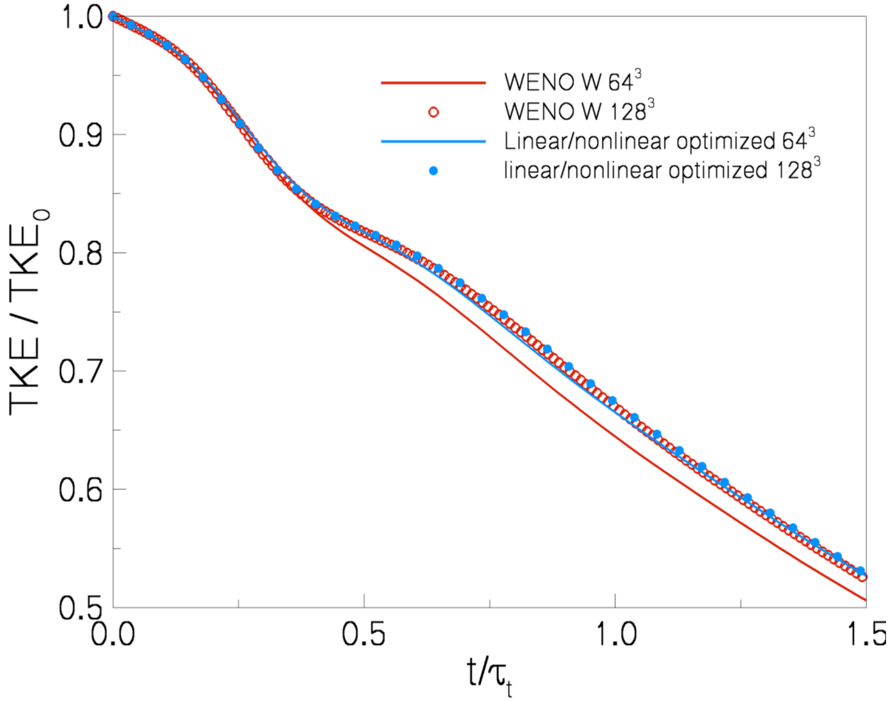
Density contours



DNS data Isotropic turbulence

M_t=1.5 and Re_θ=50

from Taylor, Wu & Martin, JCP 2007



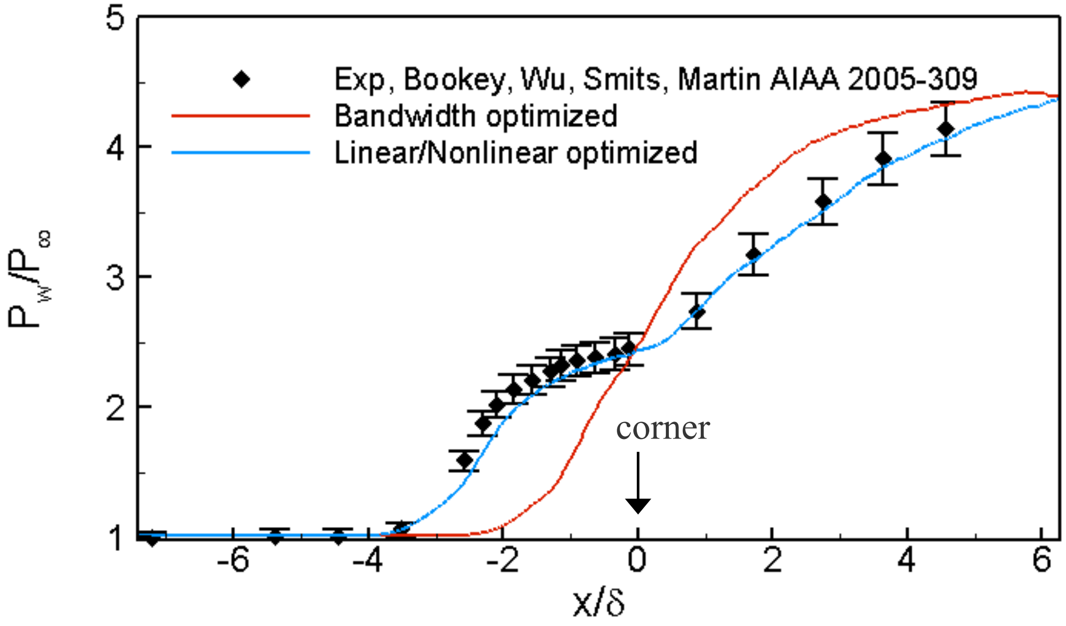
Grid convergence properties are significantly improved

Parametric studies are feasible

Linear/Non-linear Optimization for Turbulence

Taylor, Wu & Martin JCP (2007) and Wu & Martin AIAAJ (2007)

Wall-pressure distribution for STBLI
Error bars at 5%
from Wu & Martin, AIAA J, 2007



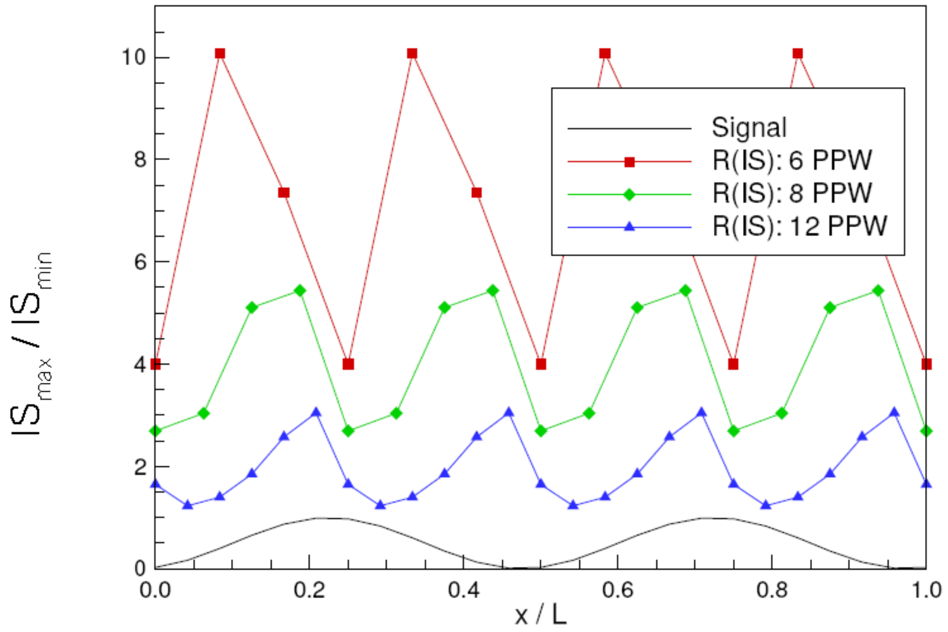
Grid convergence properties are significantly improved
Robust shock capturing and accurate turbulence

WENO Method Development

Smoothness measurement and weight evaluation

Taylor, Wu & Martin JCP (2007)

$$IS_k = \sum_{m=1}^{r-1} \Delta^{2m-1} \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \left[\frac{\partial^m}{\partial x^m} q_k^r(x) \right]^2 dx$$



$$\frac{IS_{\max}}{IS_{\min}} \le 10 \Rightarrow$$ Engage Optimal Stencil

WENO Method Development

Smoothness measurement and weight evaluation

Taylor, Wu & Martin JCP (2007)

- Absolute limiter

  Jiang & Shu (JCP '96)

  - $IS_k = \begin{cases} 0, & IS_k < \alpha_{AL} \\ IS_k, & \text{otherwise} \end{cases}$
  - Arbitrary threshold α is problem-dependent

- Relative limiter
  - $IS_k = \begin{cases} 0, & R(IS) < \alpha_{RL} \\ IS_k, & \text{otherwise} \end{cases}$
  - $R(IS) = \dfrac{\max\limits_{0 \le k \le r} IS_k}{\varepsilon + \min\limits_{0 \le k \le r} IS_k}$
  - α should now be problem-independent

WENO Method Development

Smoothness measurement and weight evaluation

Taylor, Wu & Martin JCP (2007)

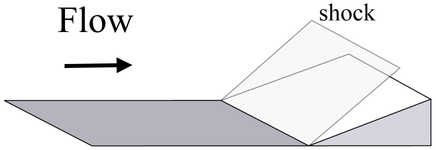
- Criterion for redefining IS_k not necessarily restricted to information from smoothness measurement values

- $$TV_k = \sum_{l=1}^{r-1} |f_{i-r+k+l+1} - f_{i-r+k+l}|$$
  - $$R(TV) = \frac{\max_{0 \le k \le r} TV_k}{\varepsilon + \min_{0 \le k \le r} TV_k}$$
  - $$IS_k = \begin{cases} 0, & R(TV) < \alpha_{RL}^{TV} \\ IS_k, & \text{otherwise} \end{cases}$$
    - WENO-3: $\alpha_{RL}^{TV} = 5$
    - WENO-4: $\alpha_{RL}^{TV} = 4$

WENO Method Development

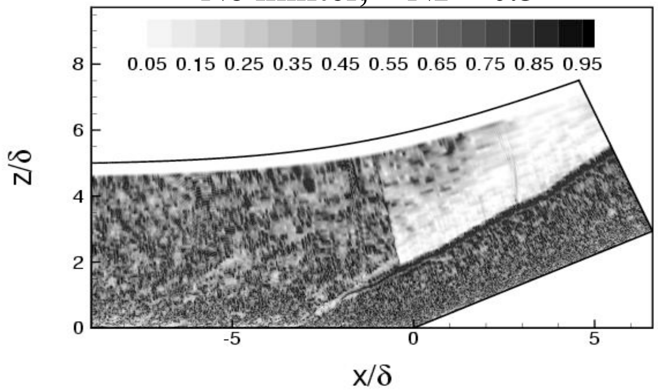
Contours of nonlinearity index in STBLI

Wu & Martin AIAAJ (2007)

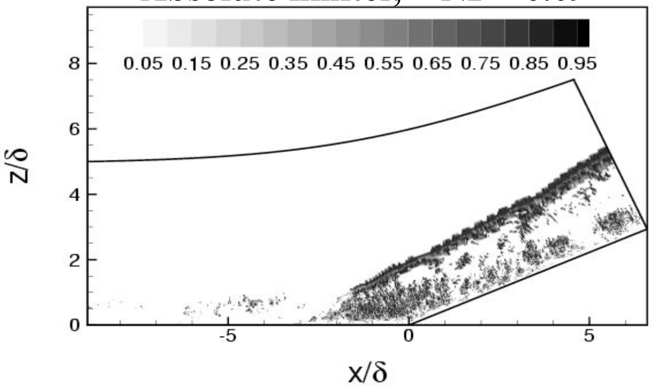


M=3 and Re_θ=2400

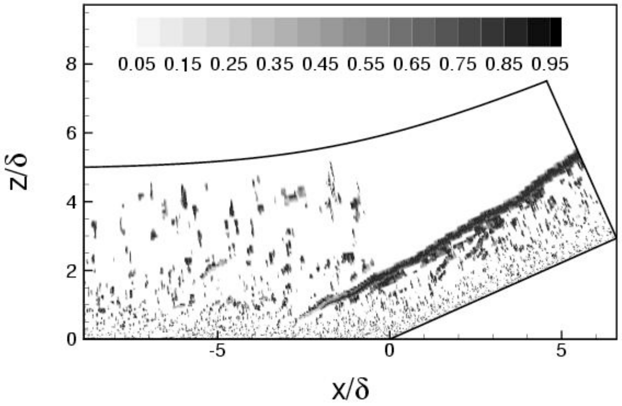
No limiter, <NI>=0.5



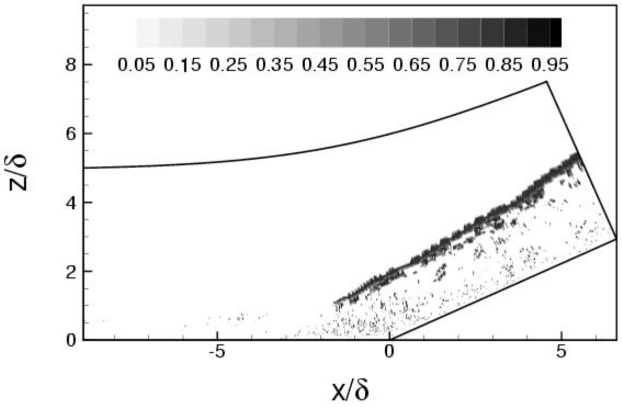
Absolute limiter, <NI>=0.09



Relative limiter, <NI>=0.09



Both limiters, <NI>=0.02



Validation of Simulations

Requires new experimental data at accessible conditions

- Laminar high-enthalpy flow:
  - GALCIT T5 Shock Tunnel at Caltech
- Cold turbulent flow:
  - IMST Wind Tunnel in Marseille (France)
  - Princeton Gas Dynamics Laboratory

    Close collaboration with Prof. A.J. Smits in Princeton
  - Mike Holden (CUBRC)

Parametric Studies

Simulation error is within experimental uncertainty

Simulation turn-around time is similar to the experiment turn around time

	Re_θ	**DNS Run time**
Isotropic turbulence M_t=1.5 0.25 M grid points	20	5 min
Turbulent boundary layer M=5 and Re_θ=6225 10 M grid points	400	18 hours
Shock wave and boundary layer M=3 and Re_θ=2400 20 M grid points	400	9 days

Run time based on a Cray X1 supercomputer
Doubles on a 2.2 GHz Xeon cluster
(Seven year old technology)

Linear/Non-linear Optimized WENO Methods

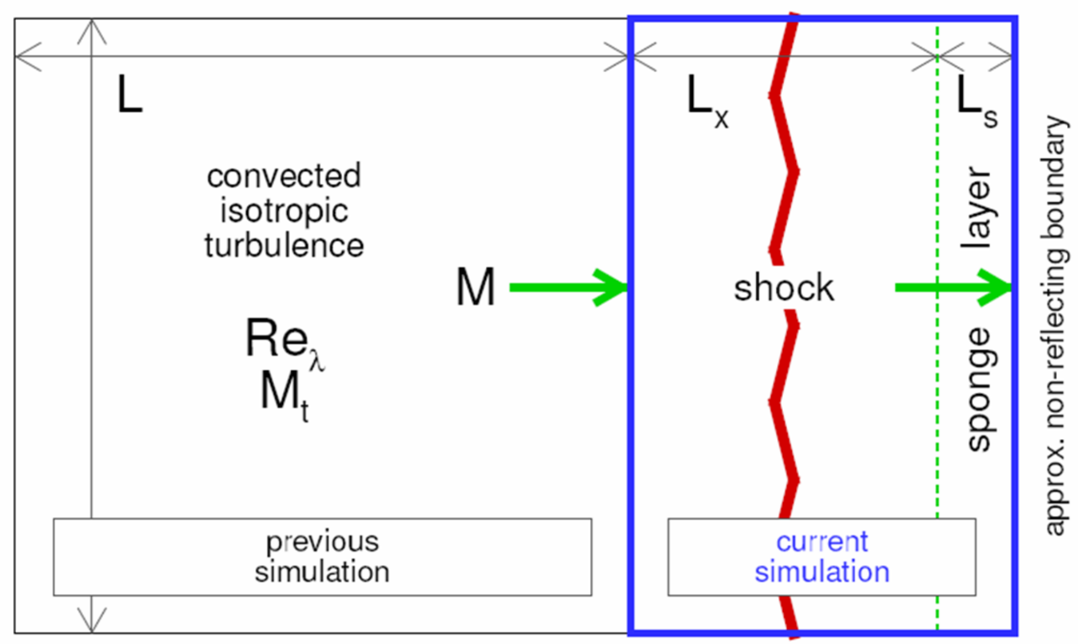
Taylor, Wu & Martin JCP (2007) and Wu & Martin AIAAJ (2007)

Testing in shock and isotropic turbulence interaction (SITI)

DNS data SITI
M=1.5 through 5
M_t=0.2 through1.3
Re_θ=35-75

$\nabla\rho/\langle\rho\rangle_\perp$

from
Taylor & Martín
(Submitted to Physics of Fluids)



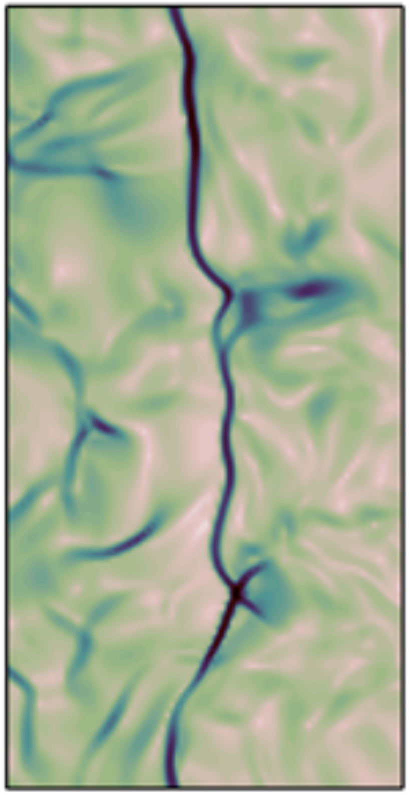
Linear/Non-linear Optimized WENO Methods

Taylor, Wu & Martin JCP (2007) and Wu & Martin AIAAJ (2007)

DNS data SITI M=2
M_t=1.3 and Re_θ=35

$\nabla\rho/\langle\rho\rangle_\perp$

from
Taylor & Martín
(Submitted to Physics of Fluids)



Having the truth we can explore physics and numerical methods for engineering applications

Linear/Non-linear Optimized WENO Methods

Taylor, Wu & Martin JCP (2007) and Wu & Martin AIAAJ (2007)

DNS data SITI M=2
M_t=1.3 and Re_θ=35
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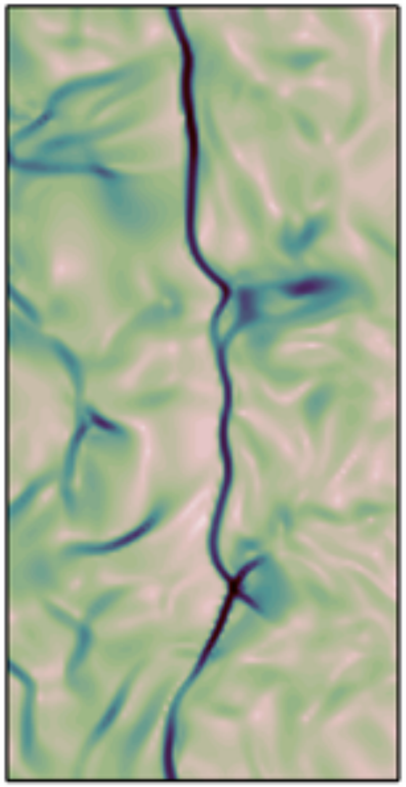

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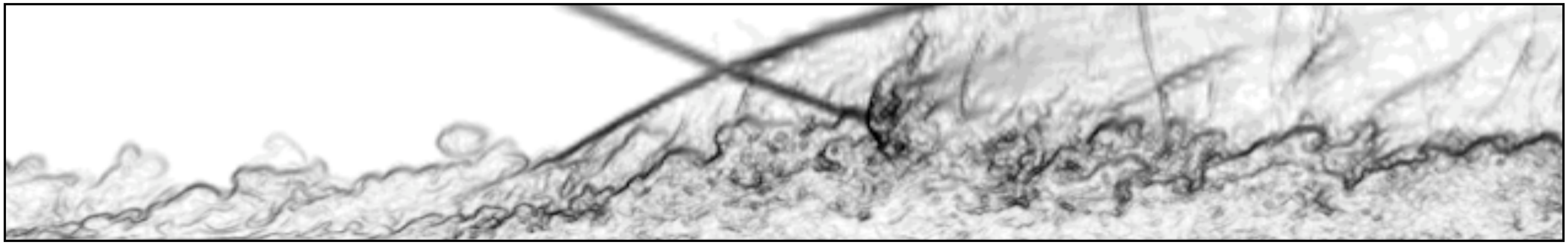
Challenges for Robust Large-Eddy Simulations



DNS data Priebe, Wu & Martín AIAA 2008-0719, also submitted to AIAAJ

Density gradient contours for a STBLI ***Mach 2.9, Re_θ=2300 and 12^o shock generator in the free stream***
Flow is from left

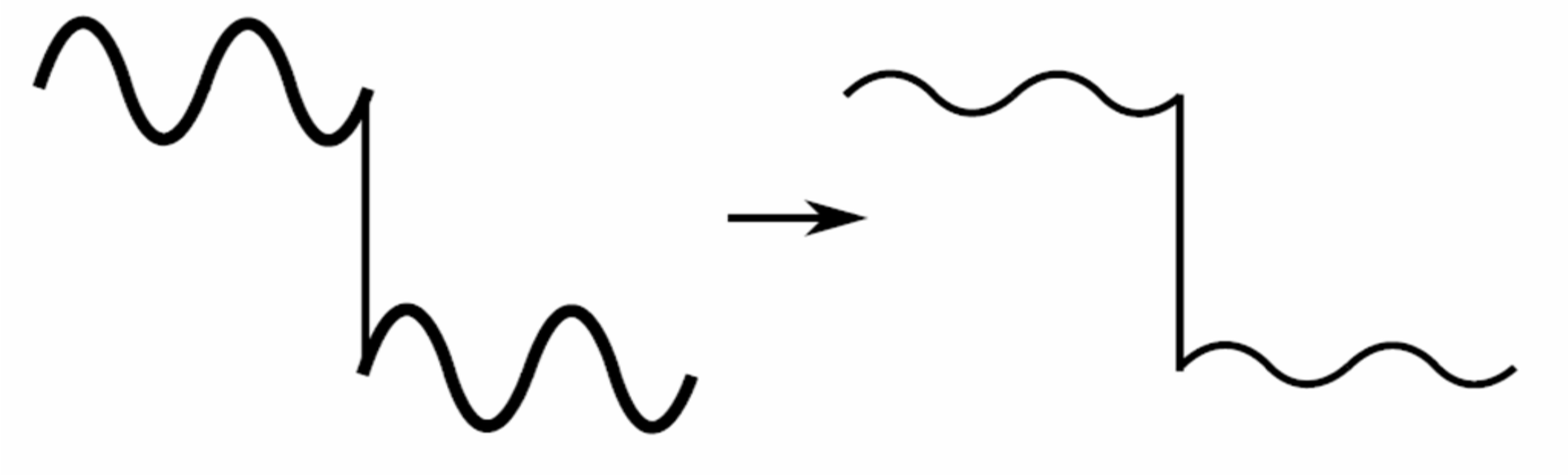
Challenges for Robust Large-Eddy Simulations
Filtering Techniques

- With the exception of static eddy viscosity models,
  most LES turbulence models require explicit application of filtering operations
  - Dynamic (Germano et al. 1991), scale-similarity (Bardina et al. 1980) and mixed (Spezial et al. 1988, Vreman et al. 1994) filter the solution to identify the smallest resolved scales
  - Approximate deconvolution model (Domaradzki 1999, Stolz & Adams 2001) relies on iterative application of filters to approximately de-filtered the solution *Here one can add a relaxation parameter to reduce oscillations but this approach does not respect the physics*

- The calculation of the unclosed terms, and in turn the global dynamics of the simulated flow are affected by the choice of filtering technique

Challenges for Robust Large-Eddy Simulations
Filtering Techniques

Ideal behavior of a shock-confining filter



Challenges for Robust Large-Eddy Simulations

Shock Confining Filters

Grube, Taylor & Martín AIAA 2007-4198

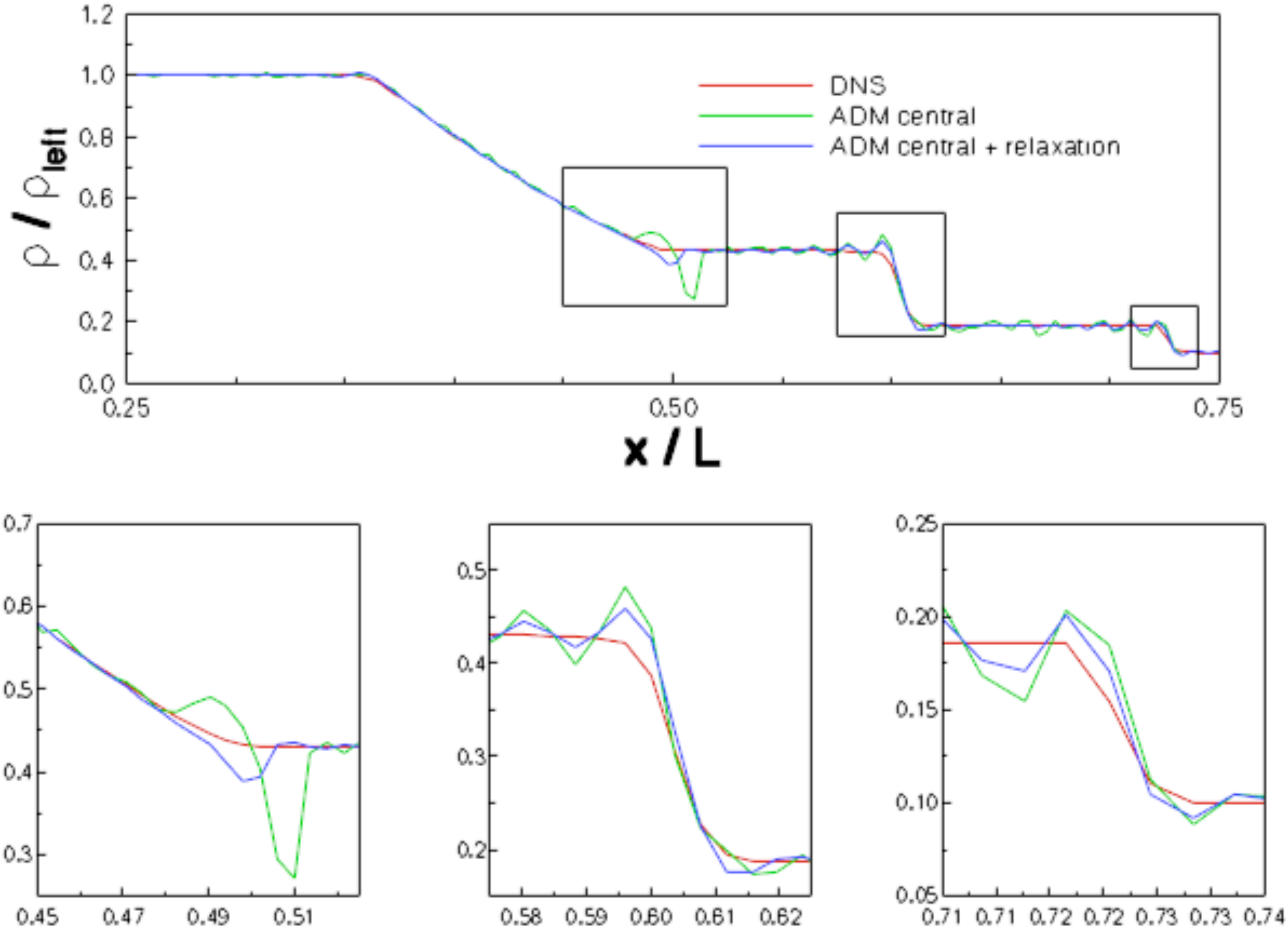
- Using the information from the WENO scheme, we can develop shock-confining filters
- Adapt filter coefficients in response to the local flow smoothness
- Ensuring global conservation of filtered variable
- Ensuring local preservation of filtered constants

Challenges for Robust Large-Eddy Simulations

Filtering Techniques without SCF

Density profiles in shocktube from Grube, Taylor & Martín AIAA 2007-4198

DNS is WENO-based



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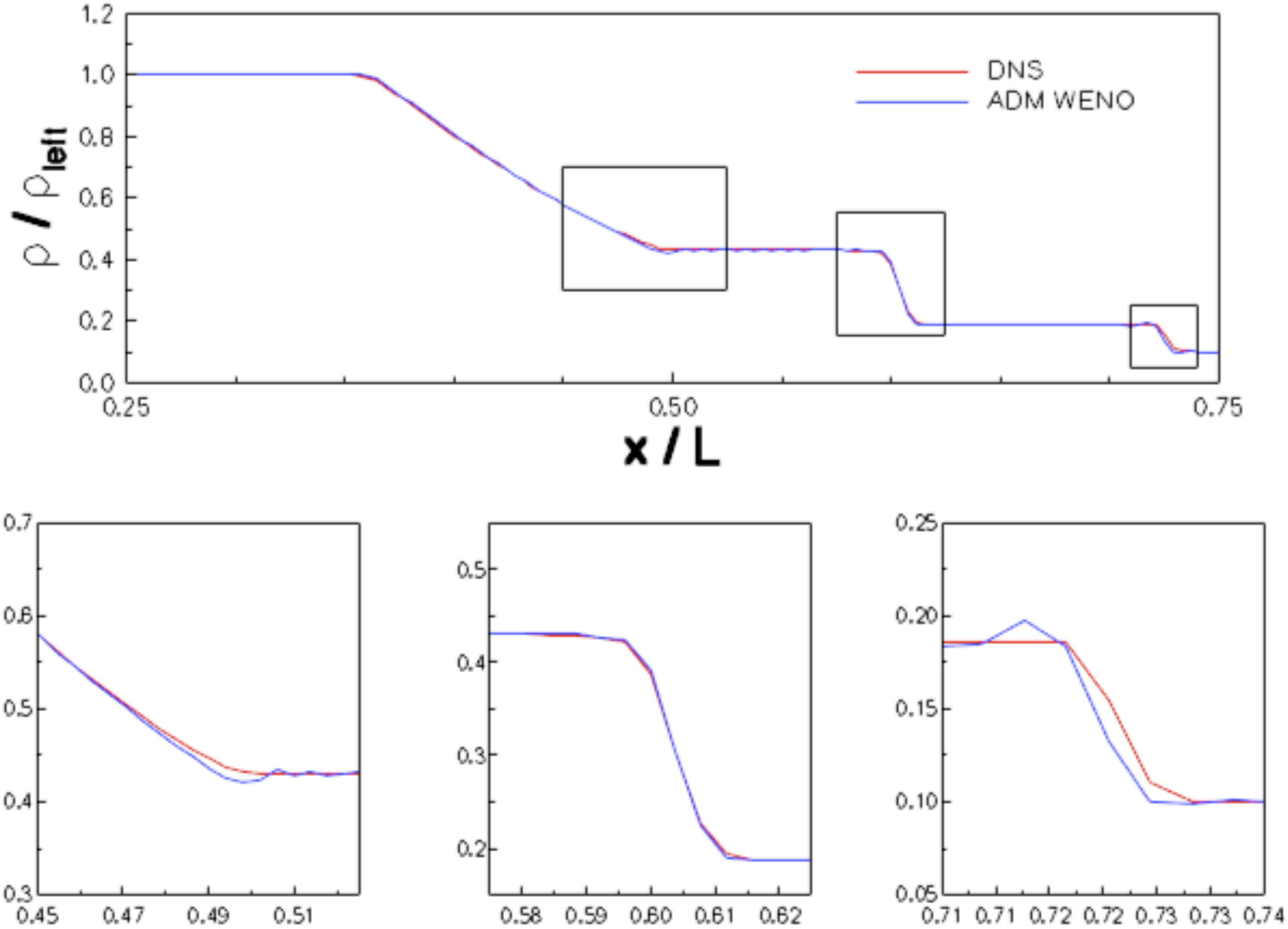

Challenges for Robust Large-Eddy Simulations
Filtering Techniques with SCF

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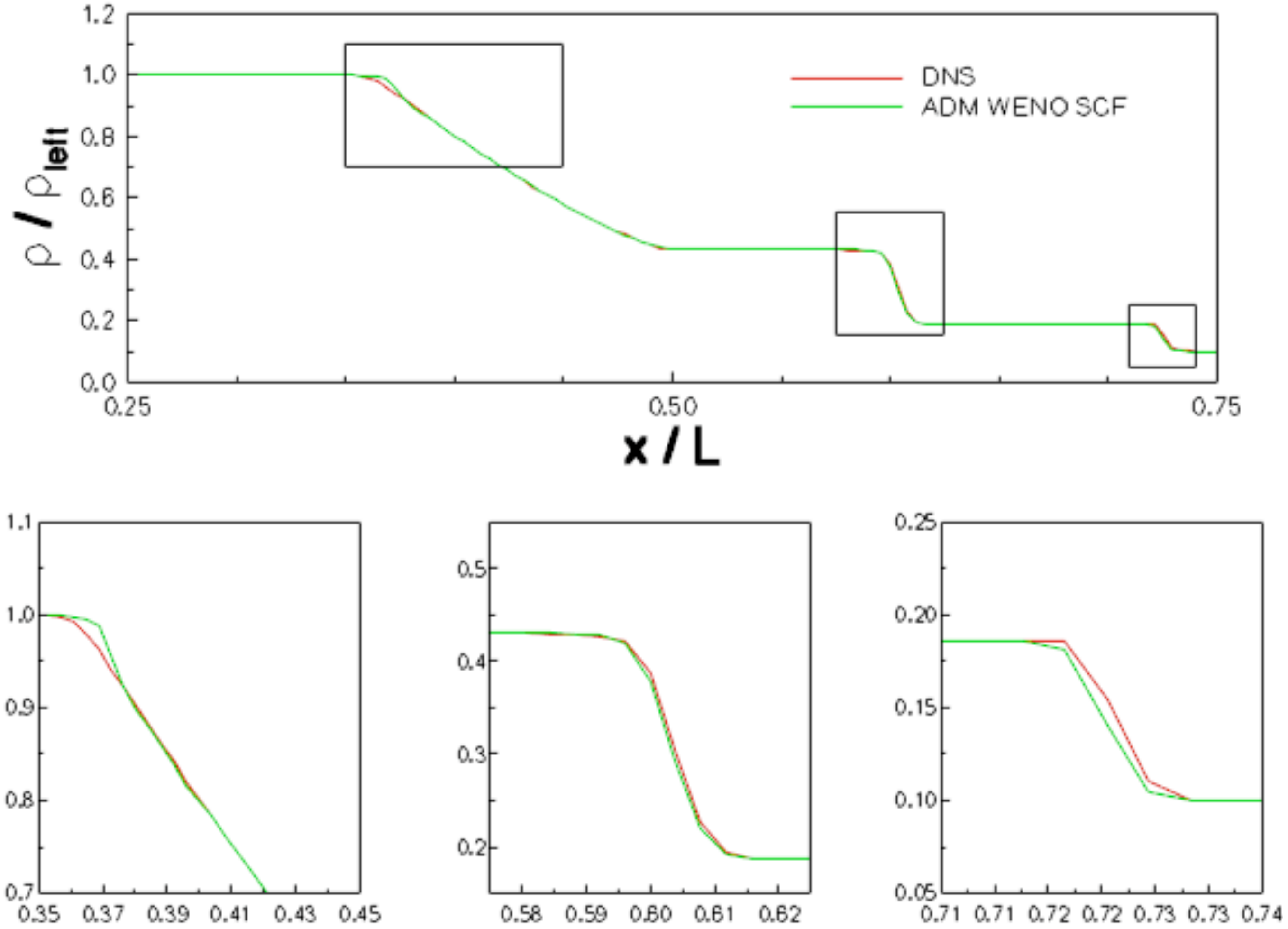
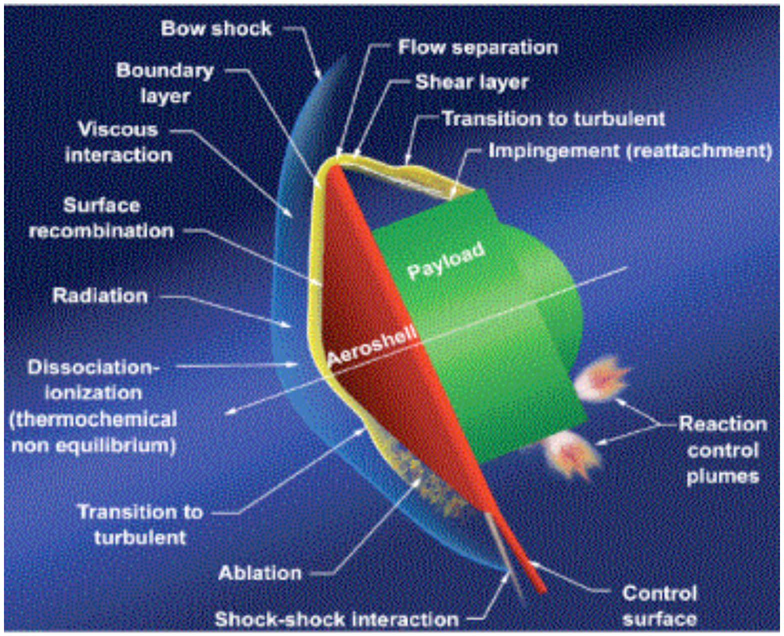
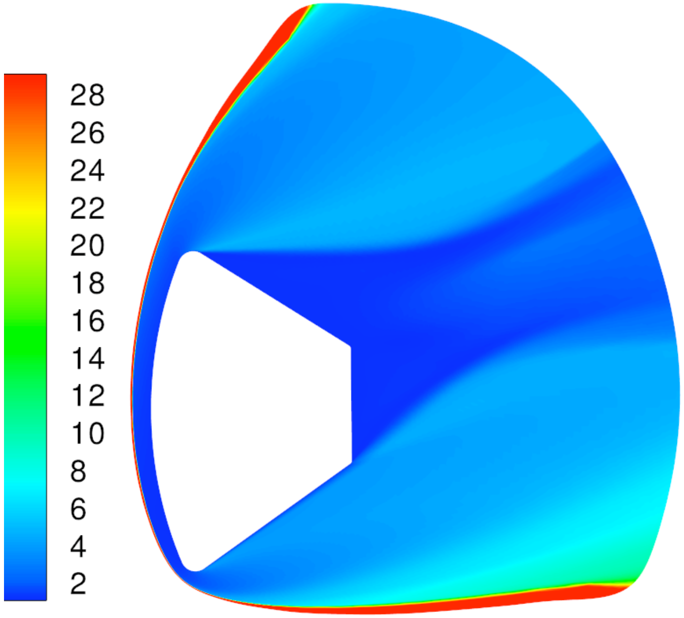


Challenges for Robust Large-Eddy Simulations
Accuracy on Unstructured Grids



Sketch of entry vehicle flow characteristics
Pittman, Batolotta, and Mansour (2006)



Crew Exploration Vehicle RANS solution
Courtesy of NASA Ames
Mach number contours

Conclusions

Numerical Challenges and Opportunities for Supersonic and Hypersonic Turbulence

- For hypersonics, the largest uncertainty in engineering design is turbulence (and radiation)
  - The development of robust large-eddy simulations is necessary

- There are abundant physical phenomena that remain unexplored
  - Direct and large-eddy simulations will open, a so far, inaccessible flow regime

- General, robust mathematical tools are necessary
  - Detailed study of recovered bandwidth and accuracy in large-eddy simulations
  - Limiters for large-eddy simulations
  - Shock confining filters
  - Implementations in complex grids

Conclusions

Detailed and accurate solutions of canonical flows are available for the first time

Taylor & Martín (Submitted to Physics of Fluids)
SITI: Mach 1.5 – 5, Mt 0.2 – 1.5
Available upon request

Grube & Martín APS 2008
Forced isotropic turbulence
Currently being gathered

Martín (JFM 2007, AIAA 2004-2337)
Turbulent boundary layers Mach 0.3 – 8
Available upon request

Wu & Martín AIAAJ 2007 and JFM 2008 raw data of (300 GB)
STBLI: Mach 3 turbulent boundary over a compression corner
Available at iCFDdatabase
(hosted at CINECA by Federico Toschi in Bologna, Italy)
http://cfd.cineca.it/cfd/repository

Priebe, Wu & Martín AIAA 2008-0719 and submitted to AIAAJ
STBLI: Mach 3 turbulent boundary layer and reflected shock interaction
Available upon request

Timely opportunity to make significant advances in this area

Database

Turbulent hypersonic flows

- Taylor & Martín (Submitted to Physics of Fluids)
  SITI: Mach 1.5 – 5, Mt 0.2 – 1.5
  Available upon request

- Grube & Martín APS 2008
  Forced isotropic turbulence
  Currently being gathered

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Questions?