The Importance of Boundary Layer Shielding in DES of Complex Flows

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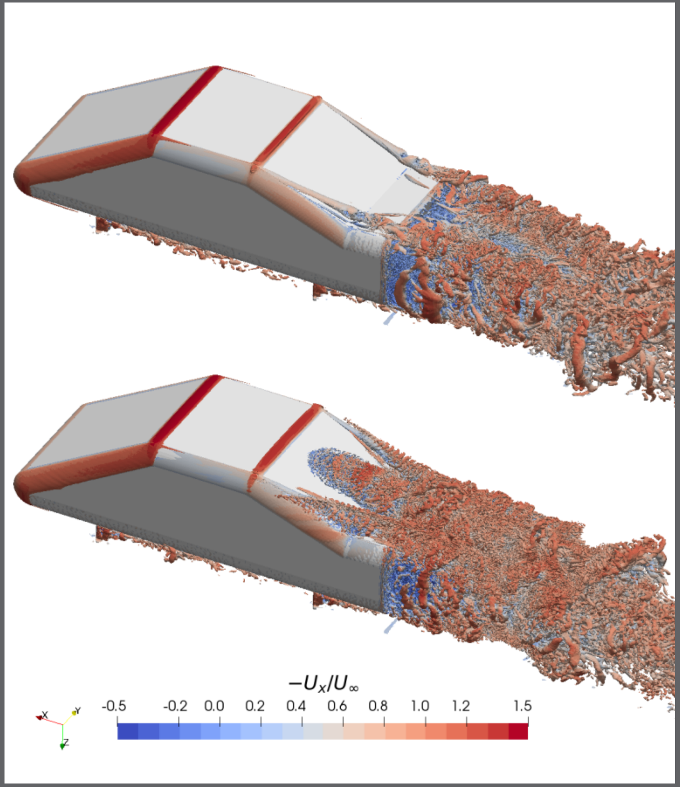

4th German OpenFOAM User Meeting (GOFUN)

Introduction

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Upstream CFD GmbH:

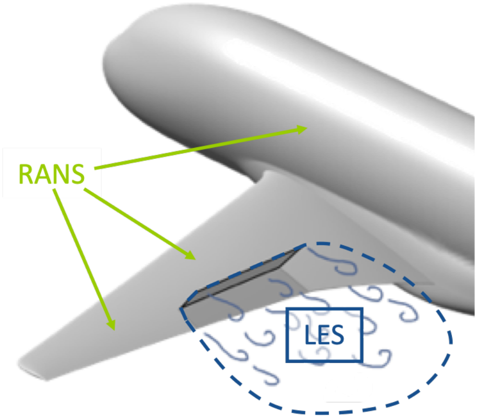
- Founded in Berlin in January 2019
- Team of five co-founders, total of 60 years professional experience
- Consultancy with expertise in:
  - Turbulence modelling
  - Aeroacoustics
  - Numerical methods
  - Optimisation
  - High-performance computing
- See upstream-cfd.com for more details
- OpenFOAM is our main CFD platform
  - All results presented today were generated with OpenFOAM
  - C. Mockett chairs the OpenFOAM Turbulence Technical Committee within the code governance structure (see openfoam.com for more details)

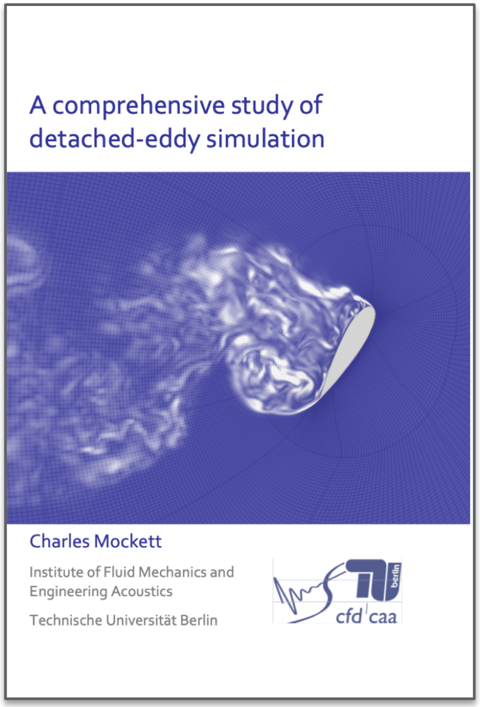
Today's talk:

- Detached-Eddy Simulation (DES) becoming more popular as computing resources grow
- Objectives of talk:
  - Increase awareness about one of the last major shortcomings of DES: Shielding
  - Present initial steps in ongoing work to resolve this shortcoming
- Web links to literature / further reading embedded in the PDF of these slides

Detached-Eddy Simulation (DES)

- A hybrid RANS-LES method:
  - RANS in attached boundary layers
    - All turbulence modelled
  - LES in massively-separated wakes
    - Most of turbulence resolved by grid and time step
- "Non-zonal":
  - No user-specification of RANS & LES zones needed
  - The model controls the placement of RANS & LES modes
- Advantages:
  - Significantly more accurate results than RANS, especially for massively-separated flows
  - Significantly lower computational expense than LES in attached boundary layers at high Re
- DES first introduced by [Spalart et al. in 1997](#) – several revisions since published





Still a useful introduction but not exactly up-to-date (2009)

PDF free to download via [ResearchGate](#)

The Grey Area problem and its mitigation

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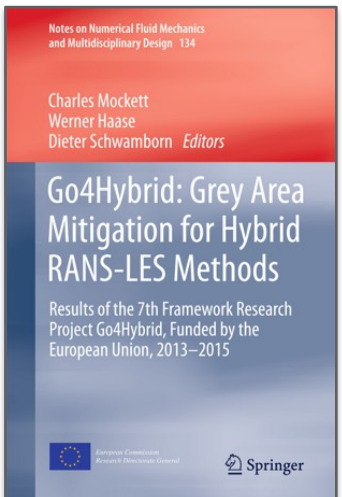
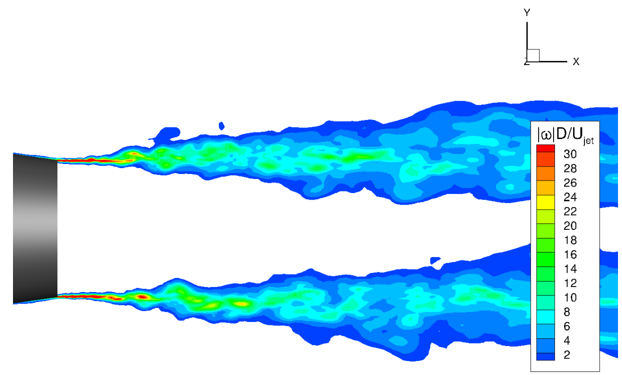
- "Grey Area": Delayed transition from RANS to LES in free shear layer following BL separation
- Many practical flows are affected, e.g. shallow separation, vortices, jets...

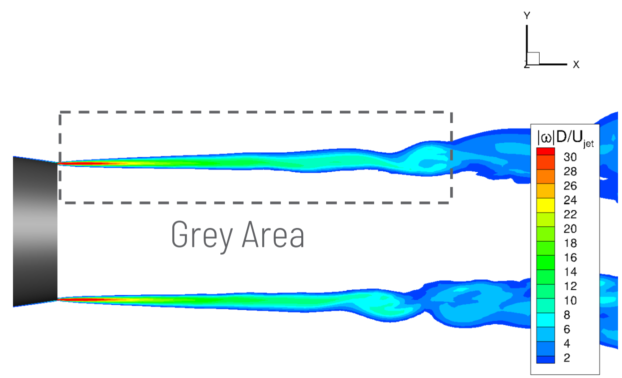


EU-funded Go4Hybrid project (2013-2015)

- We proposed a modified DES version named σ-DDES:
  - First publication: Mockett et al. (2015)
  - An extension to DDES, maintaining all key features of the original model
  - Strong reduction of Grey Area for a wide range of fundamental and complex flows: Fuchs et al. (2020)
- Results of σ-DDES better than or equivalent to standard DDES for all cases tested...
- ...until recently: Shielding problem!



What we want...



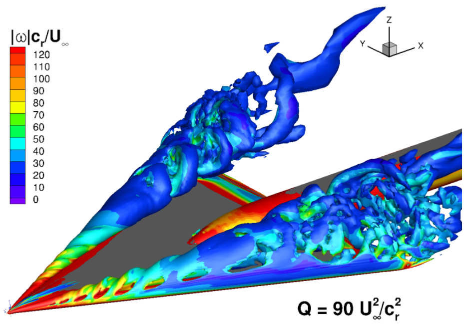
...what we get

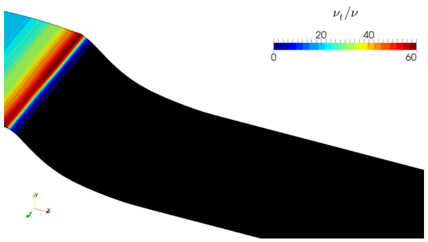
Example results with σ-DDES

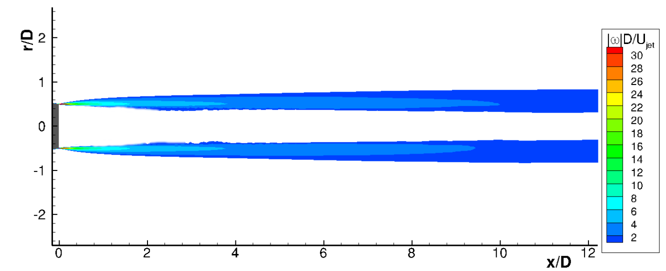
Direct comparisons with standard DDES (identical grid, numerics etc.)

Delta wing | 2D hump | Round jet

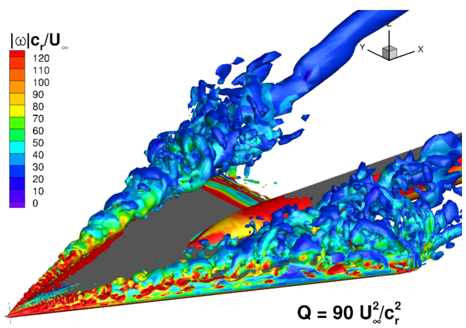
Std. DDES

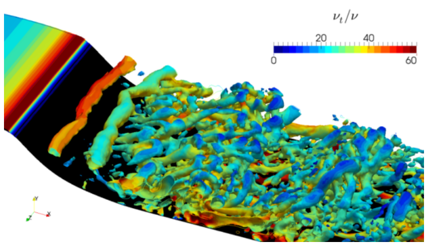


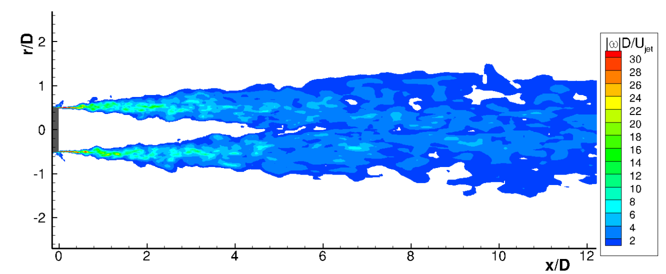




σ-DDES







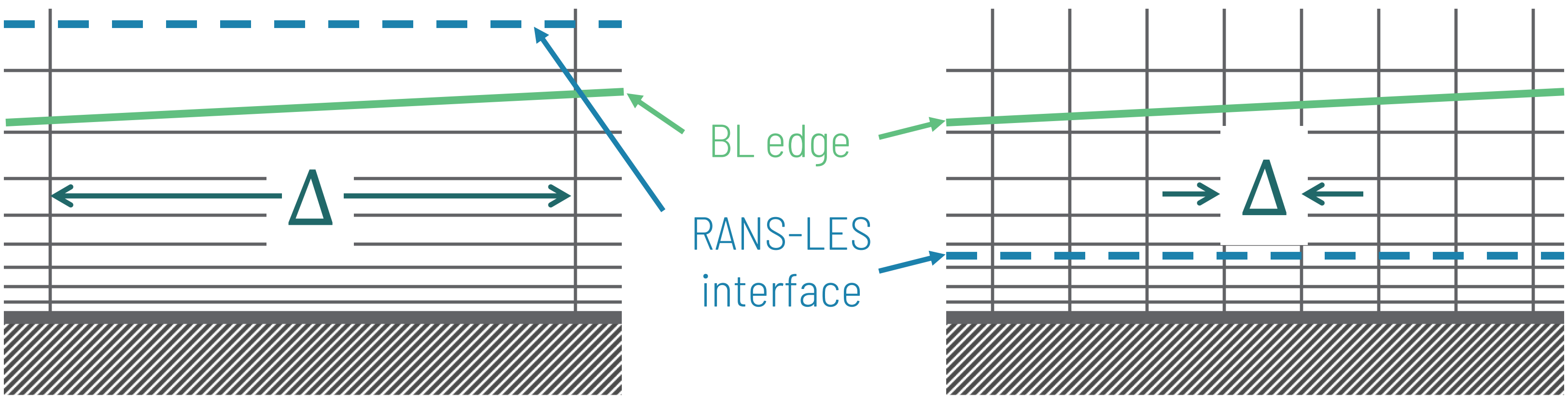
For more information see e.g.:

- Fuchs et al. (2015) – Delta wing case
- Fuchs et al. (2020) – Review of formulation, 2D hump, Ahmed body, rudimentary landing gear cases

The last (?) problem: boundary layer shielding

- Most easily explained using original 1997 DES formulation:

$$L_{DES} = \min(L_{RANS}; C_{DES}\Delta)$$

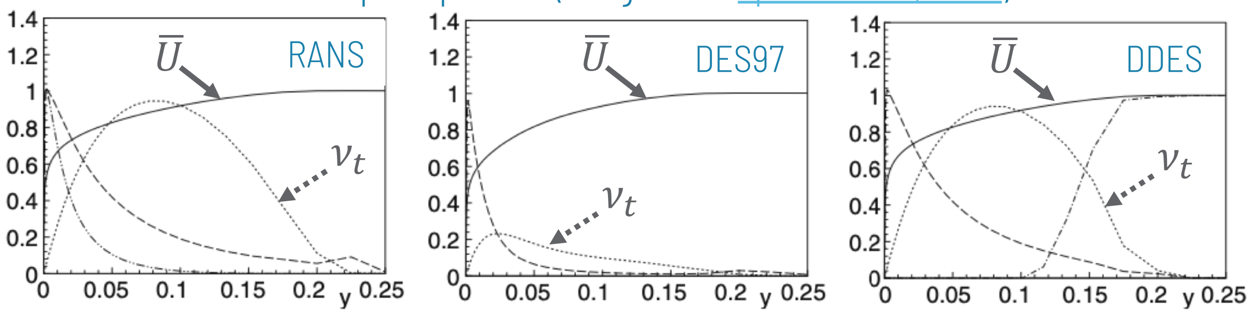


- Requirements for correct LES inside boundary layers:
  - Sufficient grid resolution to resolve the largest local turbulent scales
  - Presence of resolved turbulent content (eddies) in solution field
- Without the above, "Modelled Stress Depletion" (MSD) occurs:
  - Neither resolved (LES) nor modelled (RANS) turbulence levels are sufficient
  - Strong under-prediction of skin friction – in severe cases even "grid-induced separation"

DDES shielding function

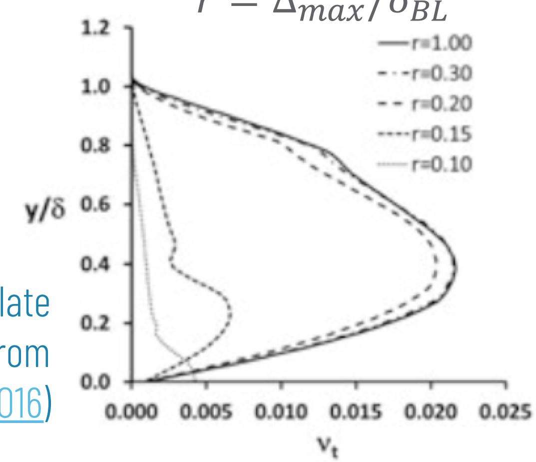
- The "Delayed-DES" (DDES) formulation of Spalart et al. (2006) introduced a shield function designed to protect the boundary layer from unwanted LES-mode incursion
  - A significant improvement, and DDES replaced the 1997 formulation as the new default

ZPG flat plate profiles (image from Spalart et al., 2006)



- However, as shown by Menter (2016), the DDES shield function does not sufficiently protect the boundary layer on finer grids
- DDES shield collapses suddenly when grid spacing Δ_{max} is refined below about $0.3 \cdot \delta_{BL}$
- An improved shielding function, giving impressive results, forms the basis of Menter's SBES approach
  - The formulation is unfortunately unpublished

$r = \Delta_{max}/\delta_{BL}$



ZPG flat plate profiles (image from Menter, 2016)

Example: SAE notchback model

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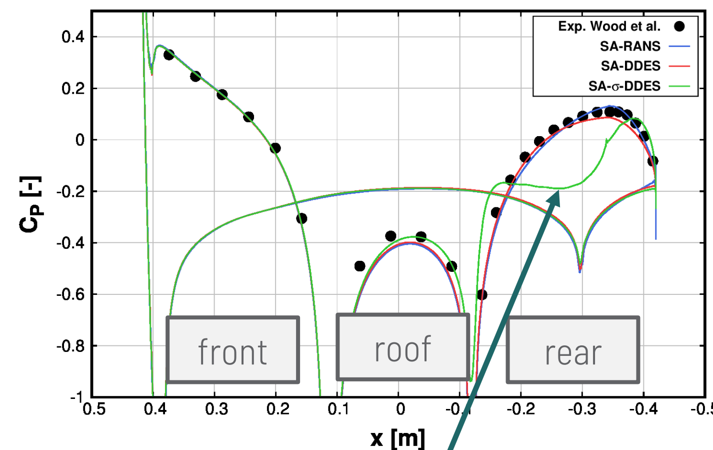
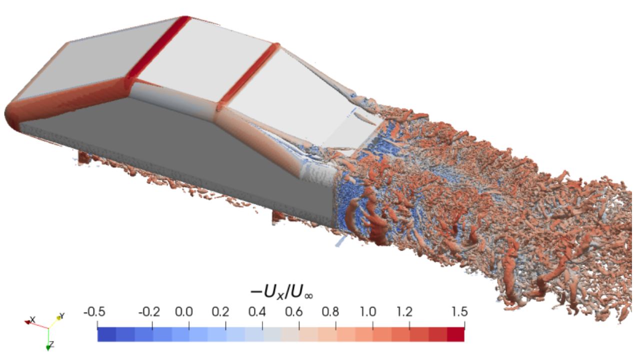
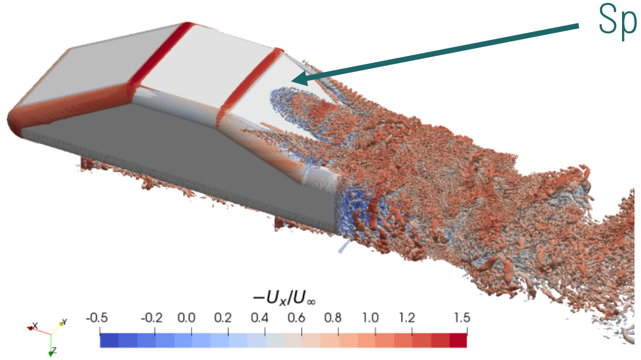
- SAE generic notchback vehicle model (Cogotti, 1998) with 20° backlight angle, $Re_L = 2.3 \times 10^6$
  - Experiments by Wood et al., 2014, studied in 1st Automotive CFD Prediction Workshop (2019)
- Grey-area improved σ-DDES model exhibits spurious separation on rear backlight
- Analysis revealed shielding function collapse was to blame
  - This was a (bad) surprise: σ-DDES shielding calibrated to give same performance as std. DDES (ZPG flat plate)
  - IDDES also showed stronger shielding collapse to DDES (results of numerous other workshop participants)



Std. DDES



σ-DDES



Spurious separation on rear slant

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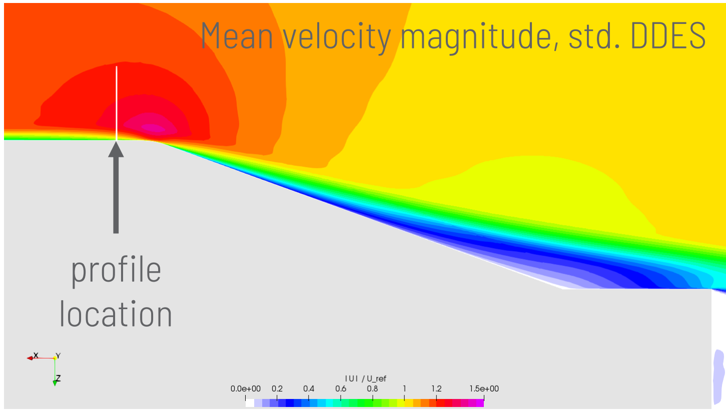
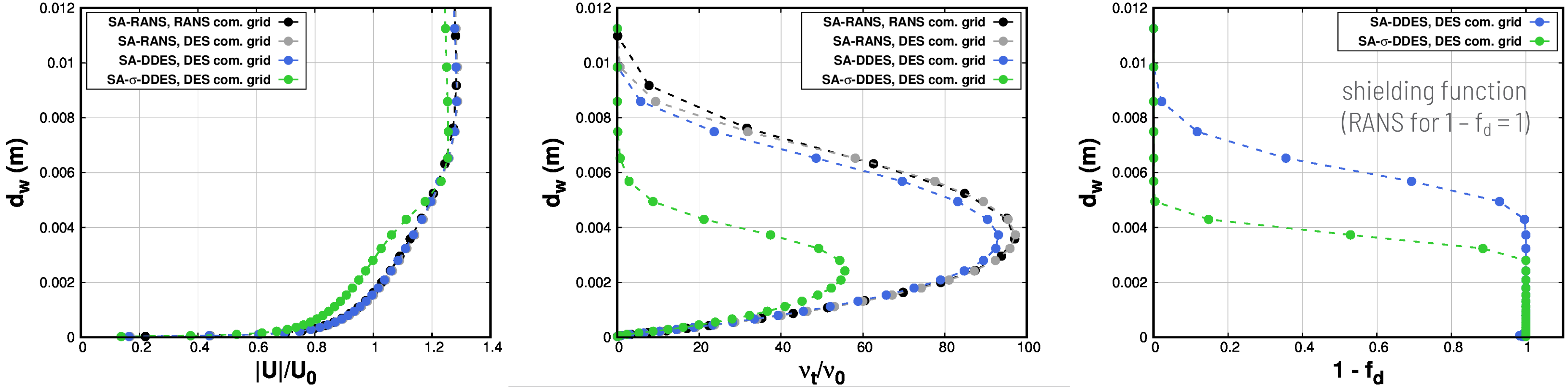


Boundary layer profiles near end of roof



Improved shielding function of Weihing et al.

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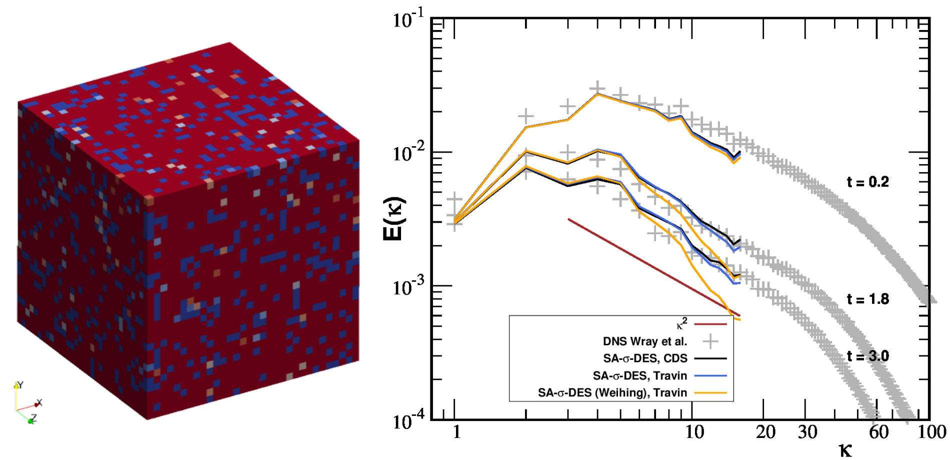
- Numerous researchers are working on improved shielding functions for DES and other non-zonal hybrid RANS-LES approaches
- We have implemented and tested an approach published by Weihing et al. (2020):
  - BL edge velocity estimated locally using Bernoulli equation
    - Drawback: Not Galilean-invariant
  - A range of further functions, e.g. to rapidly destroy the shield when free shear layers and three-dimensional turbulence are detected
  - These functions are combined in modular formulation
- Testing for a range of fundamental flows:
  - Shielding fully restored for for cases where std. DDES is known to fail
  - Sub-functions generally activate where they should, no major malfunctions
  - Drawback: Resolved turbulent regions covered in speckles of RANS-mode
    - Significantly increases dissipation
    - Degrades the grey-area performance of the σ-DDES model

Shielding function activity & energy spectra for isotropic turbulence



σ-DDES+Weihing for SAE notchback

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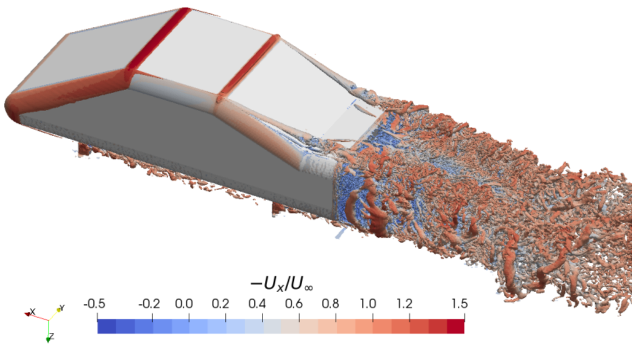
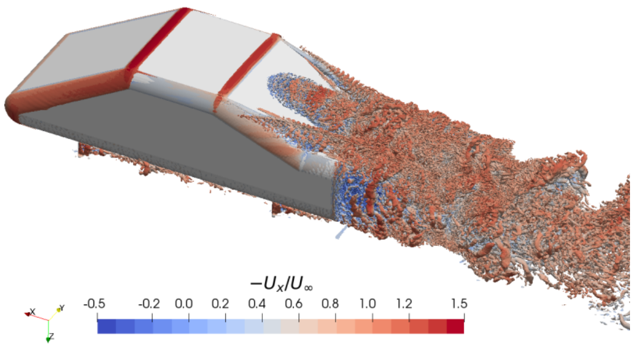
  - Experiments by Wood et al., 2014, studied in 1st Automotive CFD Prediction Workshop (2019)

- Spurious separation on rear backlight removed by Weihing et al. shielding function
- Development of resolved turbulence in C-pillar vortices seems delayed

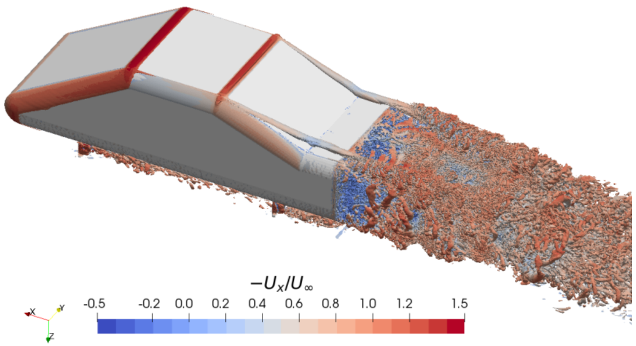
Std. DDES



σ-DDES



σ-DDES+Weihing



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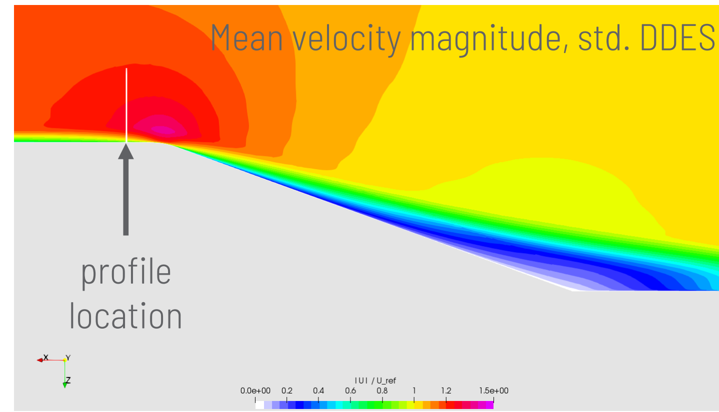
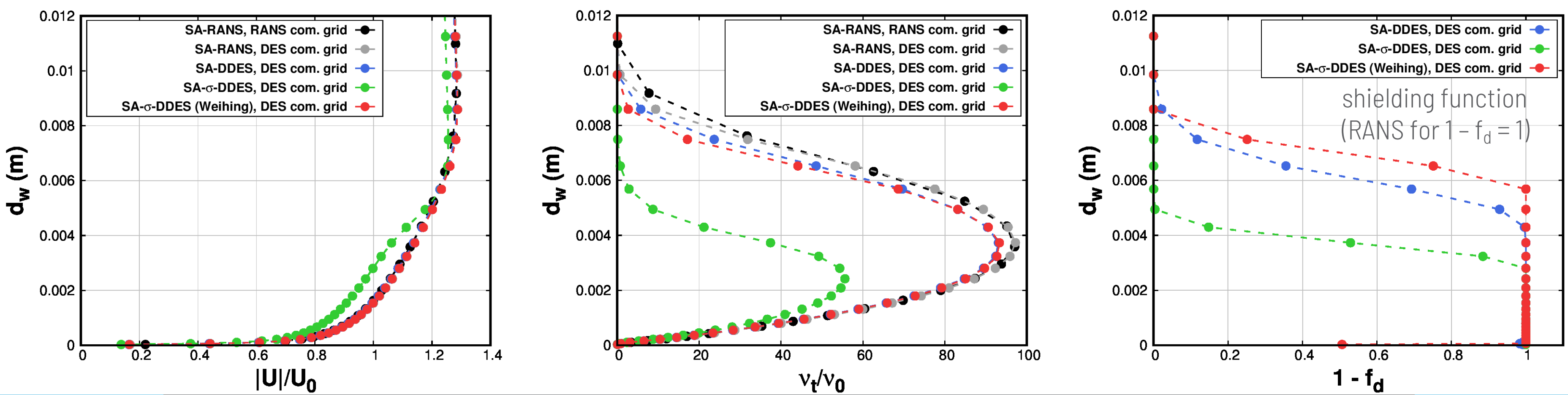


- Eddy viscosity on rear roof restored to near-RANS levels by Weihing et al. shielding function
- New shielding function successfully covers majority of boundary layer despite use with σ-DDES formulation

Boundary layer profiles near end of roof



Conclusions and outlook

- Use of DES continues to grow for complex applications, thanks in part to a range of enhancements to the approach, e.g.:
  - Significant robustness improvement with DDES (2006)
  - Extension to wall-modelled LES with IDDES (2008)
  - Grey-area improvements such as σ-DDES and Δ_{SLA} (ca. 2015)
- Boundary layer shielding remains a key unresolved* issue:
  - Mild grid refinement in the "wrong" place can cause spurious separation and severe degradation of results
  - Very dangerous for practical applications (very fine grids often needed to resolve complex geometry features locally)
  - * The SBES method of Menter appears to give excellent shielding, however the formulation is unpublished
- Weihing et al. shielding function tested in conjunction with σ-DDES in OpenFOAM
  - Good shielding performance
  - Two known drawbacks:
    - Not Galilean-invariant, hence not generally applicable (e.g. rotating wheels)
    - Increases model dissipation in LES-mode region and worsens Grey Area
- Although not perfect, the Weihing et al. approach seems a promising starting point for future developments to address these drawbacks

Thank you for your attention