Use of LEM and ODT in 3D Eulerian turbulent flow simulations

Alan Kerstein
Consultant
Danville CA, USA

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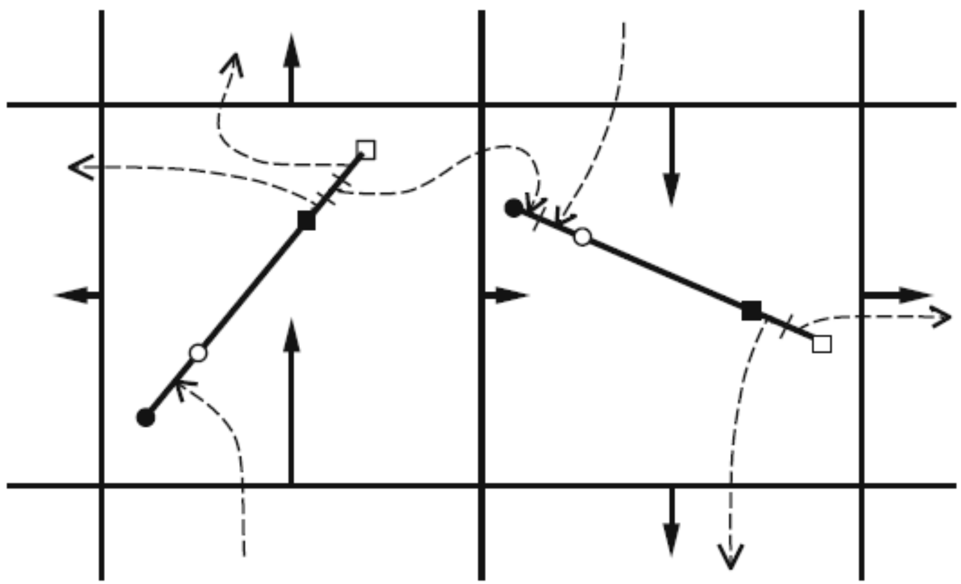
LEM and/or ODT domains can be coupled to obtain 3D simulations

- **for subgrid closure of RANS or LES**

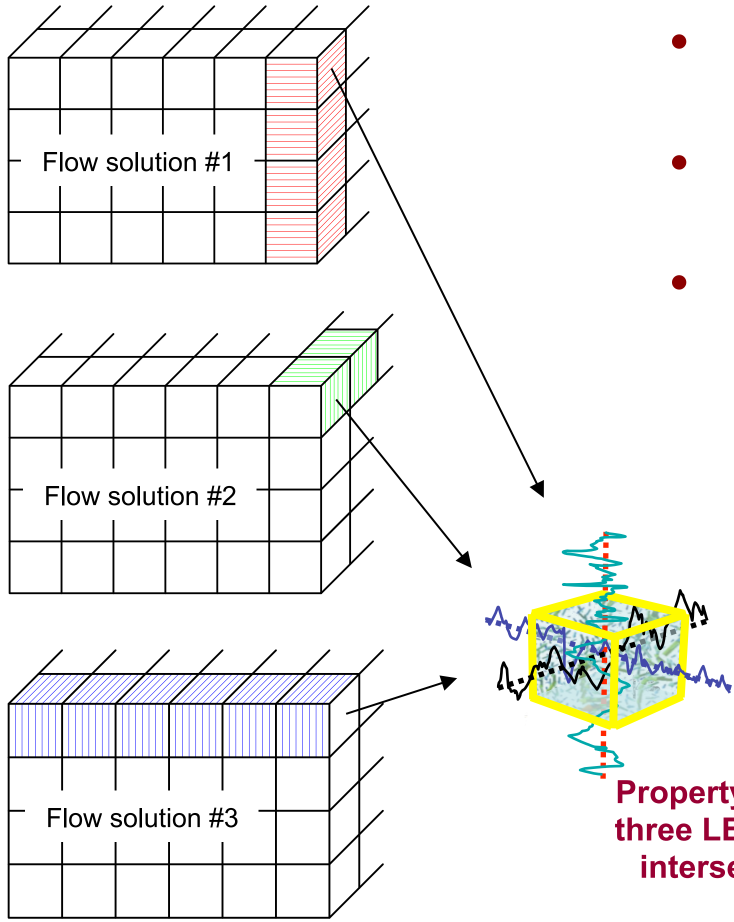
- **for autonomous 3D flow simulation**

Suresh Menon implemented a ‘splicing’ method to couple LEM domains for LES mixing-reaction closure

- 1D domains are Lagrangian objects within control volumes (CVs) in one coordinate direction
- Each domain has an input end and an output end
- Mass transfer (splicing) between them is governed by CV face fluxes from a coarse-grained 3D flow solver



Time advancement of a 3D lattice-work of coupled LEM domains can be driven by RANS input: 'LEM3D'

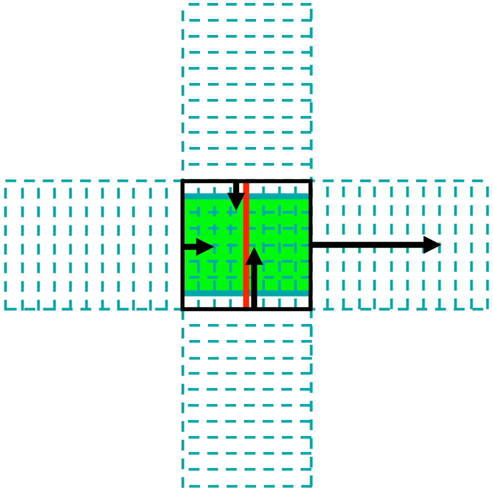


- Each LEM domain spatially refines RANS control volumes (CVs) in one coordinate direction
- Each CV is thus contained within three orthogonal LEM domains, each within a different flow solution
- Time-advancement cycle:
  - **Advancement on individual LEM domains**
    - **1D representation of small-scale motions**
    - **Requires <u>RANS eddy diffusivities</u> to determine local eddy frequencies**
  - **Cell transfers (conservative mapping) couple domains**
    - **3D representation of large-scale motions**
    - **Transfers implement displacements prescribed by <u>RANS mean velocities</u>**

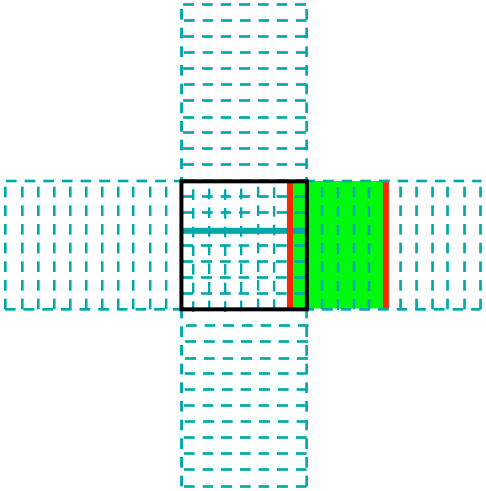
Property profiles on the three LEM domains that intersect a RANS CV

This approach can likewise be used for LES mixing-reaction closure

A 2D constant-density example illustrates the domain-coupling procedure



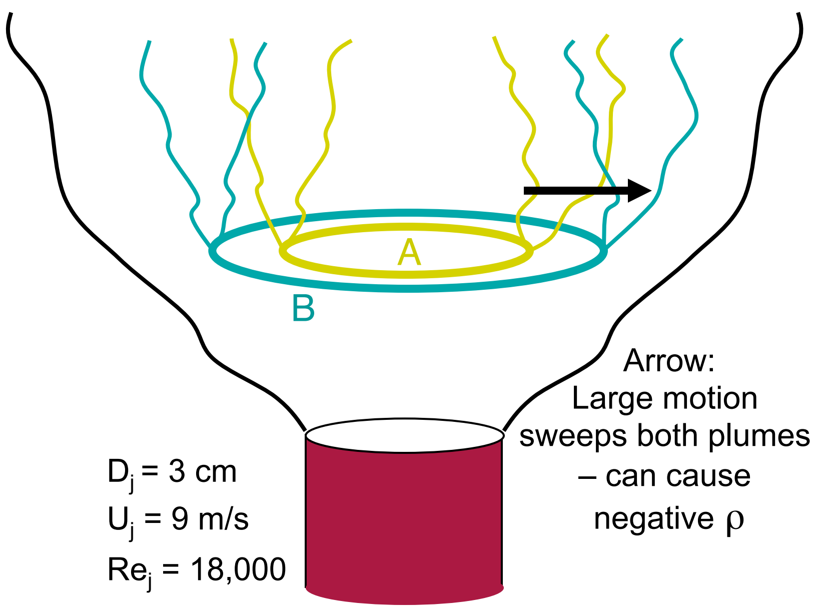
- **Arrows are RANS CV face-normal displacements (velocities × time step)**
- **In this example, there is net vertical inflow and net horizontal outflow through CV faces (box)**
- **Horizontal LEM domain: cut at red line and displace uniformly on either side, <u>leaving a gap</u>**
- **Vertical LEM domain: remove green region and insert it into the gap on the horizontal domain (between the red lines), then displace uniformly above and below the green region, causing the solid blue lines to meet**



- Advantage: Displaces fluid advectively (no mixing)
- Issue: Brings chemically dissimilar fluids into contact
- Remedy: Use coarse CVs to minimize the artifact

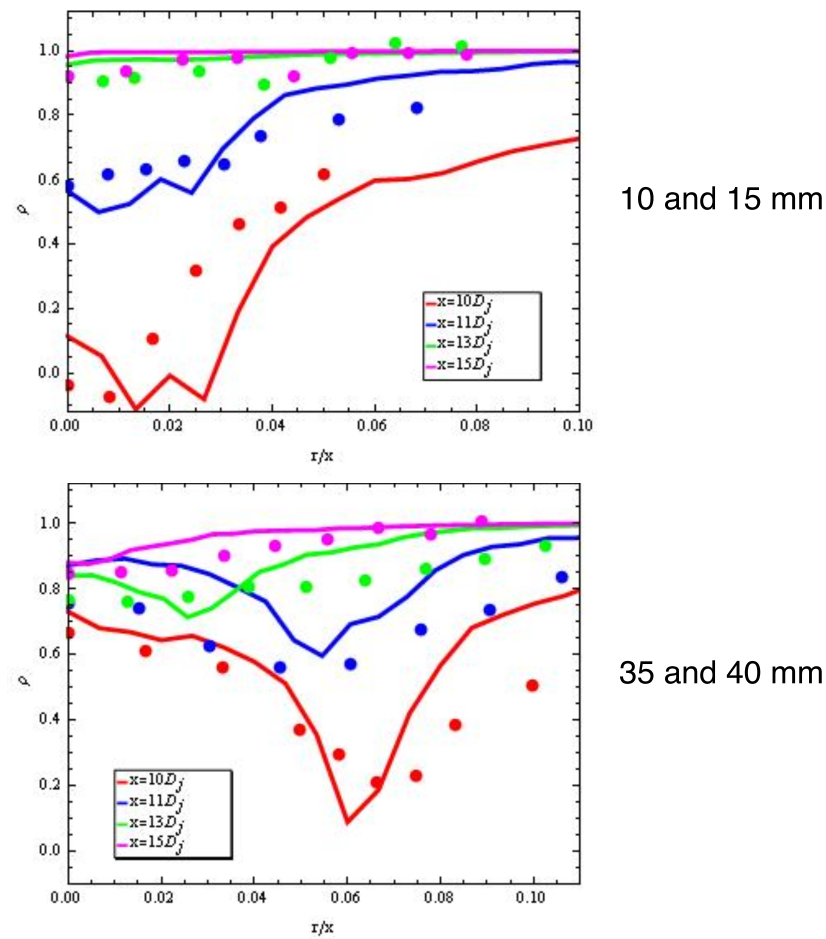
Using measured properties (surrogate RANS), LEM3D captures the mixing of scalars released within a jet

- Two ring sources (various diameter combinations) at $x/D_j = 9$ release scalars A and B, respectively
- A-B cross-correlation, ρ, is measured at various downstream locations (Tong & Warhaft, 1995)
- This configuration has not previously been modeled



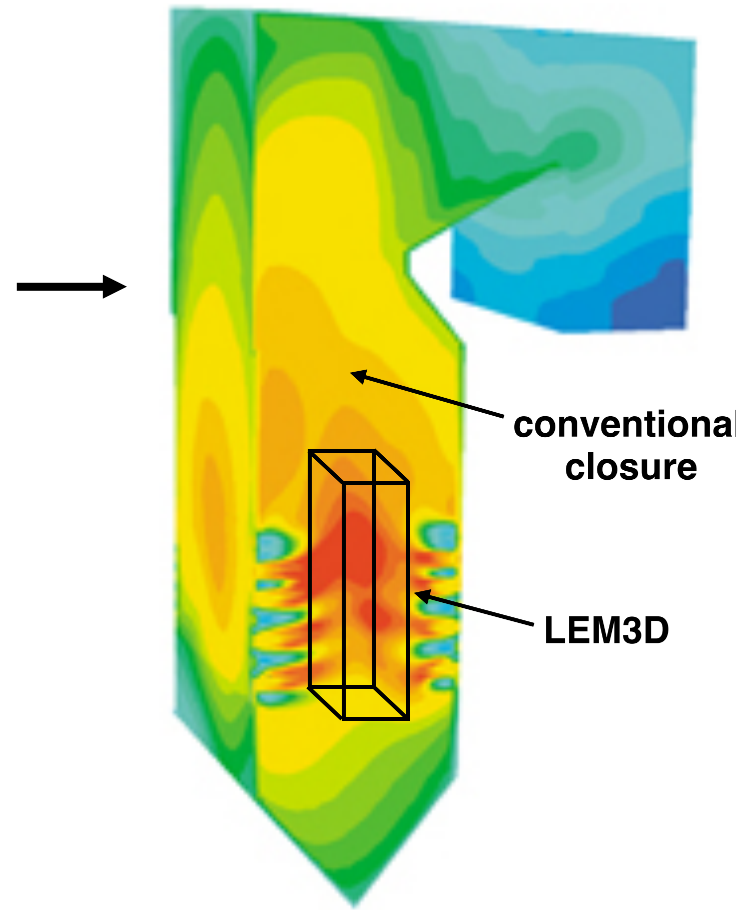
Radial profiles of ρ
(measurements: •, model: —)

Ring diameters



LEM3D is being generalized for combustion applications

- A variable-density formulation is under development (with 2-way RANS-LEM3D coupling)
- Chemical kinetics will be incorporated
- LEM3D sub-regions will be imbedded in flow simulations to resolve mixing locally
- Will validate against a purpose-built confined-jet-mixing experiment (SINTEF)
- Switching to the adaptive-mesh code will simplify the coupling algorithm
- Will couple LEM3D to LES (analogous to Suresh Menon's LES/LEM)
- Will couple LEM3D to an ODT-based 3D simulation (explained next)
- This work is a collaboration with SINTEF (S. Sannan, T. Weydahl)

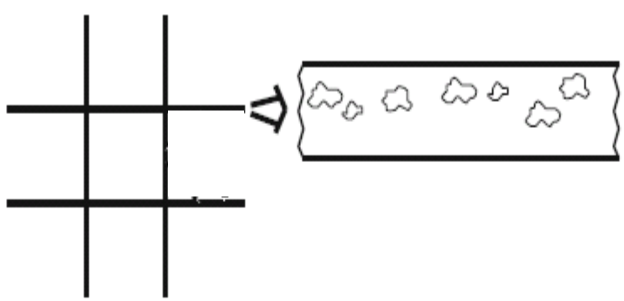


LES/LEM motivated 'superparameterization' (SP) closure of atmospheric flow simulations

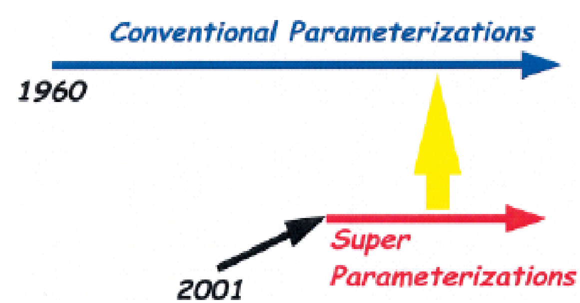
- Small scales resolved in 2D (vs. 1D in LEM and ODT)
- Deemed necessary despite high cost (NSF S&T Center)
- Cross-fertilization is ongoing, e.g., SP is adopting AME concepts

top view of a lattice-work of coupled vertical planar domains

side view of one domain (2D cloud simulation)



this approach is viewed as a climate modeling paradigm shift (Randall et al. 2003)



LEM and/or ODT domains can be coupled to obtain 3D simulations

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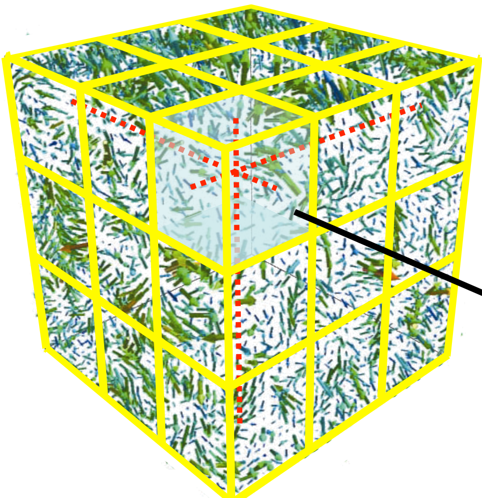
ODT domains can be coupled to obtain a 3D flow simulation (ODT3D)

- Same mesh geometry as LEM3D
- Different domain coupling because
  - for momentum, adjacent dissimilar states should be avoided
  - for momentum (but not species), some under-resolved mixing is acceptable
- Advection feedbacks between LEM3D and ODT3D:
  - LEM3D gets eddy events and CV face-normal mass fluxes from ODT3D
  - ODT3D gets thermal expansion from LEM3D
- Implementation strategy:
  - Can use coarser 3D mesh than LES due to standalone ODT capabilities
  - Incorporates large scale 3D effects to improve ODT representation of
    - **pulverized coal burners (by capturing recirculation)**
    - **stably stratified turbulence (by capturing internal waves)**
    - **Rayleigh convection (by capturing 'wind of turbulence')**
    - **etc. (greatly expands the range of possible applications)**

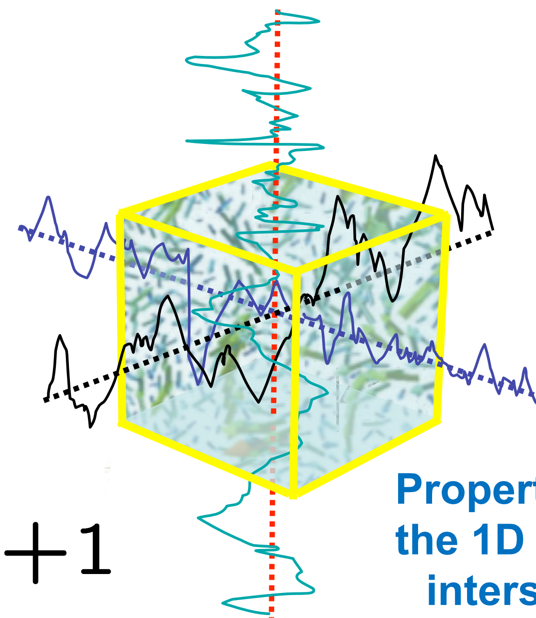
Treatment of 3D pressure-velocity coupling distinguishes two ODT3D formulations

- Incompressible formulation:
  - Continuity enforced using coarse-grained (CV scale) 3D pressure projection
  - ODT-resolved flow field is modified accordingly, a downscale coupling
- Pseudo-compressible formulation:
  - Enables domain coupling with no coarse-graining or downscale coupling
  - Hence termed 'Autonomous Microscale Evolution' (AME)
- Status
  - ODTLES (incompressible ODT3D)
    - **validated for homogeneous turbulence and various wall-bounded flows**
    - **Incorporation of passive and active (e.g., buoyant) scalars is in progress**
  - AME (pseudo-compressible ODT3D) requires
    - **adaptive-mesh ODT implementation (will configure for use in AME)**
    - **variable-property AME domain coupling (coded but not tested)**
    - **variable-property LEM3D domain coupling (future work)**

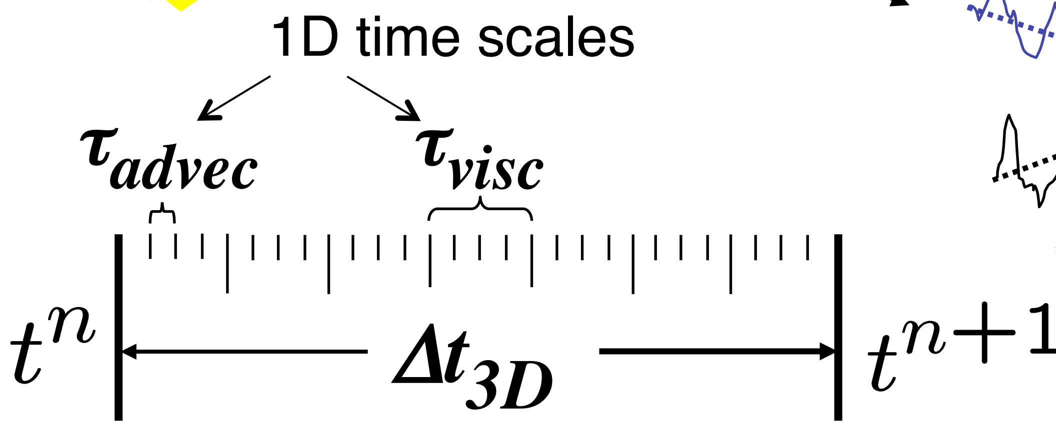
ODT3D is multi-scale in time advancement as well as spatial structure



If each 3D control volume (3DCV) contains N nodes of each intersecting 1D domain, then there are 3N nodes in the 3DCV, vs. N^3 nodes required for equivalent DNS resolution

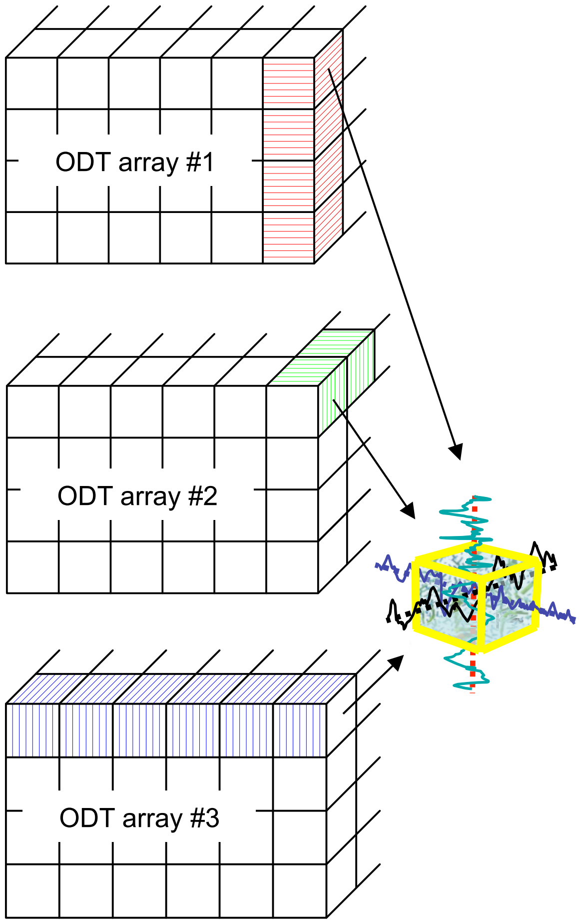


Property profiles on the 1D domains that intersect a 3DCV



ODTLES: Time advancement of a 3D lattice-work of coupled ODT domains captures all scales of motion

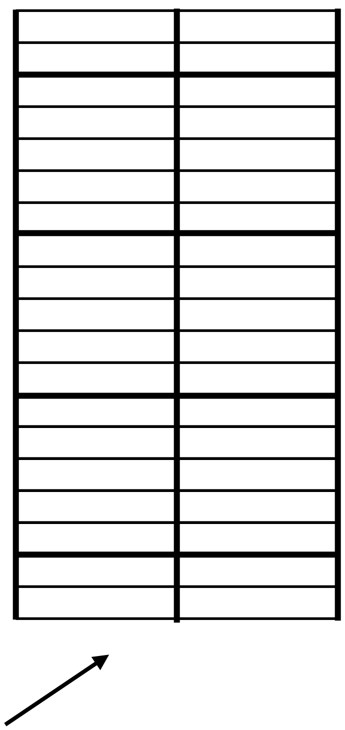
- Each ODT array spatially refines the coarse 3D partition (3DCVs) in one coordinate direction
- Each 3DCV is the intersection of three ODT domains, each within a different array (see the illustration)
- Time-advancement cycle:
  - **Resolved* 1D advancement on individual ODT domains**
  - **3D solenoidal advection couples ODT domains in each array**
    - **Time filtering assigns an 'advecting velocity' to each ODT-resolved CV face between ODT domains**
    - **Solenoidal condition then determines advecting velocities at ODT domain interior faces**
    - **The advecting velocities advect the resolved* velocity field**
  - **Coarse-grained pressure projection couples the three arrays**
    - **The adjusted coarse-grained flow field is solenoidal**
    - **'Reconstruction' applies the adjustments to the resolved velocities (downscale coupling)**



***high resolution requires subcycling (small time step)**

Solenoidal advection couples the ODT domains in each array

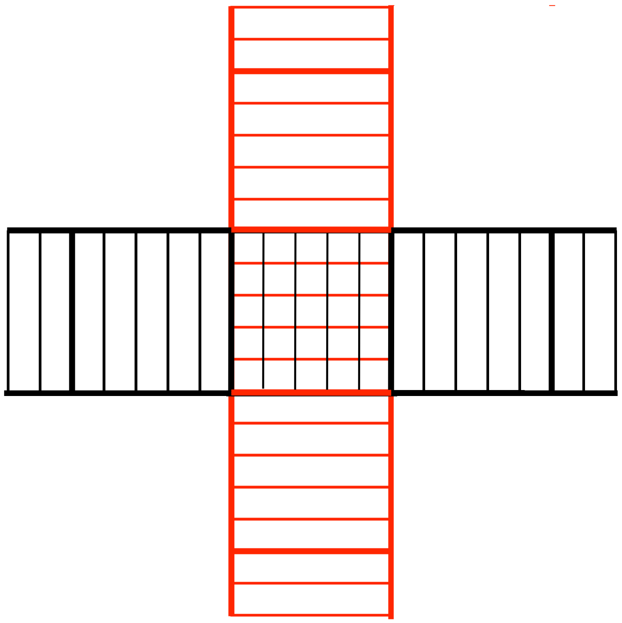
- Two adjacent vertically resolved ODT domains are shown
- ODT-resolved CV faces that separate ODT domains are vertical
- Time filtering assigns an 'advecting velocity' to each of these faces
- ODT domain interior faces are horizontal
- Solenoidal condition determines advecting velocities at these faces
- The advecting velocities advect the space-time-resolved velocity field
- Resolution of the advected field requires subcycling (small time step)



All lines are faces of ODT-resolved CVs
Bold lines are faces of 3DCVs

Coarse-grained continuity enforcement couples the three arrays

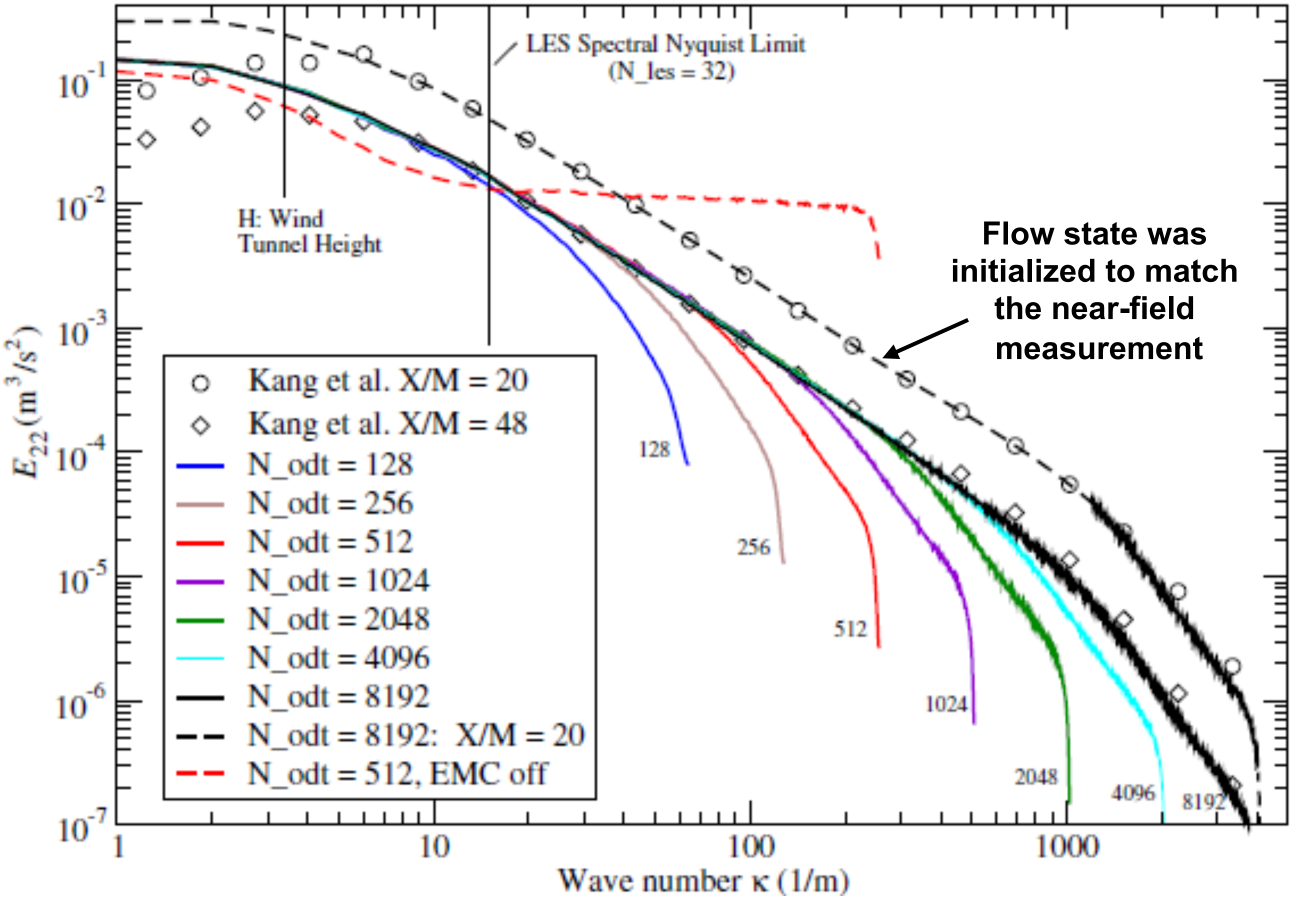
- Two orthogonal ODT domains are shown
- Coarse-grained velocities reside at 3DCV faces (bold)
- Each coarse-grained velocity is obtained by spatial averaging of ODT-resolved time-filtered ‘advecting velocities’
- Thus, pressure projection (continuity enforcement) combines inputs from all three ODT arrays
- ‘Reconstruction’ applies the adjustments to the ODT-resolved velocity field (down-scale coupling)



The first ODTLES application was homogeneous isotropic decaying turbulence

Wind tunnel flow is anisotropic at large scales

Largest ODT eddy size L_{max} = 4 * 3DCV size gives best results



<u>1D transverse energy spectra</u>

Symbols:
Re_λ = 720 measurements from Kang *et al.*, JFM 2003

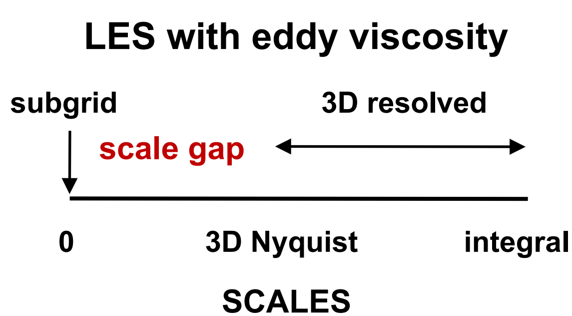
Curves:
Computed results for various ODT spatial refinements (N_odt cells per ODT line)

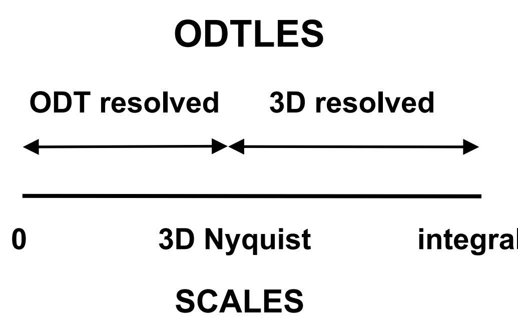
Here, ODT is not fully resolved, so an eddy-viscosity closure (‘EMC’) is applied within ODT

DNS and Smagorinsky-type LES are limiting cases of ODTLES

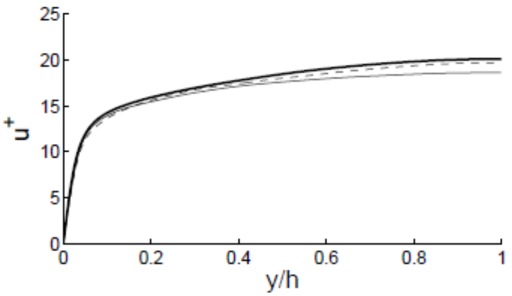
- DNS is obtained in the limit of small 3DCV size
  - As L_{max} vanishes, only small eddies are possible
  - The viscous penalty V in $S\,E = C\,(K - P - Z\,V)$ suppresses them by forcing $E < 0$

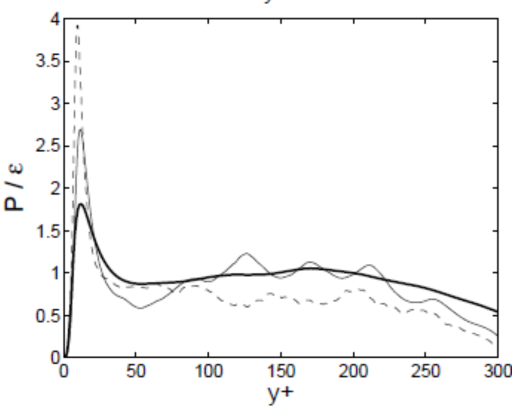
- Eddy-diffusivity LES closure is obtained for fixed 3DCV size, $L_{max} \rightarrow 0$, $C \sim L_{max}^{-2}$
  - Infinite eddy rate so randomness vanishes (law of large numbers)
  - Finite eddy-induced transport $\nu_{eddy} \sim C\,L_{max}^{2}$
  - $L_{max} \rightarrow 0$ implies a scale gap between 3D-resolved and 1D-resolved motions
  - No gap for $L_{max} \sim$ (3DCV size) which thus improves the physics compared to LES

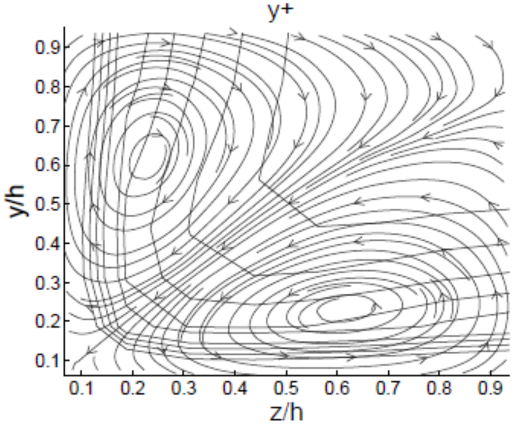




ODTLES captures 3D flow effects while fully resolving wall layers in 1D

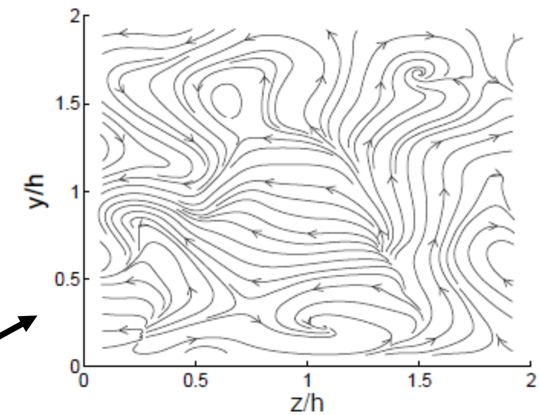


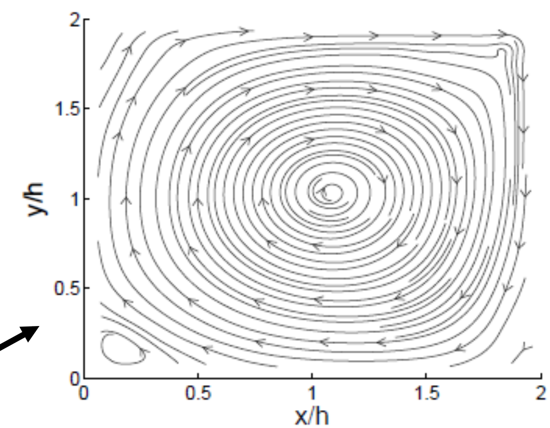




Validation cases:

- **Channel flow**: ODT3D performance is comparable to ODT, indicating that ODT3D domain coupling causes no significant loss of fidelity
- **Open channel** (no-slip wall and free-slip surface): Captures free-surface upwelling/downwelling
- **Square duct**: Captures secondary recirculation (spontaneous symmetry breaking)
- **Lid-driven cavity**: Captures wall-layer distortions induced by the primary recirculation





Detailed comparisons to DNS: Gonzalez-Juez et al. 2011