SAND2018-7037R

# A2e High-Fidelity Modeling (HFM) Project

## Overview of FY18 Q2 milestone completion

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# FY18 Q2 Milestone and background

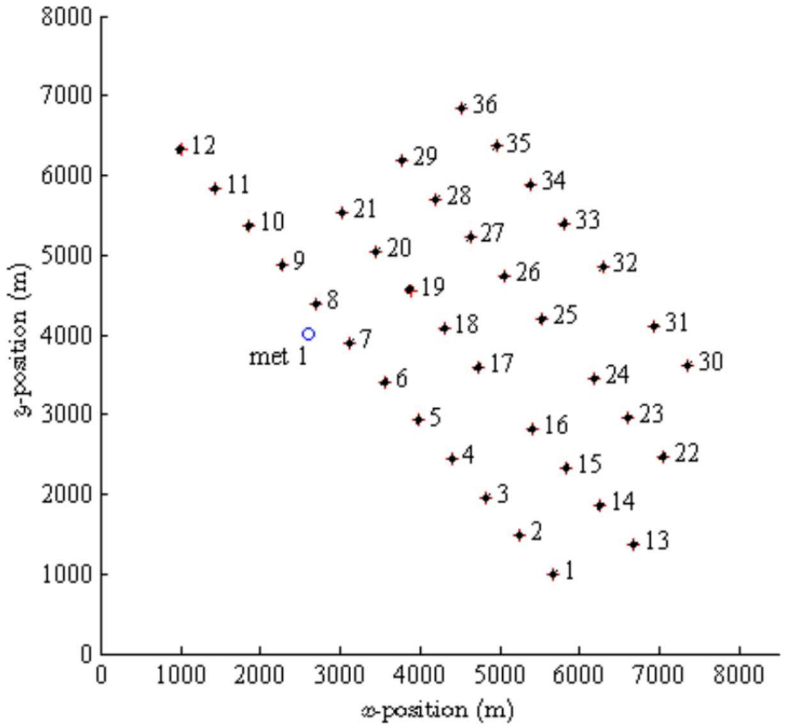
- **Milestone Description:** Annual Milestone (joint NREL/SNL): Create and disseminate documentation that compares the Nalu and SOWFA codes for actuator-line-based wind farm models, including the demonstration of the Windpark Egmond aan Zee (OWEZ). Comparisons will include simulation results for the same cases, assessing computational speed and scalability.
- **Background:**
  - The motivation for this milestone was to establish Nalu capabilities for wind farm simulations in the context of the established capabilities in the SOWFA code, and to position Nalu as the wind farm simulation tool for broader A2e research use
  - The objective was establish a baseline set of capabilities equivalent to those in SOWFA, and to prepare the Nalu code for a preliminary validation study with the OWEZ data
- **Milestone Team:**
  - NREL: Shreyas Ananthan, Matt Churchfield, Tony Martinez, Mike Sprague, Ganesh Vijayakumar, Shashank Yellapantula
  - SNL: Matt Barone, Myra Blaylock, Stefan Domino, Robert Knaus, David Maniaci

# Accomplishments for milestone completion

- Extensive team time was devoted to fixing issues around the outflow boundary condition exposed at the end of FY18 Q1
  - Compared (T-Tref) and (T-Tavg) formulations for the spatial average at a given height; the latter removes the vertical pressure gradient introduced by Boussinesq buoyancy term and should allow use of Nalu's standard open BC for inflow/outflow (has yet to be tested where flow is primarily aligned with mesh corners)
  - Final OWEZ simulations used (T-Tref) formulation, zero normal pressure gradient at the outflow boundary, and global mass correction for continuity
- Established a capability for near-turbine conformal-mesh refinement via the Percept utility
  - Capture of wake formation requires greater mesh refinement near the turbine and in its wake than in the broader atmospheric boundary layer (ABL)
  - A remaining issue is to better understand and address the impact on the flow of abrupt element-size changes and pyramid elements at the interface between two mesh-refinement levels
  - A better approach may be a non-conformal (i.e., hanging node) nesting approach, which would enable all-hexahedral-element meshes
- Implemented and tested a new fluid-structure-interaction algorithm
  - Implemented in OpenFAST-Nalu an FSI coupling algorithm that was demonstrated on a simple example to be second-order time accurate for both lock-step and different-time-step (sub-cycling) time integration

# Operational Egmond aan Zee (OWEZ) offshore wind plant

- Wind plant 10 km offshore of The Netherlands
- 36 V90 3 MW wind turbines; 70 m towers
- Turbine spacing within a row is roughly 7.1 rotor diameters (D); spacing between rows is roughly 11.1 D
- Turbines 7 and 8 were fully instrumented for mechanical loads measurements




Layout of the OWEZ wind plant; positive y-coordinate is North; positive x-coordinate is East

For details, see Churchfield et al., 2014, “A Comparison of the Dynamic Wake Meandering Model, Large-Eddy Simulation, and Field Data at the Egmond aan Zee Offshore Wind Plant”, proceedings of the AIAA Science and Technology Forum and Exposition 2015, Kissimmee, Florida, January 5–9, 2015; also published as NREL technical report NREL/CP-5000-63321.

# OWEZ ABL precursor: Nalu & SOWFA simulation details

**Precursor atmospheric boundary layer (ABL) simulation (without turbines)**:

- Required to generate initial conditions and time-dependent inflow boundary conditions for the OWEZ simulation
- Uses periodic boundary conditions to represent an “infinite” horizontal domain
- Must be run long enough to generate statistically steady atmospheric turbulence; neutral stability is chosen here

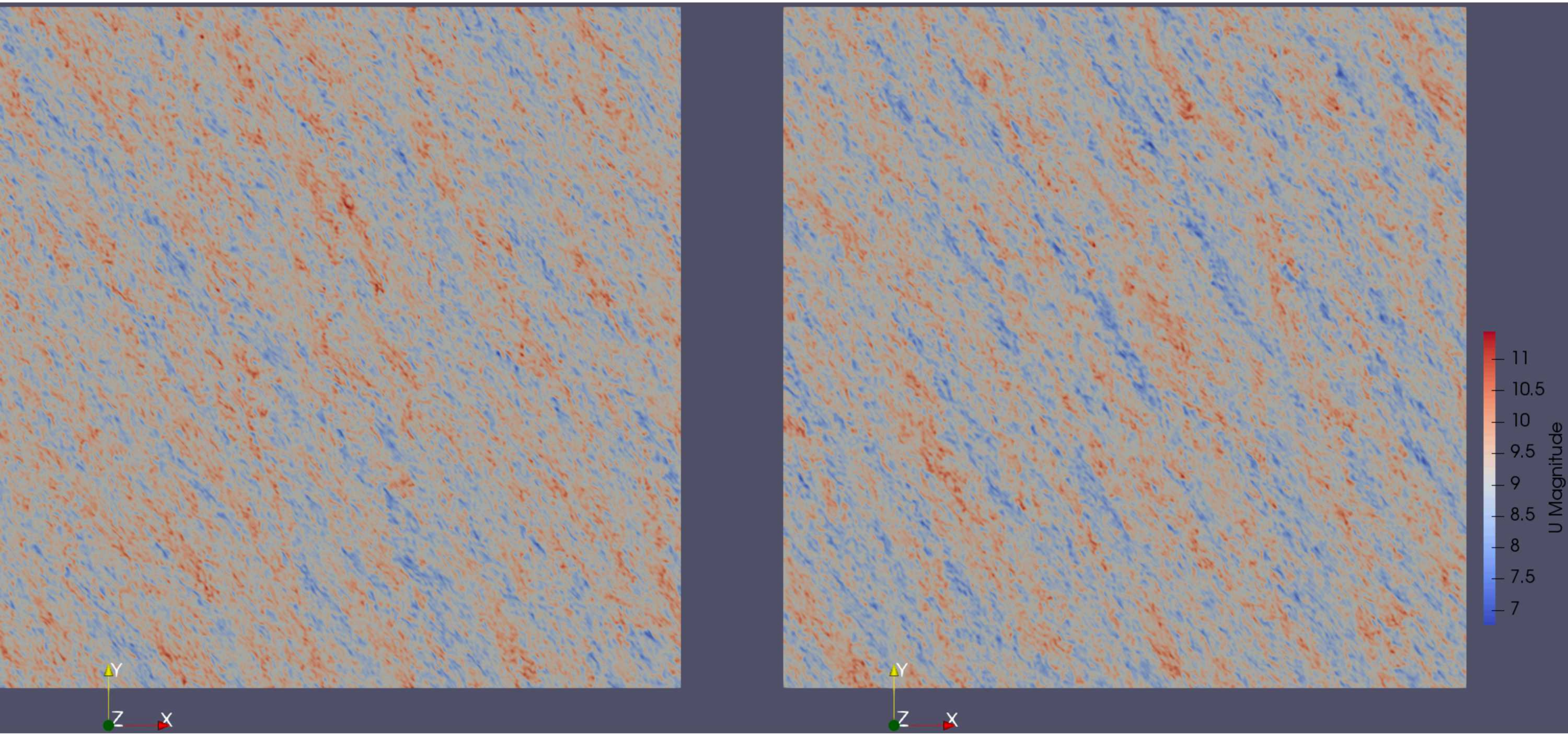
**SOWFA ABL Precursor:**

- Spatial domain & discretization:
  - 9 km x 9 km x 1km, 81M grid points (dx = 10 m)
  - Cell-centered finite-volume scheme
- Time-domain & discretization:
  - 20,000 sec simulation, dt = 0.5 sec (approx.; CFL = 0.75)
  - PISO time-integration algorithm
  - One outer-loop iteration (limits simulation to first-order time accuracy); three inner-loop iterations

**Nalu ABL Precursor:**

- Spatial domain & discretization:
  - 9 km x 9 km x 1km, 81M grid points (dx = 10 m)
  - Edge-based finite-volume scheme
- Time-domain & discretization:
  - 20,000 s simulation, dt = 0.5 s (constant)
  - Second-order backwards-differentiation-formula (BDF2) time-integration algorithm
  - Two outer-loop iterations per time step (required for second-order time accuracy)

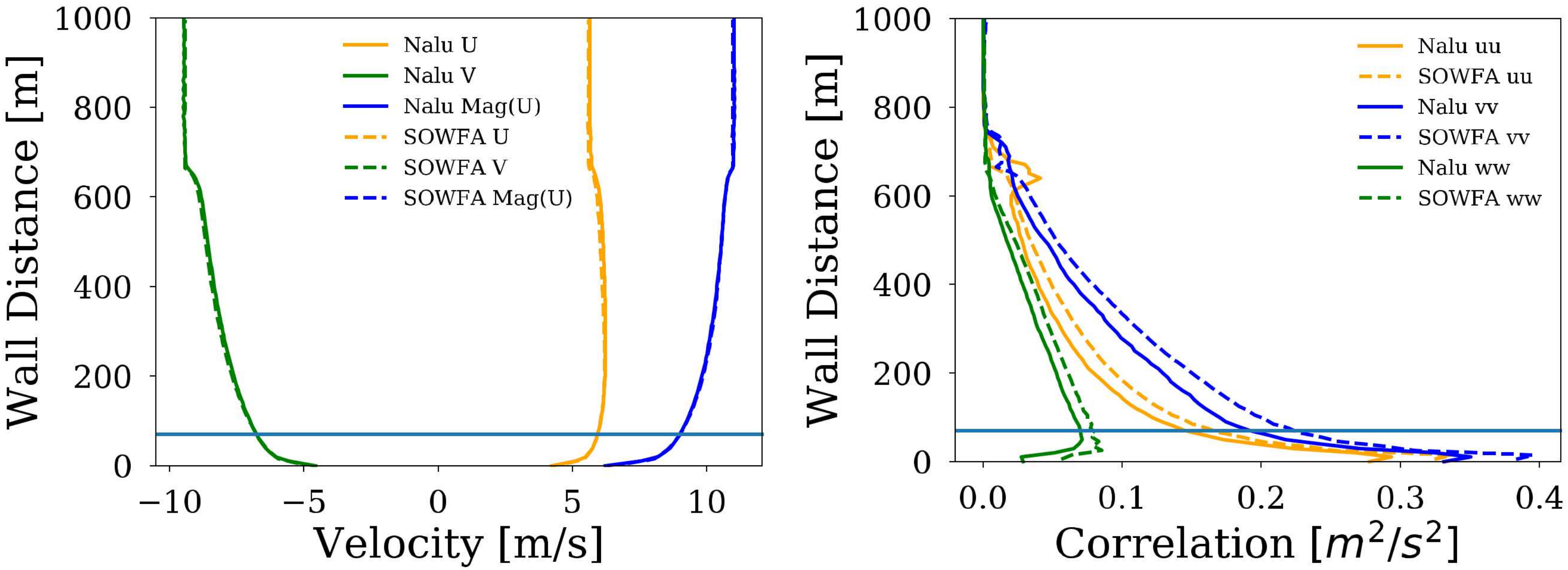
# OWEZ ABL precursor results: Hub-height velocity




*Nalu (left) and SOWFA (right) velocity magnitudes at hub height (70 m) after 20,000 s of initialization; instantaneous differences expected with different time-integration approaches and the nature of turbulent flows.*

# OWEZ ABL precursor results: Mean velocity & velocity-correlation profiles

- Velocity and velocity-correlation profiles shown below
- Time averaging performed over 16,400 s < t < 20,000 s
- Good agreement is seen in mean velocity profiles
- Differences in velocity correlations may be due to model differences, e.g.,
  - Models use different specifications of turbulent viscosity at the first grid point
  - First grid points are in different locations for the two codes




*Comparison of time-averaged velocity profiles (left) and velocity correlation (right) from Nalu and SOWFA.*



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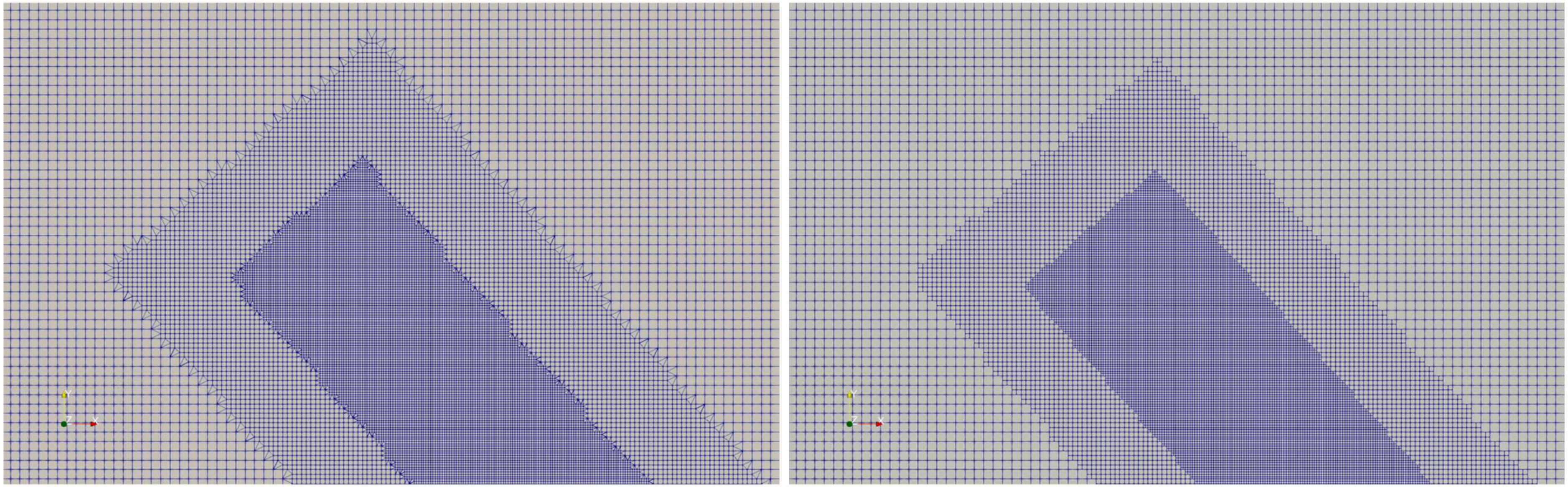
# OWEZ wind farm: Simulation details

**SOWFA:**

- 139M grid points; non-conformal ”nesting” of refined meshes
- Constant dt = 0.0625 s; PISO algorithm (1 outer iteration)
- Cell-centered finite-volume scheme
- Coupled to OpenFAST models of the 36 Vestas V90 turbines; first-order-accurate FSI

**Nalu:**

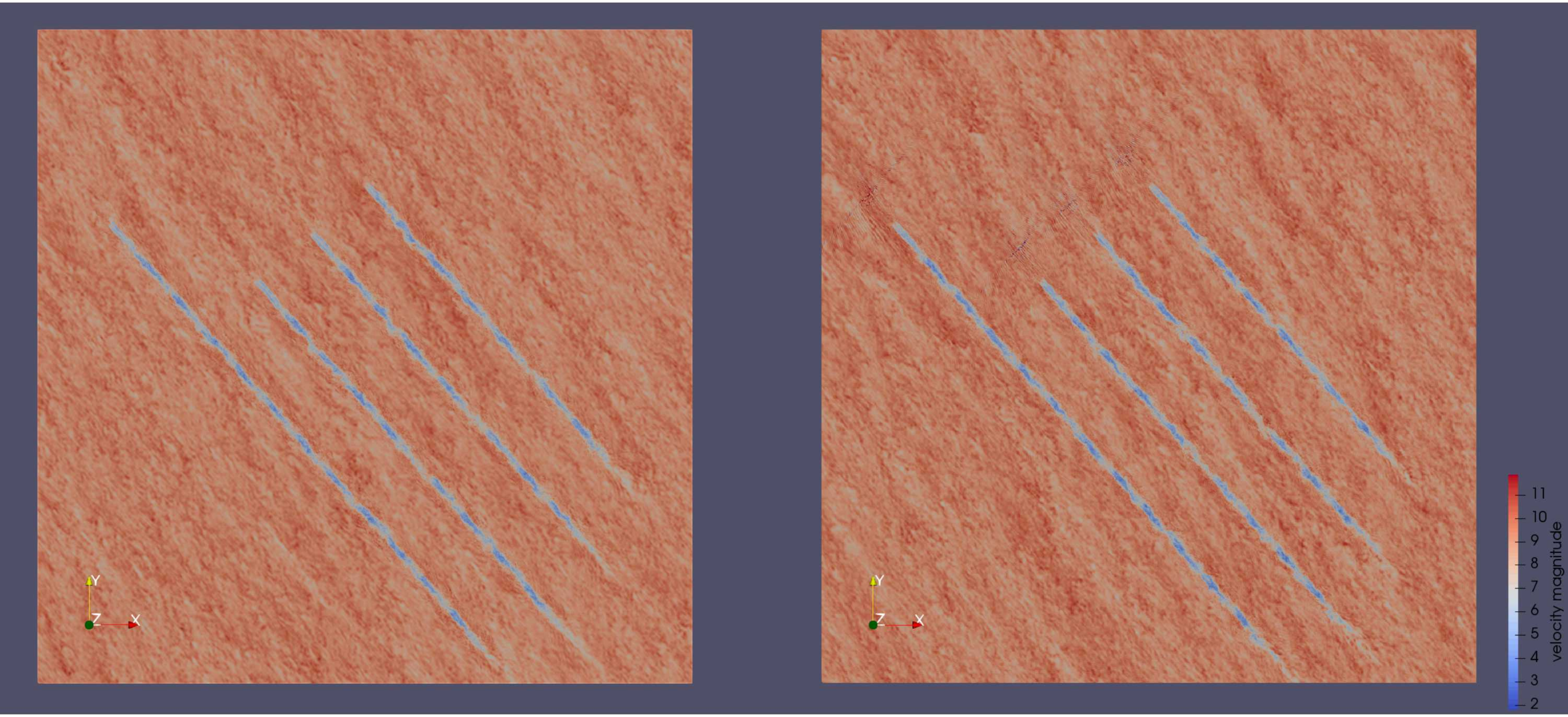
- 153M grid points; conformal ”nesting” of refined meshes
- Constant dt = 0.0625 s; BDF2 algorithm (2 outer iterations)
- Edge-based finite-volume scheme
- Coupled to OpenFAST models of the 36 Vestas V90 turbines; first-order-accurate FSI



*Nesting of refined meshes in Nalu (left) and SOWFA (right).*

# OWEZ wind farm results: Hub-height velocity

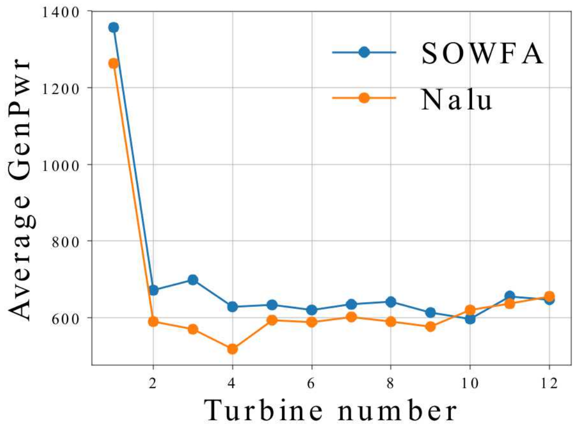
- Hub-height velocities show qualitative agreement
- Flow anomalies seen at nested-domain inlets in SOWFA results




*Velocity magnitude at hub height (70 m) for Nalu at t = 186 s (left) and SOWFA at t = 188 s (right) simulations (after initialization with ABL precursor).*

# OWEZ wind farm results: Power

*Row 0*

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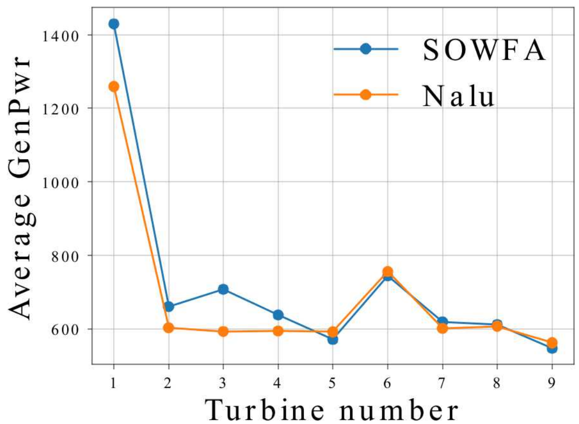


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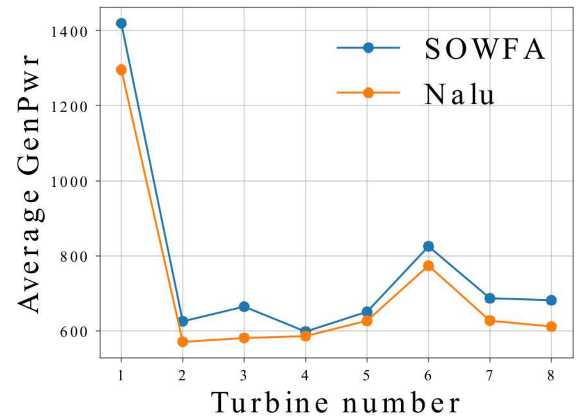


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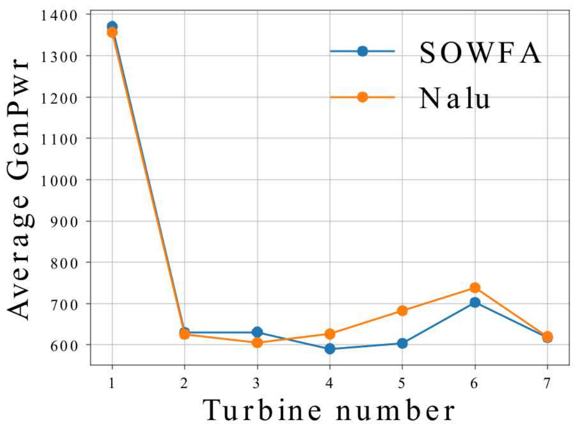



*Turbine power for each row of OWEZ averaged over 20,250 s - 20,900 s.*

- The agreement is satisfactory
- Differences can be attributed to nature of turbulent flow
    - It is expected that agreement would improve with longer averaging period

# Nalu & SOWFA preliminary timing results on Peregrine Haswell nodes

**Full ABL precursor simulations** (81M grid points; 1,440 cores; dt = 0.5 sec)
- SOWFA 2,000 sec simulation: 2.5 sec / time-step
- Nalu 2,000 sec simulation: 3.3 sec / time-step

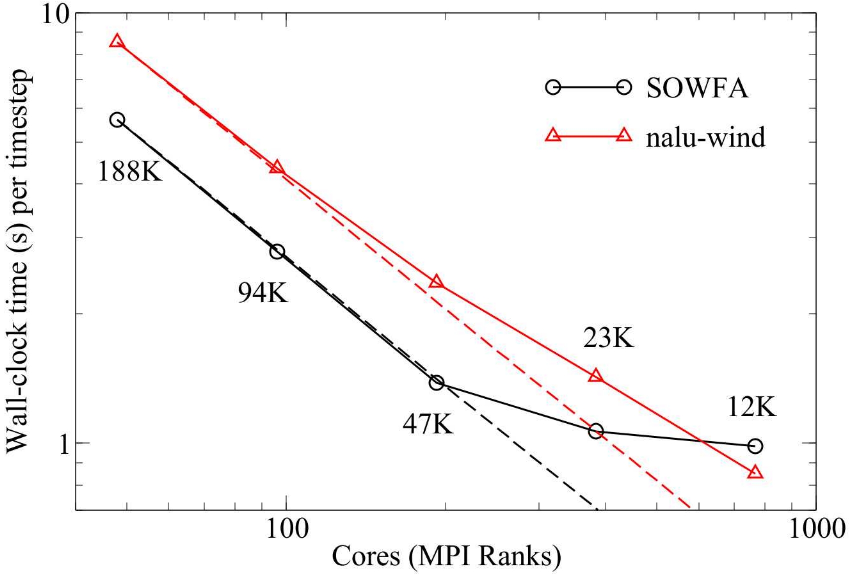
**Full OWEZ simulations (with 36 turbines):**
- **SOWFA:**
  - 139M grid points; 1920 cores; dt = 0.0625 s
  - Simulated time: 20,000 s – 22,004 s (32,060 time steps)
  - Wall clock time: 48 hrs
  - Time per time step: 5.4 s
  - **Comp. Cost*:** (wall-clock-time-s x #-cores) / (simulated-time x millions-grid-points) = **1191**
- **Nalu:**
  - 153M grid points; 1440 cores; dt = 0.0625 s
  - Simulated time: 20,000 s – 20,913 s (14,609 time steps)
  - Wall clock time: 48 hrs
  - Time per time step: 11.8 s
  - **Comp. Cost*:** (wall-clock-time-s x #-cores) / (simulated-time x millions-grid-points) = **1781**

**Comments specific to these configurations and test runs:**
- SOWFA is faster than Nalu (24% for ABL; 33% for OWEZ)
- SOWFA employs a faster, but less accurate, time-update algorithm than Nalu
- These are preliminary timing results (subject to system variability); more rigorous comparison would consider accuracy vs. computational resource through repeated runs

* Measure of computational resource divided by simulated space-time domain; a smaller number is better (this measure is appropriate when models have different resolutions and runtime core numbers)

# Nalu & SOWFA preliminary scaling results on Peregrine Haswell nodes

- A computational strong-scaling study was performed with Nalu-Wind and SOWFA for an ABL precursor simulation (no turbines)
- Good strong-scaling performance typically requires many gridpoints per core
- Simulation details:
  - 3 x 3 x 1 $km^3$ domain
  - 300 x 300 x 100 = 9 x $10^6$ grid points
  - dt = 0.5 s; run for 2000 time steps
  - Runs were performed on Peregrine's Xeon Haswell processors



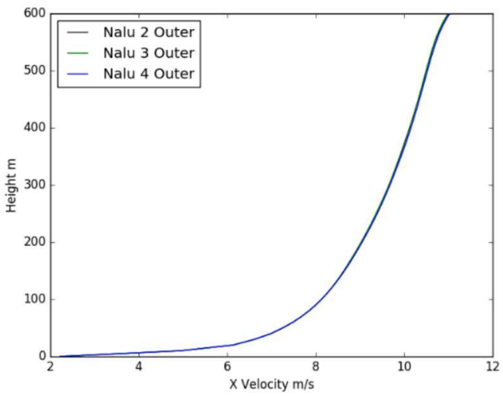

*Wall-clock time per time step (for a fixed problem size) as the number of processor cores is increased; numbers indicate gridpoints per core; dashed lines show ideal scaling*

- Strong scaling performance degrades for SOWFA with less than 47K gridpoints per core
- Nalu-Wind shows good scaling down to 12K gridpoints per core
- SOWFA algorithm uses only one outer iteration, which is faster, but less accurate, than the Nalu-Wind algorithm, which uses two

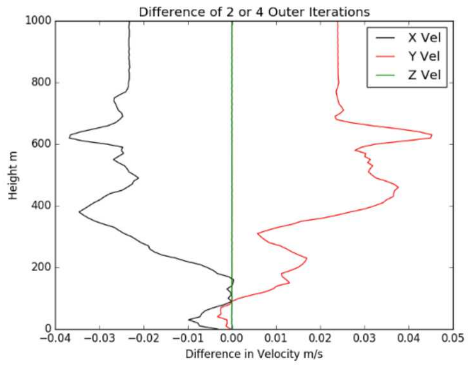
# Nalu: Compared 2,3,and 4 solver iterations per step

## Simulation Set up

- Domain size: 3 km x 3 km x 1km
- Grid resolution: 10 m – 300 x 300 x 100 nodes
- Flow: 8 m/s velocity in the x direction
- Time step: Δt = 0.5 sec, Final time: 20,000 sec
- Averaging window: 3600 sec (last window is presented)
- Iterations:
  - 2, 3, & 4 outer and 1 inner using Nalu
  - 1 outer and 3 inner to compare with SOWFA



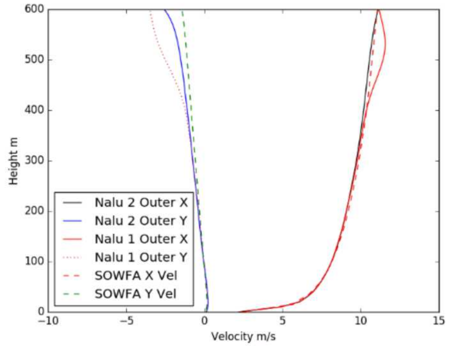

| Number of Iterations | Time for 20,000 sec using 192 processors |
|---|---|
| 2 | 63 hours |
| 3 | 93 hours |
| 4 | 121 hours |




- No significant change in solution after 20,000 seconds
  - <1% difference for velocities parallel to the ground
  - Using 2 iterations reduce running time by 50% but has same results as 4 iterations

## Nalu and SOWFA Comparison

- SOWFA is run with 1 outer iteration and 3 inner iterations
- Nalu is 1st order in time with this configuration (2nd order with >1 outer iteration)



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# HFM Verification & Validation (V&V) update

| Nalu model | Relevant links | Status Verification | Status Validation* | Code V&V notes |
|---|---|---|---|---|
| Outflow BC | Github pull/commit<br>Theory<br>Verification | C-L | I | Formal verification limited to simple stratified laminar channel; future work will test BC with heated flat plate in turbulent flow. Fixed outflow issue exposed in FY18 Q1 for CVFEM discretization. |
| Top ABL BC | Github pull/commit<br>Theory<br>Verification | C | I | |
| AL coupling (FSI) | Github pull/commit<br>Theory<br>Elliptic wing testing | C-F | I | Implemented in OpenFAST-Nalu an FSI coupling algorithm that was demonstrated on a simple example to be second-order time accurate for both lock-step and different-time-step (subcycling) time integration. Some verification work remains for actuator-line/BeamDyn coupling. |
| Coriolis term | Theory | C | I | In process of adding online documentation showing verification results that were completed internal to project. |
| Buoyancy term | Github pull/commit<br>Theory<br>Verification | C | I | |
| Atmospheric forcing term | Github pull/commit<br>Theory | C | I | In process of adding online documentation showing verification results that were completed internal to project. |
| Wall model | Github pull/commit<br>Theory | C-F | I | In process of adding online documentation showing verification results that were completed internal to project. Further testing of wall model implementation in Nalu was performed in Q2. Spatially and temporally averaged turbulent flow quantities from OWEZ turbulent atmospheric boundary layer were compared against the profiles predicted by SOWFA and were found to compare accurately. |
| ABL-Precursor inflow coupling | Github pull/commit<br>Theory<br>Verification | C | I | |

**Status Key**

| | | |
|---|---|---|
| Complete | C | Testing complete |
| Complete-Further | C-F | Testing complete, further studies will better quantify or reduce prediction uncertainty. |
| Complete-Limited | C-L | Tests complete, but the study does not capture the complete model capability. |
| Incomplete | I | |

*Note: Validation work will transfer to the Wake Dynamics project, with support from the HFM project.

## Comments and next steps

- The fix for the outflow boundary-condition will be cleaned up and merged into the `master` branch of Nalu-Wind
- Capability for non-neutrally stable flows is needed; planned for completion by end of FY18 Q4
- As with all incompressible-flow CFD solvers, bulk of simulation time (and barrier to strong scaling) lies in the linear-system solvers
  - The ExaWind Exascale Computing Project (ECP) will continue focusing on reducing time to solution and performance portability
- Overall, SOWFA and Nalu are providing simulation results with satisfactory agreement
- For the ABL and actuator-line simulations described here, SOWFA provides faster time to solution
  - SOWFA uses less-accurate time-stepping algorithm that limits simulations to first-order time accuracy
  - Nalu shows better strong scaling performance at lower numbers of gridpoints per core
- Experiences setting up and running the OWEZ case will inform the user-documentation required for completion of the FY18 Q4 milestone