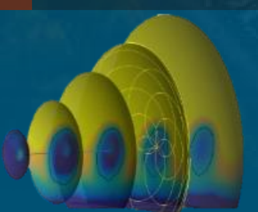
SAND2021-12536PE

Wind Energy Physics-Based Modeling Through High-Performance Computing

October 7, 2021




Energy & Earth Systems Seminar Series

DEVELOPED BY

David Maniaci and Alan Hsieh

Wind Energy Technologies Department (Org 8921)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia Wind Energy Program Strategy

- Rotor Innovation & Operations
- Offshore Design Optimization
- Wind Plant Data Science & AI
- Grid Integration & Power Systems
- Solutions to National Security Tech. Barriers

Controls and Sensors	Cross-cutting capabilities in both experimental control algorithms and innovative sensor technology are key to fundamental wind plant performance
Plant Experimentation	Design experimentation and facilities integrating instrumentation, components and plant functionality to deliver state-of-the-art validation for onshore/offshore plants
Advanced Modeling	Modeling system engineering concepts and components with advanced simulations providing insights, optimization and validated results for onshore/offshore plants

Mission Statement:

Sandia's Wind Energy Technologies Department leads scientific research that furthers the modernization, resilience, and sustainability of our nation's critical energy assets.

As a trusted DOE laboratory, we strive to advance innovation using world-class testing and computational capabilities to enable and maintain a global supply of clean, affordable and dependable wind-generated energy.

High-Fidelity Modeling in Wind Energy

Why is the High-Fidelity Modeling (HFM) important? HFM Provides:

Pathways to understanding wind plant physics and reducing wind plant losses

Simulation-data and knowledge foundations for the next-gen design tools

The capability to explore disruptive technology innovations quickly and with confidence

Optimization of new technology prior to demonstration or qualification testing

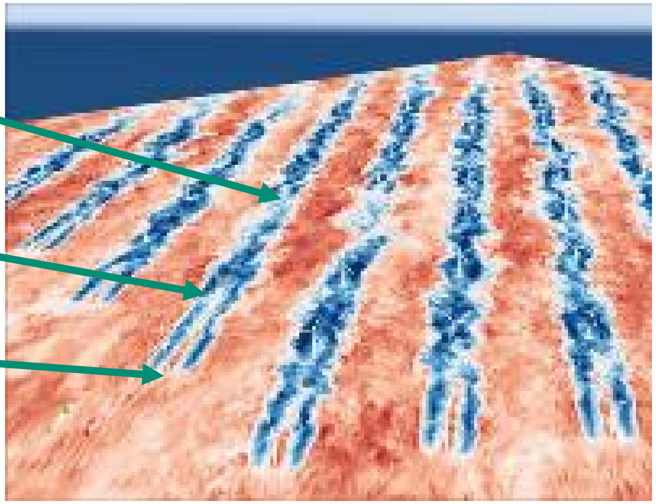
Photo by Gitte Nyhus Lundorff, Bel Air Aviation Denmark – Helicopter Services

Can we <u>predict</u> and <u>understand</u>:

Impact of wakes on downstream turbines?

Evolution of the wakes?

Formation of the wakes?



Lilligrund wind farm (Churchfield)

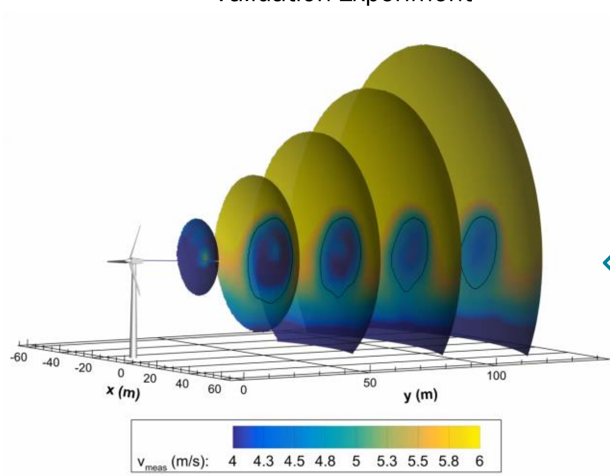
Verification, Validation, and Uncertainty Quantification

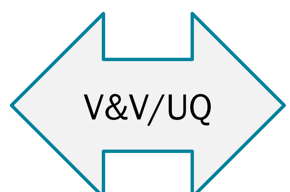
The application of V&V/UQ processes mitigates the risk of using the data from computational models for making decisions for wind energy applications

- Ensure that the predictive capability of the suite of models being developed across the wind program is established through formal V&V/UQ processes.
- Quantitatively determine where models are valid and where improvements are necessary
- These tools will be adopted by the wind industry or used to improve in-house software

Validation Focused Program

Validation Experiment





Computational Modeling

Prediction → Innovation

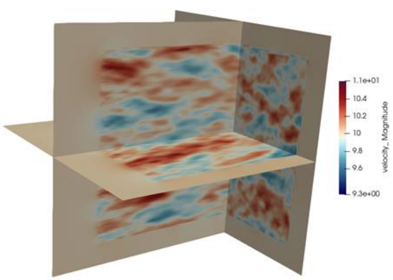
Wind Plant High-Fidelity Modeling Projects

Thrust lead: Paul Crozier

High Fidelity Modeling

Improving high-fidelity wind farm and wind plant models – atmosphere and blade resolved simulations to more accurately capture turbulence and turbine wake interactions.

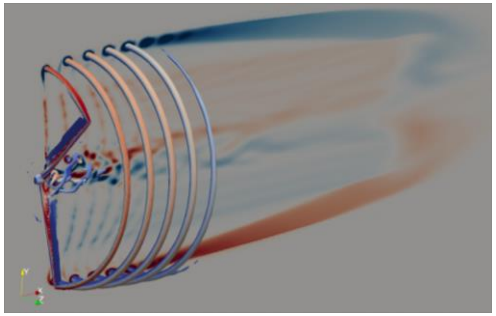
- Leverages SWiFT data from past wake steering experiment.
- Predict fundamental physics of next-generation offshore platforms



- Synthetic turbulence “injection” inside a CFD domain

NaluCFD leveraged to create Nalu-Wind

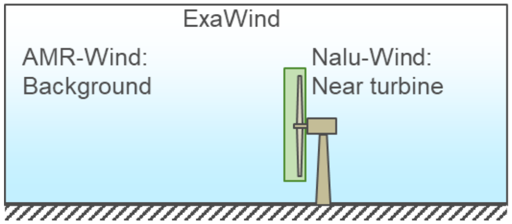
https://github.com/NaluCFD/Nalu
https://github.com/Exawind/nalu-wind



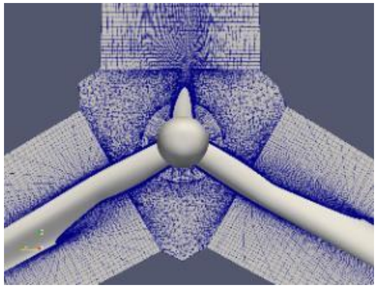
- Flow structure around 5MW turbine using Nalu-Wind

ExaWind

Developing a code suite for wind applications to efficiently run on next-generation exascale HPC platforms. Started with CPUs, moving to GPUs. Multi-lab effort, hybrid solver built on AMR-Wind and Nalu-Wind code bases.



- Near-body mesh developed for 5MW turbine in Nalu-Wind

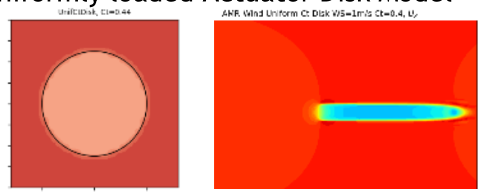


HFM Toolkit for Wind Resource Characterization and Wind Farm Development

Joint project with NREL, SNL, and General Electric
Funded through DOE Technology Commercialization Fund (TCF)

- Develop Exawind software suite into industry-ready tool for wind farm siting and wind resource assessment, accounting for blockage effects, turbine-to-turbine variations

Uniformly loaded Actuator Disk Model



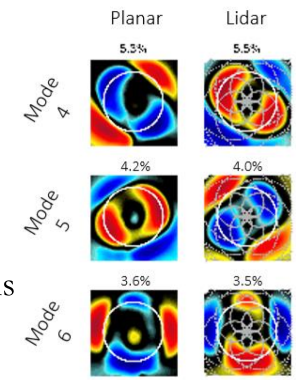
Wind Plant V&V/UQ Project

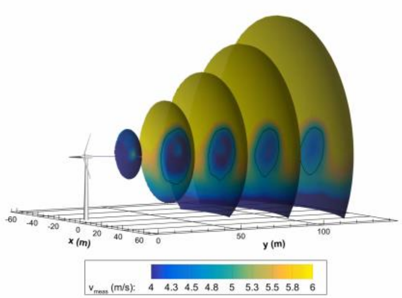
Thrust lead: David Maniaci

Verification & Validation

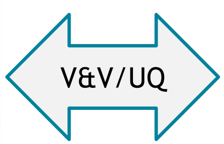
Apply formal methods to establish environmental regimes and operational conditions where computational models can be trusted for wind plant applications.

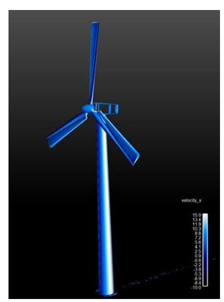
- Establish best practices for wake predictions using mid- and high-fidelity models
- Develop enhanced validation techniques for wake assessment
- Integrate experiment gaps analysis with experimental planning and instrumentation development





Validation Experiment
(SWiFT Facility)



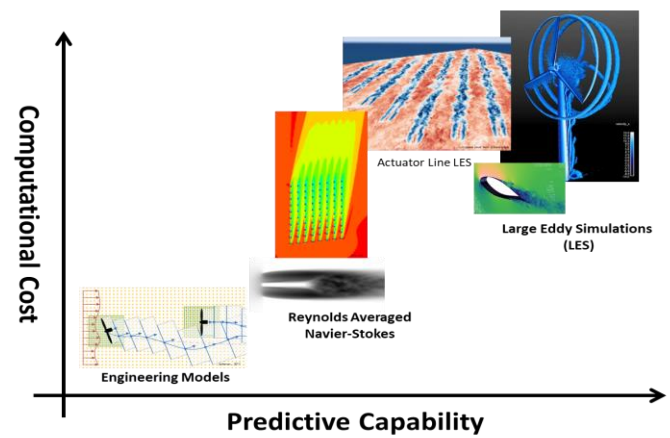


High-Fidelity Modeling
(Nalu-Wind/Exawind)

Uncertainty Quantification

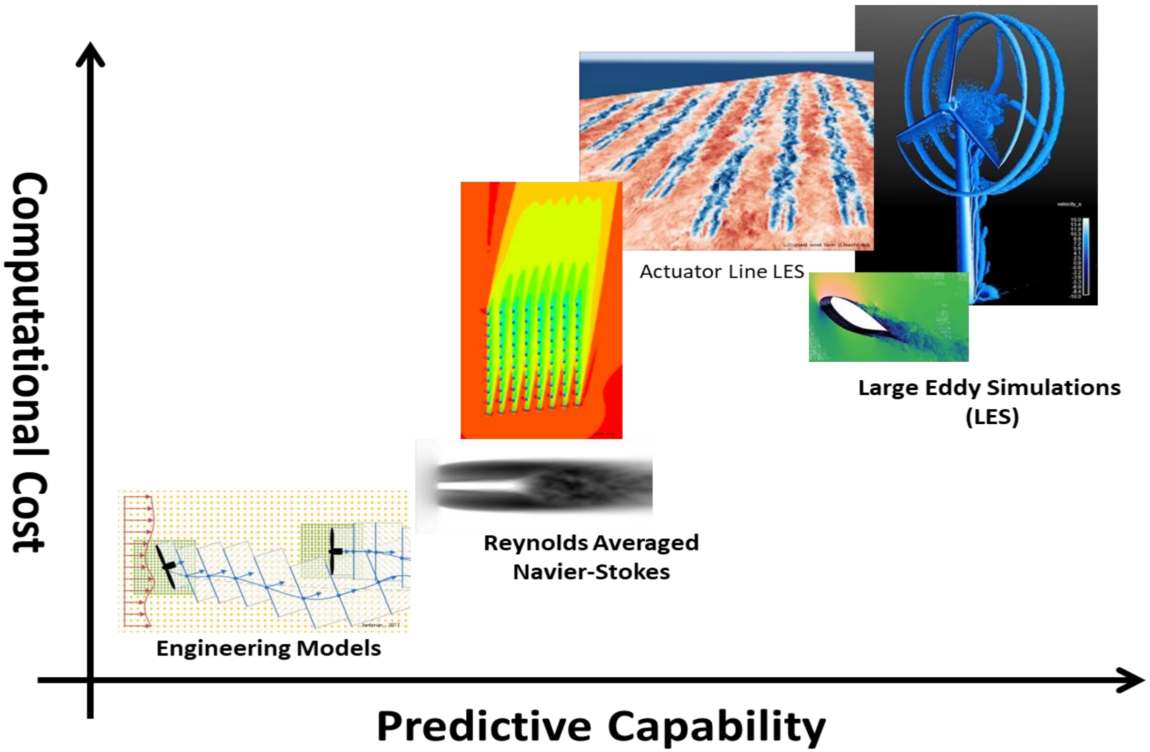
Develop formalized techniques for uncertainty characterization of wind plant models including advanced methods to reduce overall computational burden.

- Multifidelity UQ methods leverage low- and high-fidelity simulations to optimize uncertainty estimation
- Development of wind farm model hierarchy for a range of wind energy applications
- Leverage machine learning techniques for state-of-the-art data analysis and decision making



Multifidelity Strategies for Uncertainty Quantification

Wind Industry Relies on Many Levels of Computational Models



Wind plant challenges for UQ

- **High-fidelity** state-of-the-art modeling and simulations with HPC
- **Severe** simulations **budget constraints**
- **Significant dimensionality** driven by model complexity

Objectives of the study:

1. Demonstrate multifidelity (MF) surrogate efficiency for **efficient forward UQ**
   → Uncertainty's impact on wind plant performance
2. Leveraging MF strategies for **efficient inverse UQ**
   → Uncertainty characterization
3. Adaptation of MF sampling strategies for **Optimization Under Uncertainty** workflows
   → Wind plant's performance augmentation under uncertainty

Wake Model Hierarchy:

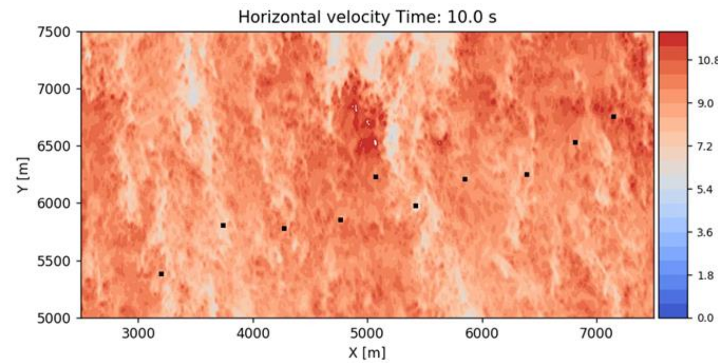
- Blade Resolved (ExaWind)
- **LES Actuator Line** (>ExaWind)
- **LES Actuator Disc** (>ExaWind)
- Vortex Method Free Wake
- **RANS 3D** (**WindSE** > ExaWind)
- **DWM (FAST.Farm + TurbSim)**
- **BEMT (FAST-AeroDyn+TurbSim)**
- Empirical Wake Model (FLORIS)

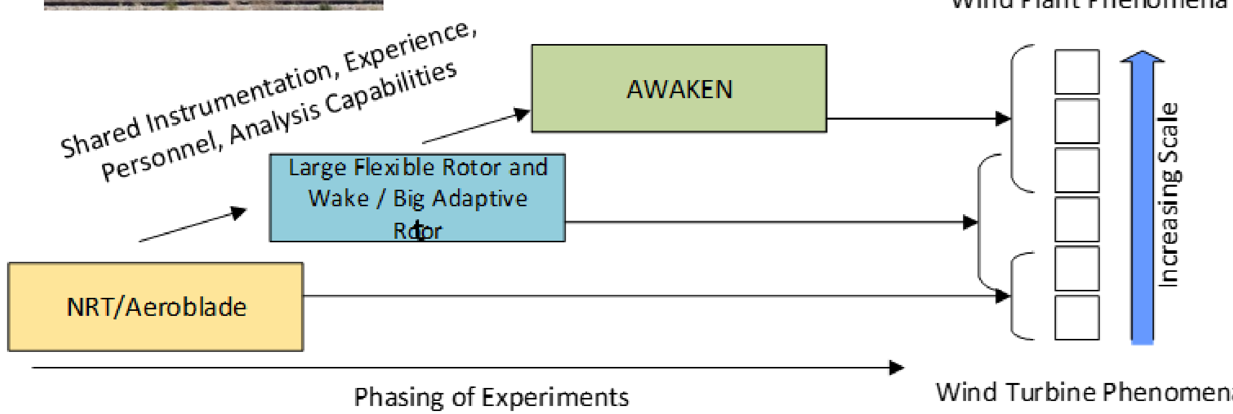
Coordinated Hierarchy of Validation Experiments

National Rotor Testbed

Rotor Aerodynamics Aeroelasticity & Wake Experiment

The American Wake ExperimeNt (AWAKEN)





National Rotor Testbed (NRT)

Sandia National Laboratories

Recently completed work

- First kW*hours of electricity produced
- Safe operation in region 2 and 2.5
- Rotor fully commissioned except for >3 hours in region 3 with pitch control

Ongoing work

- Address pitch system dynamics in region 3
- Measure spanwise bending moments to show scaled wake design
- Tune torque constant to achieve tsr = 9
- https://github.com/ckelley2/NRT

Rotor Aerodynamics, Aeroelasticity, and Wake Experiment

RAAW
Rotor Aerodynamics Aeroelasticity & Wake Experiment

- Recently completed work
  - Formalized agreement between NREL, Sandia, and GE to use 2.8 MW turbine in Lubbock Texas
  - Discussion with three aerodynamic measurement experts on MW-scale turbines
  - Quantification of blade deflection uncertainty using photometrics calculator
- Ongoing work
  - Instrumentation purchases for inflow and wake
  - Design of experiment

NREL NATIONAL RENEWABLE ENERGY LABORATORY   Sandia National Laboratories   GE Wind Energy

The American Wake ExperimeNt (AWAKEN)

AWAKEN is a multilab project including Sandia, PNNL, LLNL, and lead by NREL

Experiment will be conducted from January 2022 to September 2023 within 5 wind plants near the DOE ARM site in north central Oklahoma

Collaborators include GE, 3 wind plant owner operators, DOE ARM, NOAA, universities, and potentially NSF

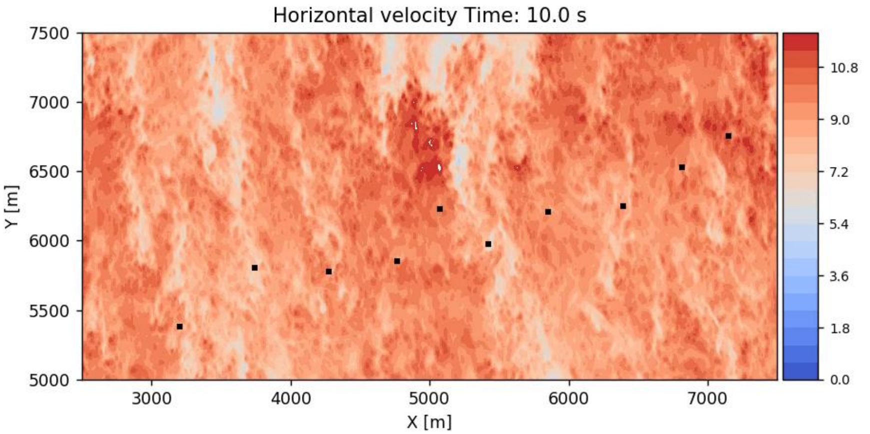
The goal is to collect validation data and improve understanding on the interaction between the atmosphere and wind plants:

- including momentum transport between atmosphere and wind plants
- turbulence development within wind plants
- upstream wind plant blockage
- wind plant wakes and their effects on downstream plants
- control strategies for improved performance

Sandia developed the Instrumentation Development Roadma to assess gaps in instrumentation for future DOE field campaigns and provide recommendations for development

The AWAKEN project will help validate our HFM tools to increase wind plant simulation confidence leading improved wind turbine and wind plant design and operation

Nalu Simulation of Thunder Ranch

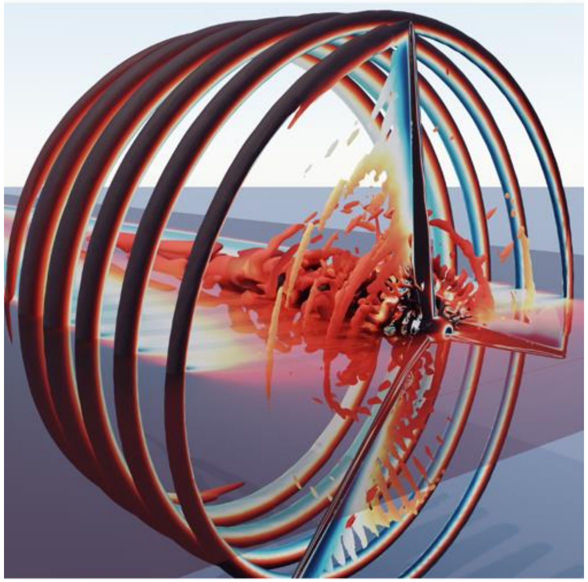


Nalu-Wind and OpenFAST

Nalu-Wind Overview

Nalu-Wind is a generalized, unstructured, massively parallel, incompressible flow solver for wind turbine and wind farm simulations. The codebase is a wind-focused fork of NaluCFD; NaluCFD is developed and maintained by Sandia National Laboratories. Nalu-Wind is being actively developed and maintained by a dedicated, multi-institutional team from National Renewable Energy Laboratory, Sandia National Laboratories, and other institutions as part of the ExaWind code stack.

- https://github.com/exawind/nalu-wind
- Critical for blade-resolved simulations
- Leverages the high-performance leadership class computing facilities available at DOE national laboratories including Sandia (Skybridge, Chama, Ghost, Attaway)

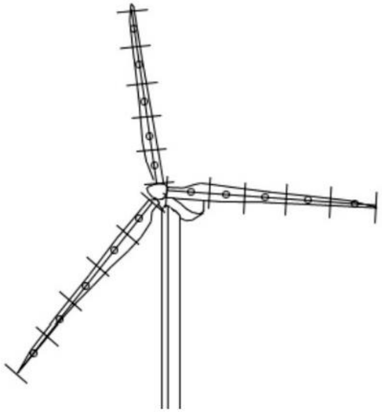


Nalu-Wind Simulation of the NREL 5MW Turbine (Ananthan, S. et al.)

OpenFAST Overview

OpenFAST is an open source conglomeration of engineering models to capture the aerodynamic and structural loading as well as other systems that make up a wind turbine.

- https://github.com/openfast
- Whole-turbine simulation code
- Includes models for blades, control systems, flow-structure interaction, drivetrain, etc.
- Computes rotor power, thrust, blade flap root-bending moments, and other structural quantities of interest



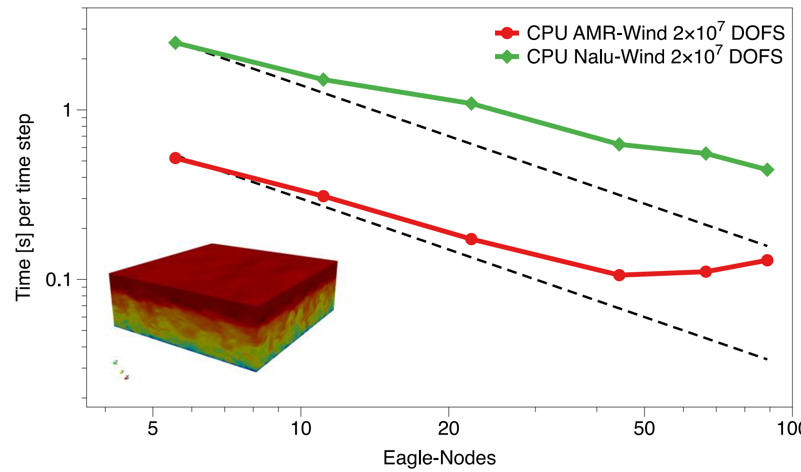
OpenFAST blade discretization

AMR-Wind

AMR-Wind Overview

AMR-Wind is an incompressible-flow computational fluid dynamics code, built on the AMReX library, that functions as a structured-grid background solver with adaptive mesh refinement.

- https://github.com/Exawind/amr-wind
- Structured-grid discretization exploits efficiency of data structures and multi-grid solvers
- Uses very different linear solvers and preconditioners than Nalu-Wind
- Five times faster than Nalu-Wind for comparable ABL simulations
- Coupled to Nalu-Wind through overset meshes

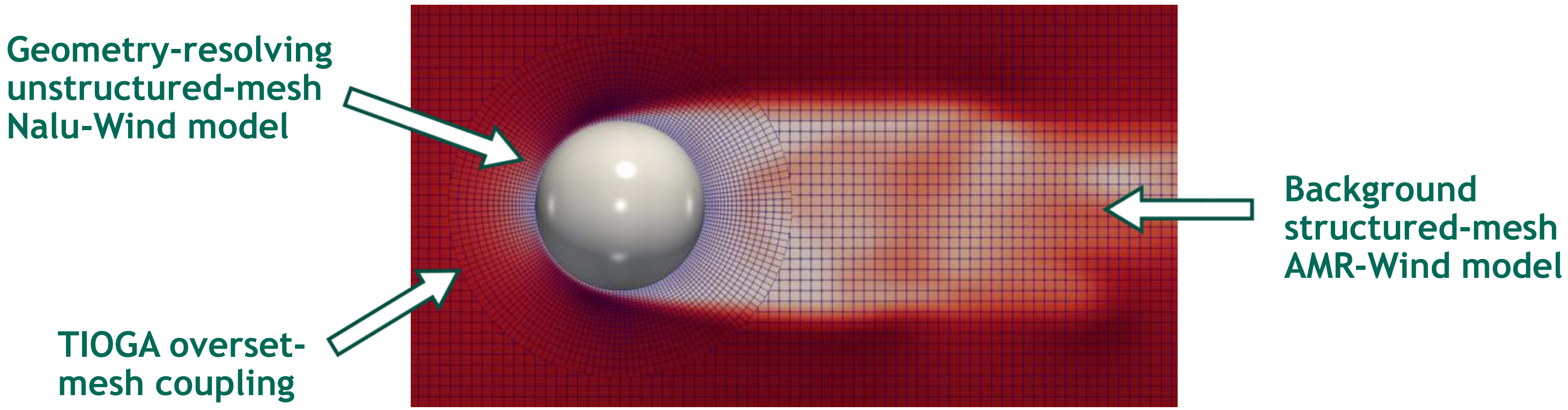


Strong-scaling study comparison between Nalu-Wind/AMR-Wind of a 5 x 5 x 1 km³ domain for a neutrally stable ABL

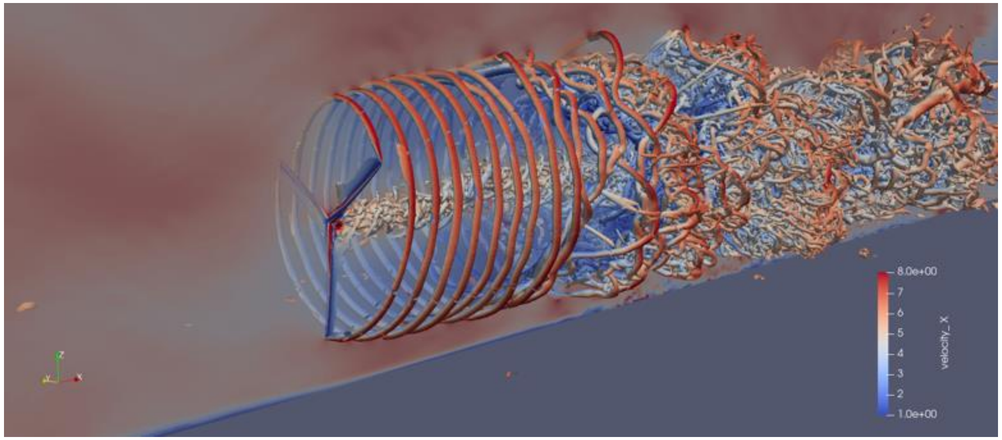
AMR-Wind, Nalu-Wind, OpenFAST and their underlying libraries constitute the "ExaWind" software suite

ExaWind hybrid solver: AMR-Wind + Nalu-Wind

Nalu-Wind/AMR-Wind flow over a sphere



- Modeling approach for high-fidelity, blade-resolved simulations



Source: Sprague, et al., 2021, ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling, 2021 Exascale Computing Project Annual Meeting, NREL Tech. Report NREL/PO-5000-80015

- Example of AMR-Wind/Nalu-Wind simulation of wind turbine rotor in turbulent flow

Verification and Validation

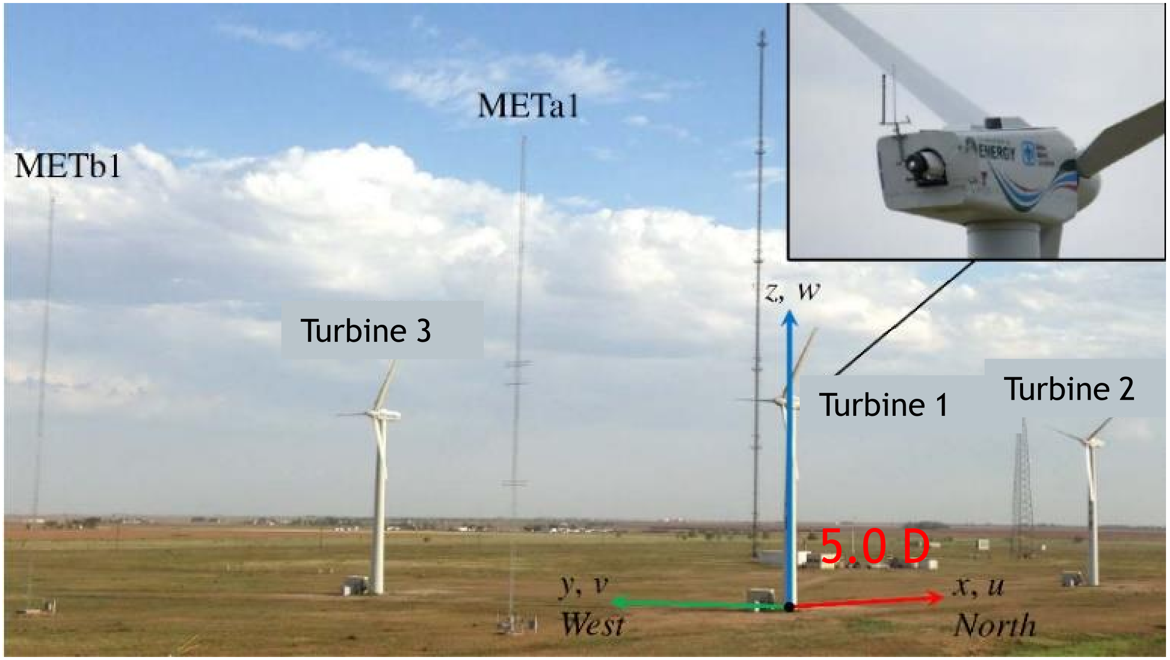
Wind Research Example of High-Fidelity Modeling Application

Investigating simulation code reliability using direct comparison to validation experiments

1. Detailed instrument data from the Sandia-operated Scaled Wind Farm Technology (SWiFT) facility
2. High-fidelity simulation data from the large-eddy simulation code Nalu-Wind and OpenFAST

Hsieh et al., 2021. "High-fidelity Wind Simulation Methodology with Experimental Validation". *Journal of Wind Engineering and Industrial Aerodynamics.* **218**:1104754. pp. 1-18.

- Authors: Alan Hsieh, Ken Brown, Nate DeVelder, Tommy Herges, and David Maniaci (8921); Robert Knaus and Phil Sakievich (1541); Lawrence Cheung, Myra Blaylock, and Brent Houchens (8751)
- Validating the capabilities of Nalu-Wind for modeling the atmospheric boundary layer (ABL) inflow into a wind plant under neutral conditions
- Interaction of that inflow with a wind turbine and its wake
- Effects of mesh resolution on the results



SWiFT: Scaled Wind Farm Technology

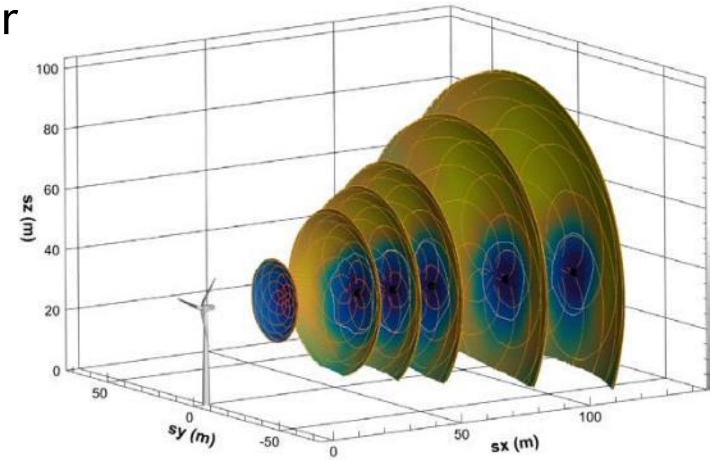
- Texas Tech University's National Wind Institute Research Center in Lubbock, Texas

- Meteorological Evaluation Towers (MET)
  - 2.5 D in front of 1st turbine
  - 60 meter tall – 6 heights
  - 3D sonic anemometers and thermometer

- SpinnerLidar for Wake Measurements
  - Technical University of Denmark (DTU)

- Vestas V-27 Turbines
  - Rotor diameter = 27 m
  - Hub height = 32.1 m
  - Strain gages: root-bending & tower
  - Rotor azimuth and yaw angle measurements
  - Nacelle accelerometer measurements

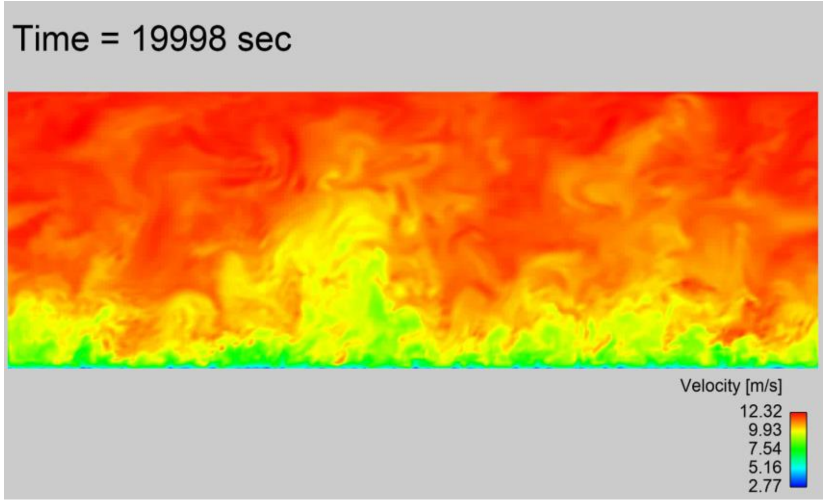
Lidar Planes



Simulation Workflow

1. Precursor/ABL Simulation

- Nalu-Wind is run by itself
- Run for a long-time (~20,000 seconds) to establish converged turbulent flow field
- Lower grid spacing and time step requirements



2. Turbines Simulation

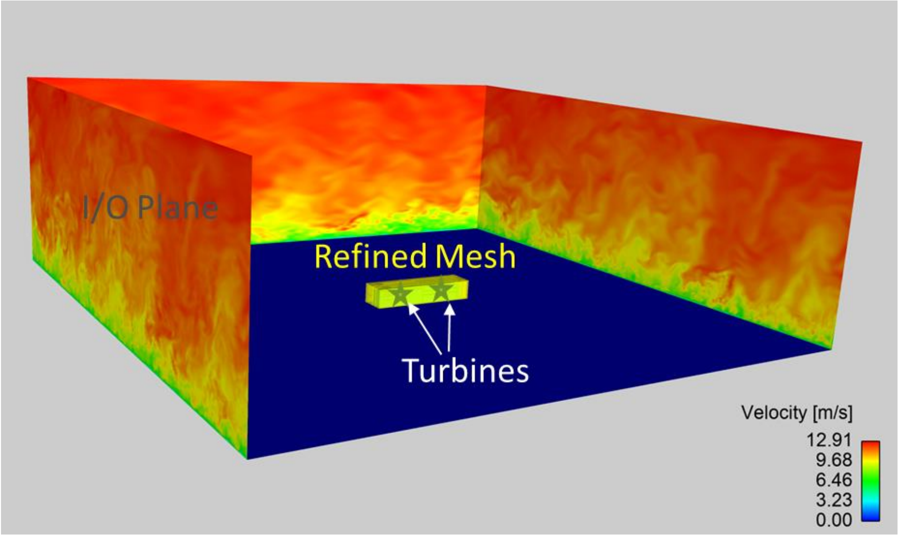
- Nalu-Wind is coupled to OpenFAST
- Strict grid spacing and time step requirements for modeling small-scale structures and blade movement
- Run for a comparatively short time (~10 min – 1 hr)

Mesh Refinement

The impact of mesh refinement was explored with three different meshes for both the atmospheric precursor and turbine simulations

Flow field needs to be refined around turbines more than the background ABL to capture inflow-turbine-wake interactions

Work with Aerosciences Department (1515) to construct/design complex meshes



Description of different precursor meshes used

Mesh	Elements	Δx	Proc.	Walltime (s)/It
$Coarse_P$	1.125e6	20 m	768	0.6
$Medium_P$	9e6	10 m	768	1.2
$Fine_P$	72e6	5 m	768	9.8

Description of different turbine meshes used

Mesh	Elements	Δx_{min}	Proc.	Walltime (s)/It
$Coarse_T$	11.7e6	1.25 m	768	6.6
$Medium_T$	22.5e6	0.625 m	768	12.8
$Fine_T$	45.5e6	0.3125 m	2304	12.3

Precursor Selection Methodology

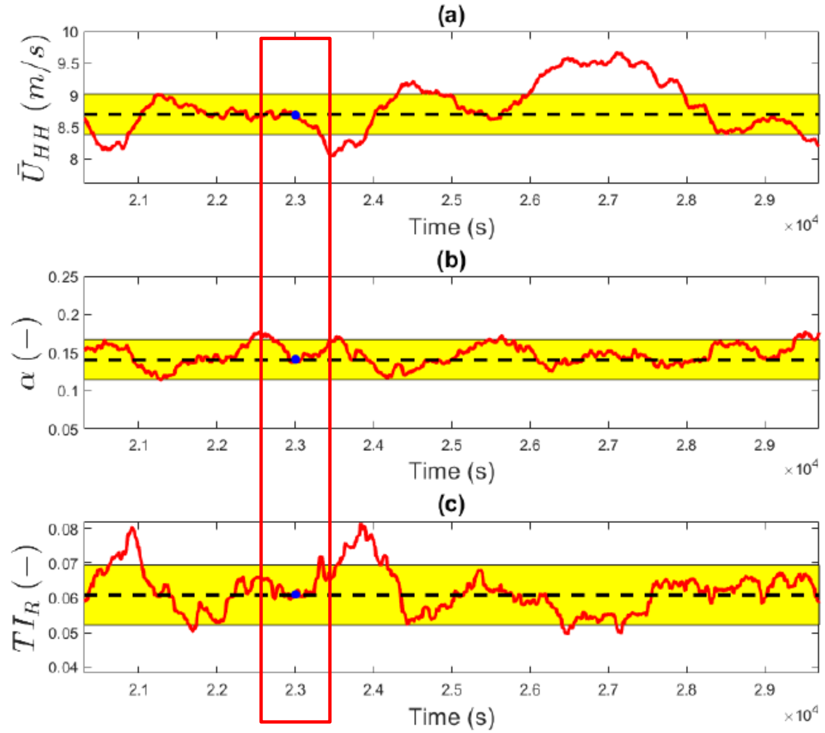
Stochastic nature of wind combined with fewer tuning parameters in high-fidelity models presents challenge

Using parameter sweeps to match local simulated atmospheric quantities of interest (hub-height wind speed, wind shear, and turbulence intensity) as closely possible with experimental data

Reduce atmospheric error propagating into the turbine and wake

	$\overline{U}_{HH}$ [m/s]	α [-]	TI_R [-]
Experiment	8.695 ± 0.935	0.141	0.0608
Simulation	8.686 ± 0.752	0.141	0.0614

10,000 second precursor simulation search window

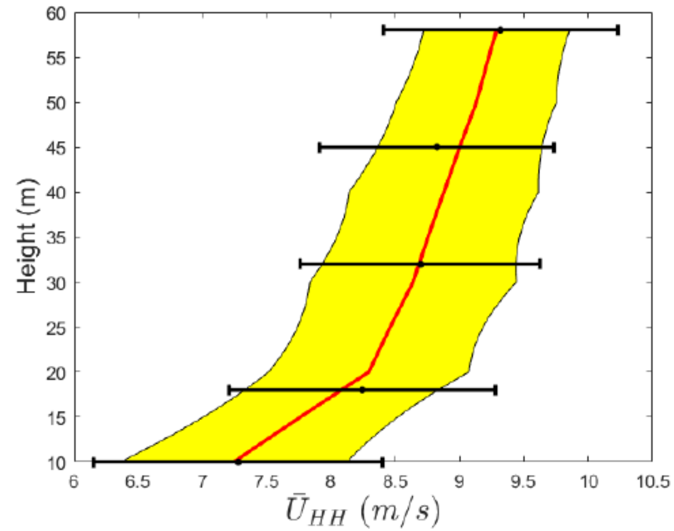


Simulation 10-min Avg:
Exp. Value:
Exp. Std. Dev:
Selected bin:

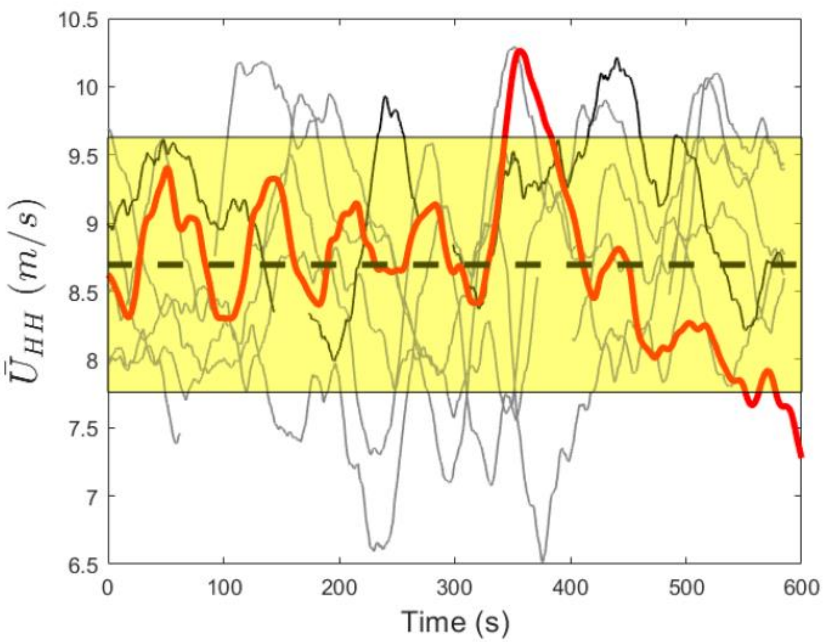
Compared other atmospheric quantities of interest between simulation and experiment

Observed simulated profiles are realistic and mostly lie within experimental bounds of uncertainty

Wind Shear Profile: Red (Exp); Black (Sim)



Temporal wind profile comparison



Experimental Avg: (- - - -)

Experiment St. Dev: ( )

Experiment Individual Bins: ( )

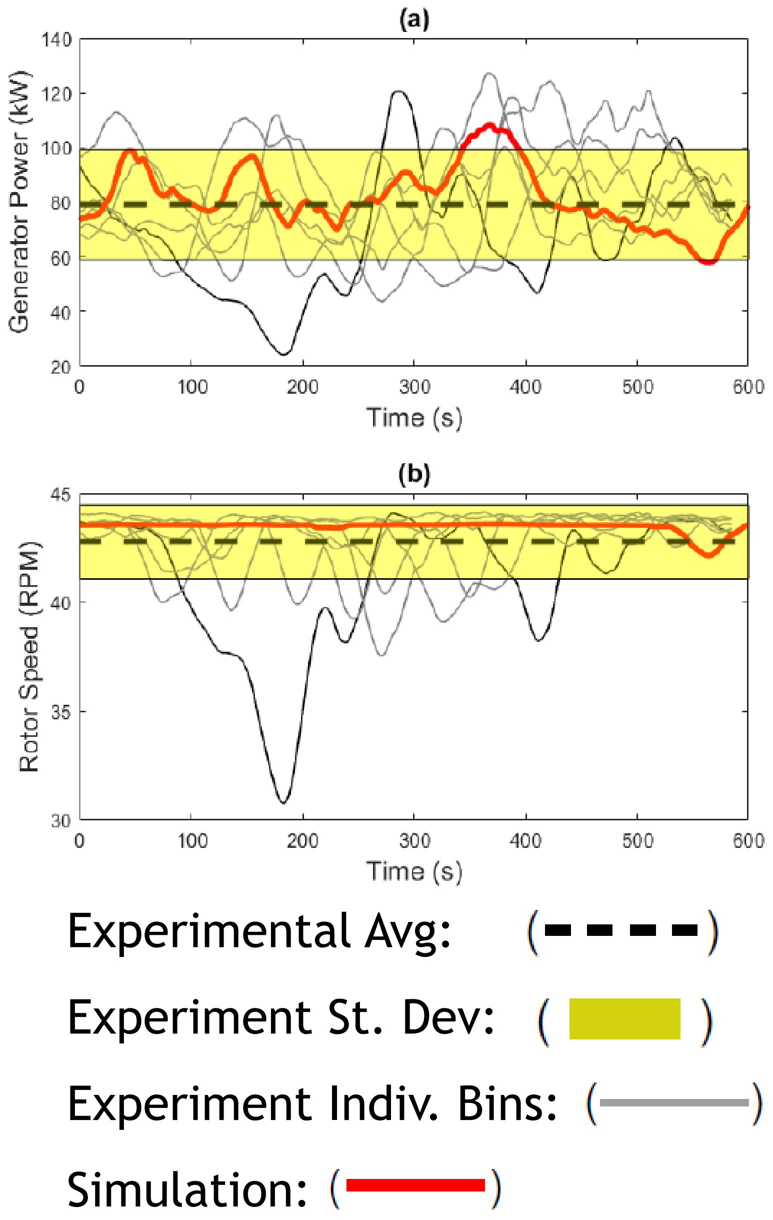
Simulation: ( )

Similarly turbine quantities of interest were compared between simulation and experiment

Identification of top factors behind simulation/experimental discrepancies, leading to future code improvements

Example: Reduction outliers in rotor speed, caused by corresponding wind speed reductions, observed in exp. are not captured in simulation

	Generator Power (kW)
Experiment	79.1 ± 20.1
Simulation	81.7 ± 14.2



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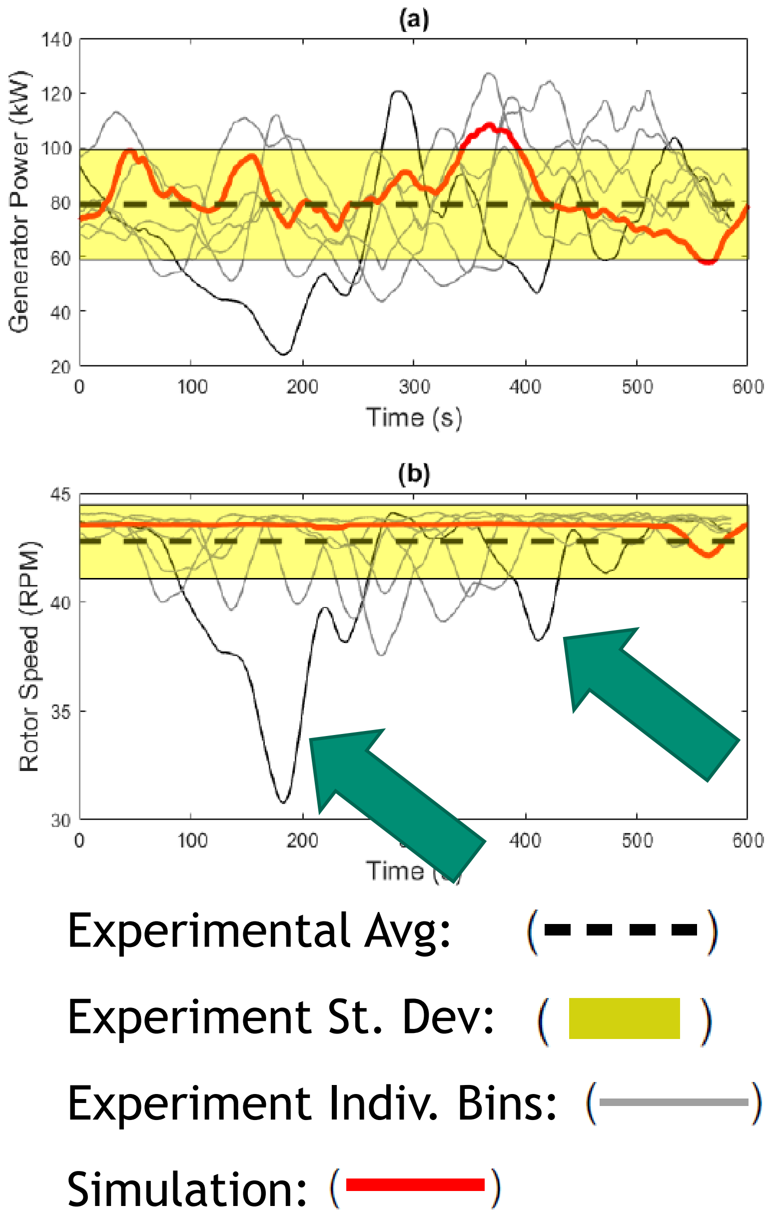

Precursor Results and Validation

Compared other atmospheric quantities of interest between simulation and experiment

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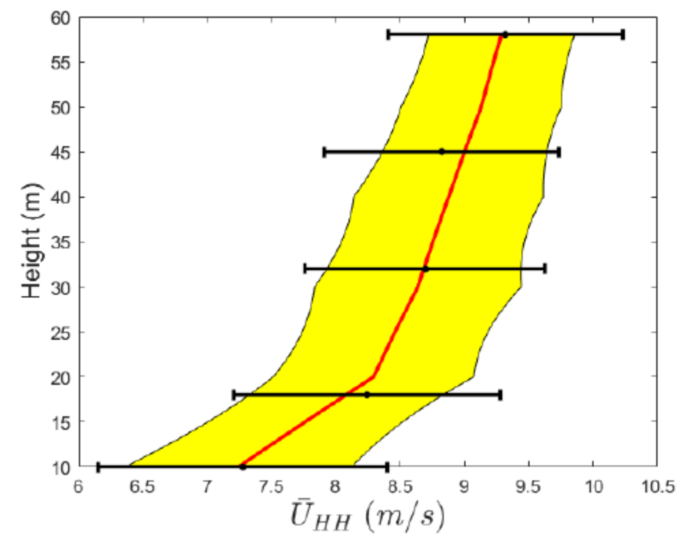
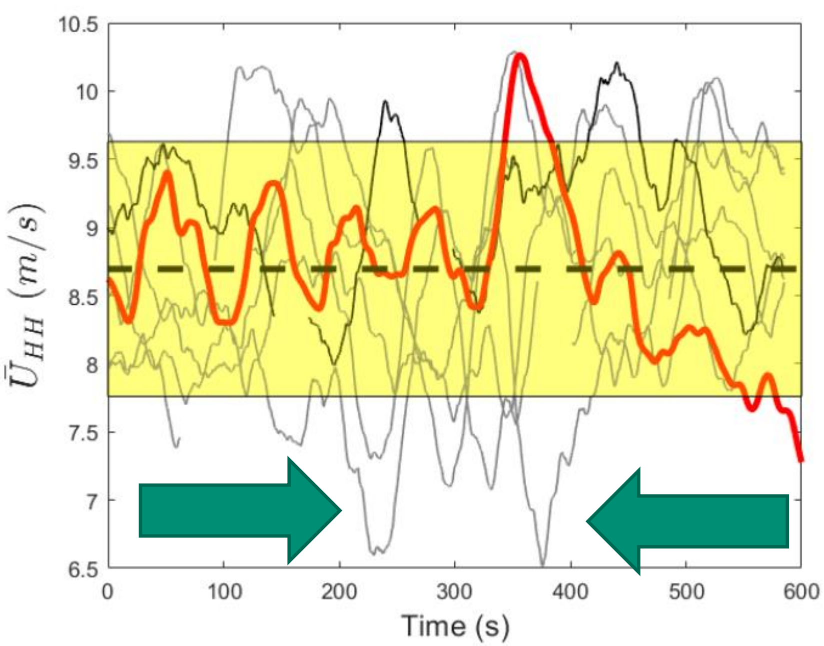


Temporal wind profile comparison



Experimental Avg: (- - - -)

Experiment St. Dev: ( )

Experiment Individual Bins: ( )

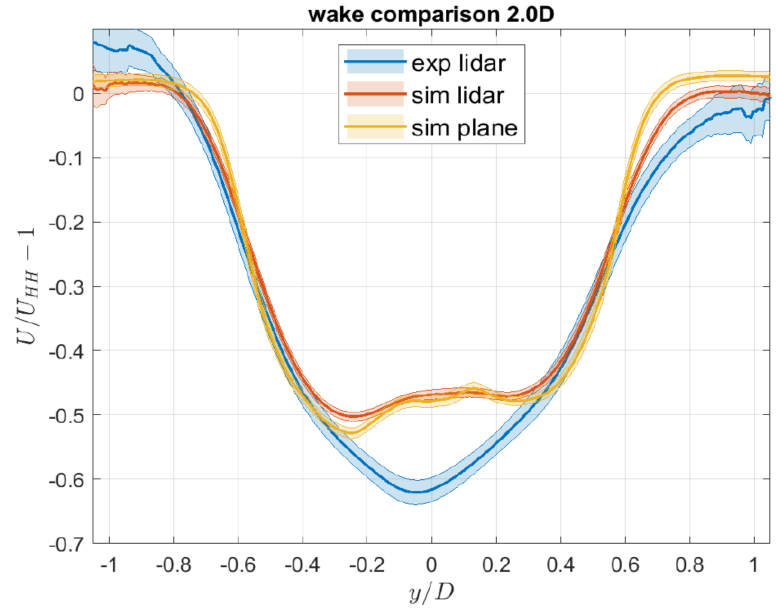
Simulation: ( )

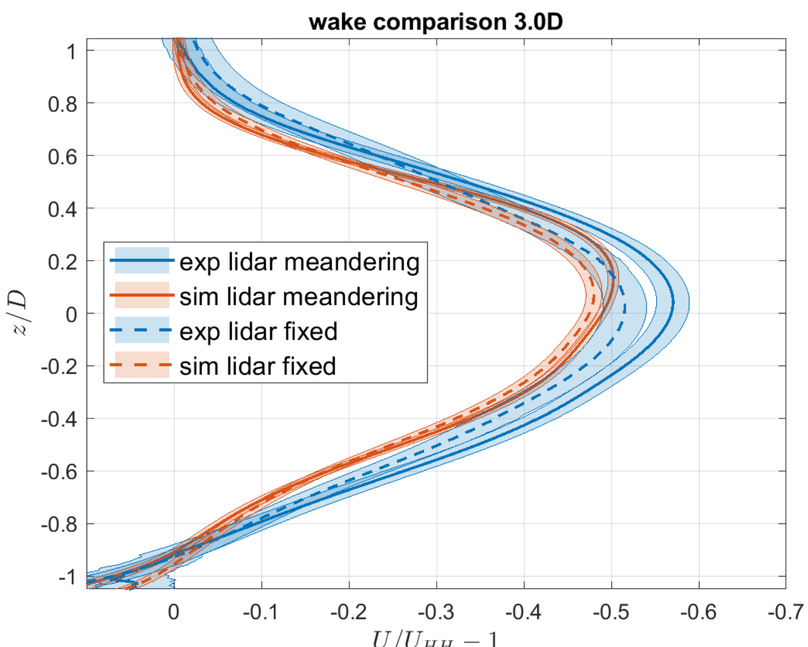
Validation of Inflow, Turbine, and Wake Quantities
Wake Results and Validation

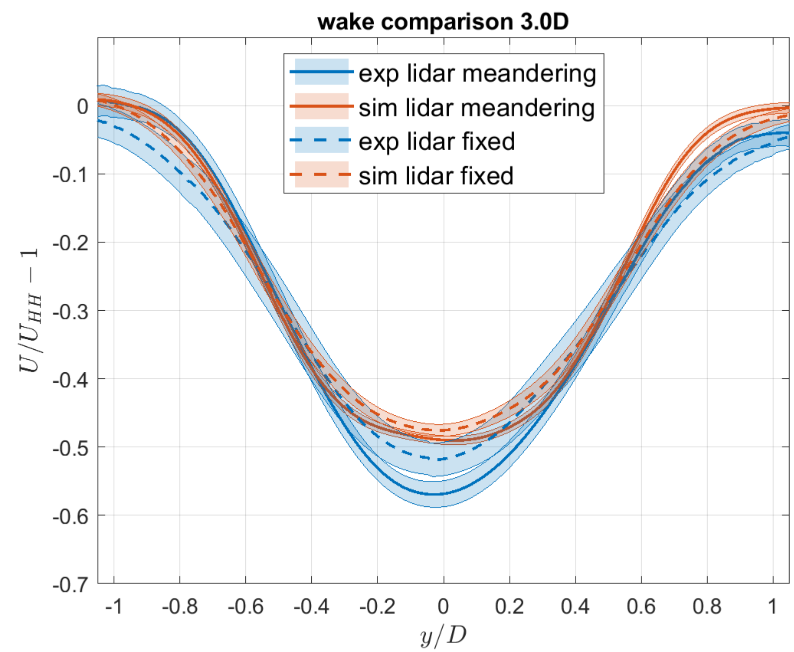
Compared simulated and experimental wake profiles at different downstream distances and reference frames

Identified issues within the simulated near-wake (~2D) region

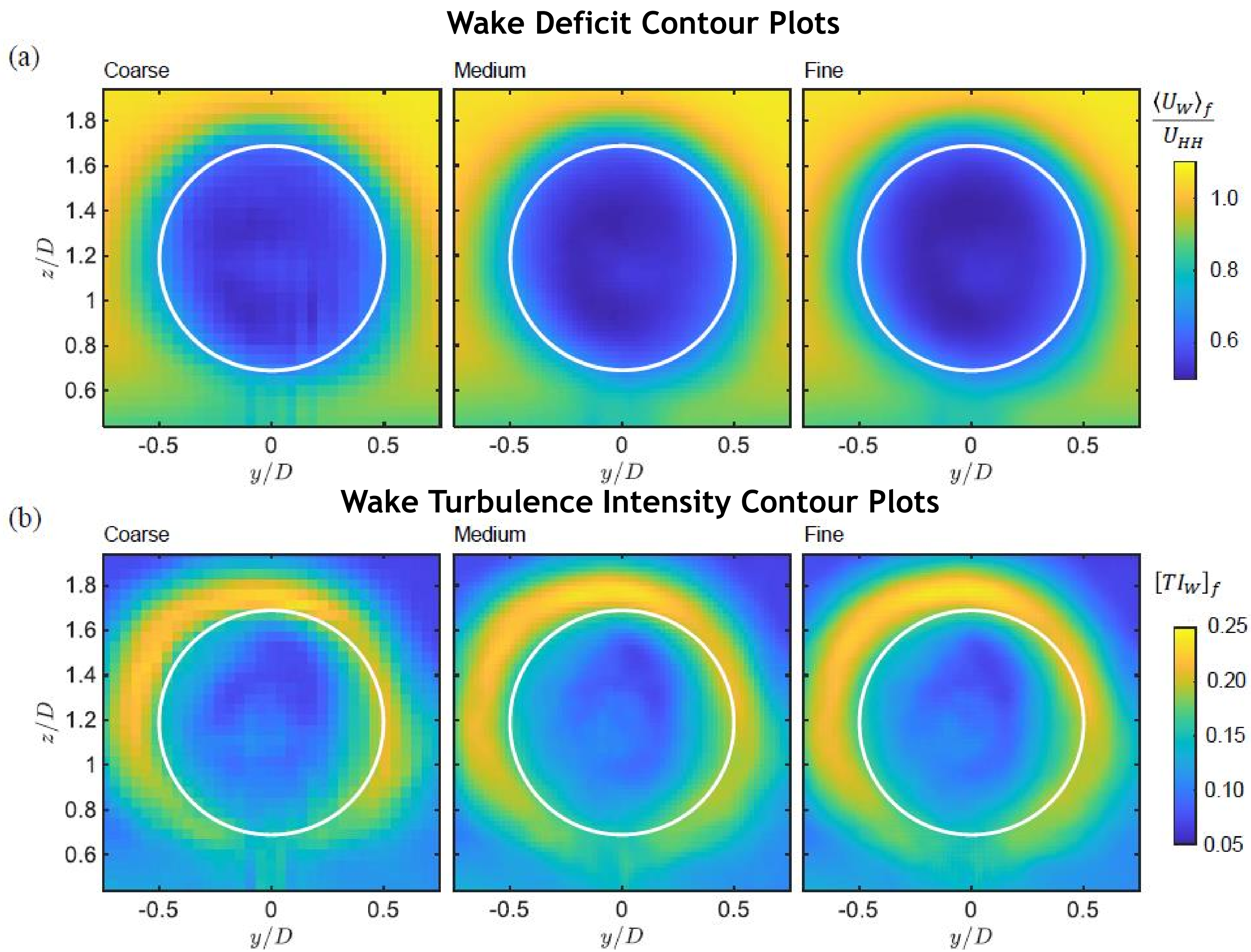
Observed good agreement between simulated lidar and plane results







Simulations for Advanced Wind Energy Applications
Mesh Refinement Effects on Wake Quantities



Concluding Remarks

Summary:

- A simulation methodology to effectively match the simulated atmospheric inflow with field data was developed to promote high confidence validation of high-fidelity LES simulations
- Methodology was applied for an experimental validation case with comparisons of Nalu-Wind simulation results to data from the SWiFT facility
  - With matching atmospheric inflows, good agreement was observed for several QoIs including turbine generator power and wake widths at different downstream distances
  - Quantified uncertainty bands for experimental and simulation results

Areas of Collaboration:

- Develop and maintain Nalu-Wind/OpenFAST codes for wind energy applications
  - Development of virtual SpinnerLidar model in Nalu-Wind
  - Improved efficiency for the Nalu-Wind actuator models
- Increased reliability of Nalu-Wind and OpenFAST models
  - Debug numerical artifacts present in flow field
- Refined mesh creation for turbine simulations
- Simulated results interpretation
  - Using expertise, identify sources of discrepancy for simulated data with experimental results

Future Research Collaboration Plans and Opportunities

Verification & Validation

Working with Org 1541 (Computational Thermal and Fluid Mechanics) to develop and maintain high-fidelity wind farm simulation codes for validation studies

- Robert Knaus, Phil Sakievich, and Neil Matula

Also collaborating with Org 8751 (Thermal/Fluid Science and Engineering) for running and analyzing wind farm simulations

- Myra Blaylock, Lawrence Cheung, and Brent Houchens

Future Planned Collaborative Research
As more emphasis is placed on offshore simulation capabilities, with larger wind turbines and harsh ocean environments, efficient high-fidelity computational models are of higher priority than ever

- Perform series of targeted validation studies for the newly developed AMR-Wind code suite
- Perform validation studies for Exawind code suite expansion to offshore wind

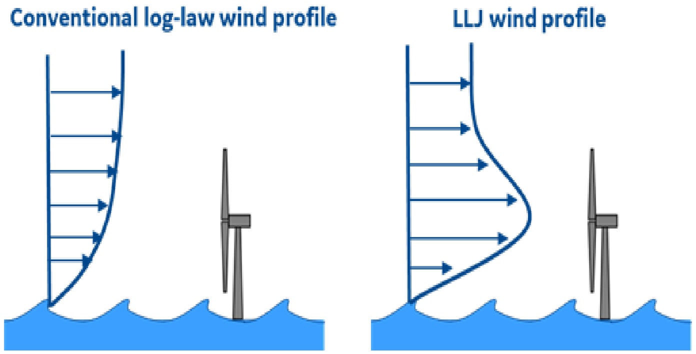
Other Projects

AWAKEN Project

- Assess Nalu-Wind and AMR-Wind simulation capabilities for a full-scale wind farm with several dozen wind turbines
- Address any scalability concerns with significant increase in simulated problem size
- Expand virtual instrumentation capabilities of simulation codes

RAAW Project

- Assess Nalu-Wind/AMR-Wind hybrid code for detailed blade-resolved simulations using experimental validation
- Expand virtual instrumentation capabilities of simulation codes



Future Research Collaboration Plans and Opportunities

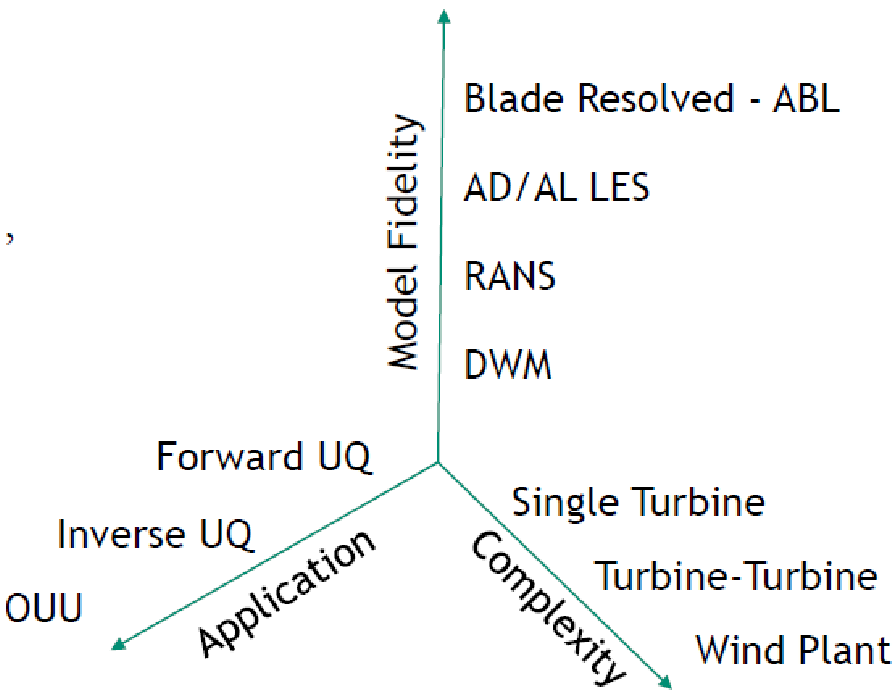
Multifidelity Uncertainty Quantification

Working with Org 1463 (Optimization and Uncertainty) to develop and apply advanced uncertainty quantification techniques to complex wind energy problems

- Gianluca Geraci, Tom Seidl, and Michael Eldred

Future planned research for wind UQ

- **Dakota integration:** Integrate the Sandia-based UQ-toolkit Dakota with the Exawind code suite and other wind farm computational models
- **Forward uncertainty quantification**: Assess and quantify uncertainty's impact on wind plant performance
- **Inverse uncertainty quantification**: Using experimental field data for model calibration and input parameter estimation
- **Optimization under Uncertainty**: Augmenting wind plant performance under uncertainty
- **Advanced UQ for experimental validation**: Application of aforementioned UQ strategies towards experimental validation



Multi-dimensional UQ Work Planning Trade-Space

Future Research Collaboration Plans and Opportunities

High Fidelity Modeling

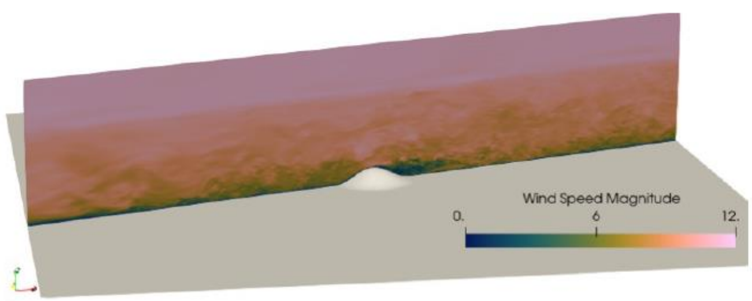
Working with Orgs 1541 (Computational Thermal and Fluid Mechanics) and Org 8751 (Thermal/Fluid Science and Engineering) to improve high-fidelity wind farm and wind plant models

- Phil Sakievich, Robert Knaus, Neil Matula, and Lawrence Cheung

Future planned research

- Develop and demonstrate wind farm simulations in an offshore atmospheric environment
- Perform blade-resolved multi-turbine simulations in turbulent atmospheric flow
- Expand multi-phase-flow and complex terrain capabilities in Exawind code suite

Complex terrain modeling in AMR-Wind and Nalu-Wind



ExaWind

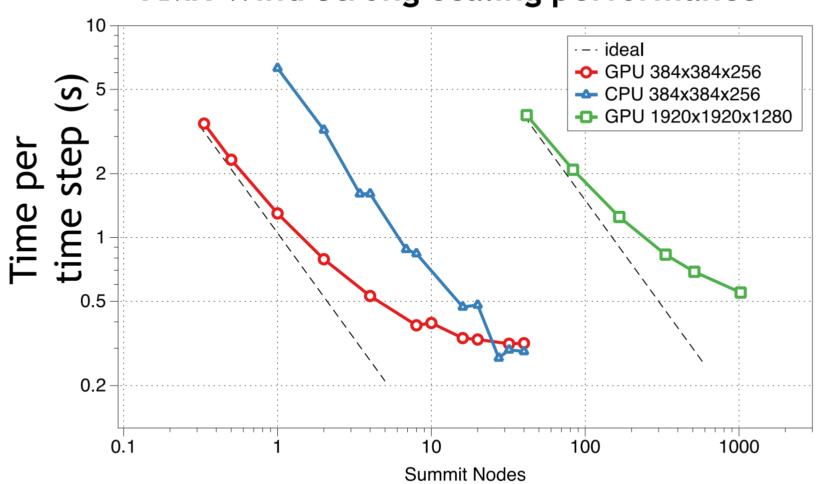
Working with multiple orgs within Centers 1400 and 1500 to develop the Exawind code suite to efficiently run on next-generation exascale HPC platforms.

- Orgs 1442, 1446, 1465, 1541, 8751, etc.

Future planned research

- Ensure critical dependencies (Trilinos, Hypre, AMReX, etc.) of Exawind software stack are optimized for GPUs
- Continue to reduce time to solution by better strong/weak scaling through algorithmic and software advances

AMR-Wind Strong-scaling performance



Thank You

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