UFLORIDA NHERI
Powell Family Structures and Materials Laboratory

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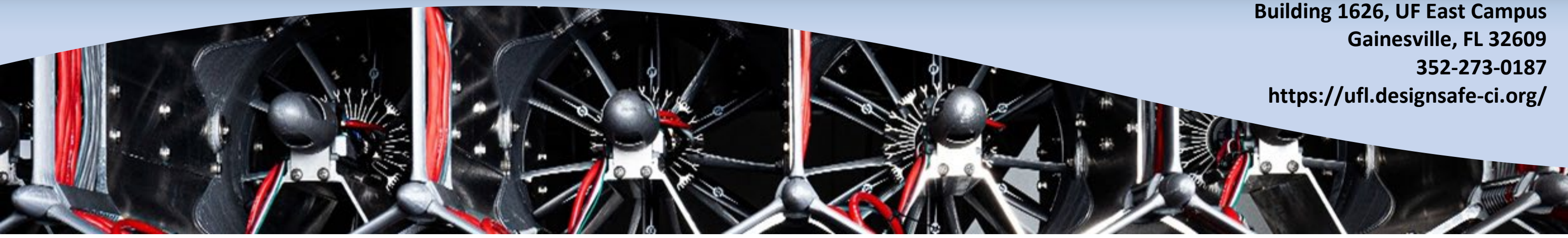

Boundary Layer Wind Tunnel Simulation of Transient and Non-Synoptic Wind Events

Workshop Report

University of Florida NSF NHERI Experimental Facility

May 19, 2021

National Science Foundation

Workshop Overview

This one-day, virtual user workshop presented the transient and non-synoptic flow simulation capabilities of the boundary layer wind tunnel at the University of Florida NSF NHERI Experimental Facility, enabled by the new Flow Field Modulator (FFM). Invited speakers presented their active research in transient and non-synoptic flow measurement, modeling, and simulation. Presenter and participant discussions focused on research needs in field observations, laboratory simulation, and modelling techniques as well as code-based approaches for transient wind load design.

Workshop Goals

- Present the new simulation capabilities provided by the FFM and discuss limitations
- Present FFM benchmark datasets and experimental protocols established to date
- Solicit feedback on future FFM development that will complement user proposal preparation
- Generate interest in writing proposals that utilize the FFM
- Publish a workshop report on the latest research in transient and non-synoptic event simulation and experimental design

Agenda

The agenda was divided into a morning session on the UF EF and an afternoon session focused on key science themes related to non-synoptic and transient flow presented by invited speakers.

Background and Resources	
Introductions	
10:00 am – 10:20 am	**Welcome, Goals for the Day, and Participant Introductions** Jennifer Bridge, *Assoc. Prof. & Director, UF NHERI EF*
UF NHERI Experimental Facility Capabilities	
10:20 am - 10:40 am	**EF Overview** Jennifer Bridge, *Assoc. Professor & Director, UF NHERI EF*
10:40 am – 11:00 am	**Flow Field Modulator: Theory of Operation** Brian Phillips, *Assoc. Professor & Assoc. Director, UF NHERI EF*
11:00 am – 11:30 am	**Flow Field Modulator: Capabilities and Benchmarking** Ryan Catarelli, *Research Scientist & Wind Engineering Technical Manager, UF NHERI EF*
11:30 am – 11:50 am	**Discussion**
Break (11:50 am – 1:00 pm)	

Research Planning: Science Themes	
Phenomenology → Target Boundary Layer Characteristics (1-2pm)	
1:00 pm – 1:05 pm	Kurt Gurley, *Professor & Assoc. Director, UF NHERI EF*
1:05 pm – 1:20 pm	**The Need for New and Revised Targets of Transient Winds** Frank Lombardo, *Asst. Professor, University of Illinois, Urbana-Champaign*
1:20 pm – 1:35 pm	**Measuring Engineering-Relevant Characteristics of Non-Stationary Wind (NSW) Events** John Schroeder, *Professor, Texas Tech University*
1:35 pm – 2:00 pm	**Discussion**
Bluff Body Aerodynamics: Kinematic and Dynamic Similitude (2-3pm)	
2:00 pm – 2:05 pm	Brian Phillips, *Assoc. Professor & Assoc. Director, UF NHERI EF*
2:05 pm – 2:20 pm	**Scaling Concerns for Experimental Simulations of Tornado-Induced Wind Loading** Fred Haan, *Professor, Calvin University*
2:20 pm – 2:35 pm	**Gust Fronts, Vortical and Convective Systems, Rolls, and Intermittency: Changing Dynamic of Wind Fields** Ahsan Kareem, *Professor, University of Notre Dame*
2:35 pm – 3:00 pm	**Discussion**
Break (3:00 – 3:15 pm)	
Physical Simulation Techniques (3:15-4:15 pm)	
3:15 pm – 3:20 pm	Forrest Masters, *Professor & Assoc. Director, UF NHERI EF*
3:20 pm – 3:35 pm	**Narrowband Components in Two-Celled Vortices Generated in a Tornado Simulator** Delong Zuo, *Assoc. Professor, Texas Tech University*
3:35 pm – 3:50 pm	**AI-Empowered Wind Tunnel for Transient Aerodynamics** Teng Wu, *Assoc. Professor, University at Buffalo*
3:50 pm – 4:15 pm	**Discussion**
Computational Wind Engineering Methodologies (4:15-5:15 pm)	
4:15 pm – 4:20 pm	Forrest Masters, *Professor & Assoc. Director, UF NHERI EF*
4:20 pm – 4:35 pm	**Generation of Tornado-Like Vortices for Wind Engineering Applications** Girma Bitsuamlak, *Professor, Western University*
4:35 pm – 4:50 pm	**Sensitivity of Large-Eddy Simulation Peak Pressure Load Predictions to Boundary Layer Turbulence** Catherine Gorlé, *Asst. Professor, Stanford University*
4:50 pm – 5:15 pm	**Discussion**
Workshop Wrap-up (5:15-5:30 pm)	

Attendees

The workshop was attended by researchers from a range of US and international universities as well as government agencies (NIST and the Florida Department of Transportation) and engineering practice. The workshop had 64 attendees, not including the UF leadership team. Eight of the attendees were the invited speakers, 19 of the attendees are currently eligible to submit NSF proposals, and 14 of the attendees (22%) were female.

Presentations

The presentation slides are in the Appendix in the order they were delivered and provide detailed content related to each session.

Session Summaries

UF NHERI Experimental Facility

Speakers: Jennifer Bridge, UF NHERI EF Director
Brian Phillips, UF NHERI EF Associate Director
Ryan Catarelli, UF NHERI EF Wind Engineering Technical Manager

The University of Florida (UF) NHERI Experimental Facility (EF) provides physical simulation tools for scale model experimental testing of flow conditions and resulting loads on building models. The primary experimental resource is the Boundary Layer Wind Tunnel (BLWT), enabling precise control of target velocity profiles at a range of model scales with the automated roughness element grid, the Terraformer. More information on the theory of operation and characterization of the BLWT Terraformer can be found in Catarelli et. al (2020a). An automated instrumentation gantry enables efficient flow measurements throughout the tunnel and a gantry-mounted, stereoscopic particle image velocimetry (PIV) system provides three-dimensional, time-resolved velocity measurements at the test section.

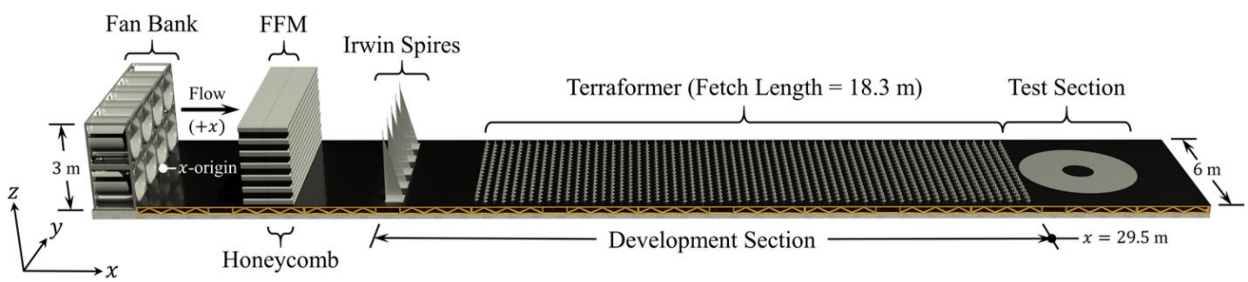

Figure 1. Boundary Layer Wind Tunnel profile

The new Flow Field Modulator (FFM) offers optional active flow control in the BLWT with a honeycomb array of 319 individually controlled fans. The FFM slides into the BLWT downwind of the main fan bank. Each cell has a 1-hp brushless DC motor with electronic speed controller and can achieve a maximum sustained steady state velocity of 20.3 m/s and an acceleration of 95.8 m/s^2. The maximum open-loop frequency response is approximately 2 Hz. The FFM can generate non-monotonic and spatiotemporally nonstationary flows. By controlling the speeds of each fan row, a range of mean velocity profiles can be achieved. Instantaneous fan speeds can be fluctuated to achieve target turbulence properties.

The UF EF provides users full project support, from the initiation of a research idea through project closeout. EF PIs and staff can assist with proposal preparation, including feasibility assessment, experimental design, budgeting, facility documentation, and data management planning. For NSF users, the EF offers up to 24 days of setup and testing in the BLWT at no cost to the NSF project. For non-NSF researchers or NSF researchers requiring additional testing time and support, published service rates are available on the UF NHERI EF DesignSafe website: https://ufl.designsafe-ci.org/project-types/. In addition to the experimental resources, the UF EF offers test specimen design and fabrication support with a skilled design and engineering staff, a full-service machine shop, multiple 3D printers, and a large format CNC router. A detailed description of the UF EF can be found in Catarelli et al. 2020b.

From Phenomenology to Target Boundary Layer Characteristics

Moderator: Kurt Gurley, UF NHERI EF Associate Director

Speakers: Frank Lombardo, Assistant Professor, University of Illinois at Urbana-Champaign
John Schroeder, Professor, Texas Tech University

Transient and non-synoptic events are responsible for a large amount of windstorm damage. The ability to simulate such events in a boundary layer wind tunnel opens the opportunity to study their impact on the built environment and ultimately improve structural design. Key to these studies is achieving the appropriate boundary layer simulation targets with particular focus on flow conditions that are likely to have the most damaging impacts on the structures being studied. Field observations of non-synoptic wind events provide a basis for selecting and designing simulation targets for the FFM.

There is currently a lack of defined or standard target profiles for transient events, in large part due to a deficiency of data collected with engineering applications as the focus. Recording engineering-relevant, non-synoptic wind event data presents several challenges due to the high variability and spatially localized nature of the phenomena. Coordinated instrument deployment strategies are critical to capturing relevant parameters, including turbulence, vertical flow components, directional changes, flow acceleration, and thermal impacts. Tower-based and remote sensing data acquisition approaches can be used together to construct 3D time history and turbulence parameters.

Bluff Body Aerodynamics: Kinematic and Dynamic Similitude

Moderator: Brian Phillips, UF NHERI EF Associate Director

Speakers: Fred Haan, Professor, Calvin University
Ahsan Kareem, Professor, University of Notre Dame

Consideration of appropriate scaling techniques is critical to designing effective experimental simulation of transient wind events. In particular, the simulation of different aspects (scales and parameters) of tornado-induced loading may be better accomplished with different experimental tools. Tornado simulators (such as those at Texas Tech University, Iowa State University, and Western University) are best suited to study the impacts of swirl ratio, tornado geometry, and turbulence spectra while transient simulation in a boundary layer wind tunnel (such as the UF EF BLWT with FFM) can better simulate a wide range of Reynolds numbers, surface roughness conditions, and vortex translation. There are open questions regarding the best methods for quantifying spectra for transient flow, including the impacts of the pressure gradient.

In the case of downbursts, bluff body aerodynamics are impacted by the height of maximum downburst outflow velocity relative to the building height. Realistic, non-stationarity in the flow modeling, bluff body aerodynamics, and the structural response requires time-frequency analysis tools. The next generation of codes and standards require a proper simple representation of transient influence on design considerations. A generalized gust front factor (GFF) may be a useful tool for accounting for gust fronts in design. GFF can account for kinematic effects, rise-time effects, nonstationary effects, and transient aerodynamic effects within a familiar code framework.

Physical Simulation Techniques

Moderator: Forrest Masters, UF NHERI EF Associate Director

Speakers: Delong Zuo, Associate Professor, Texas Tech University
Teng Wu, Associate Professor, University at Buffalo

There are significant differences in the impacts of tornado-like and boundary layer-type flows on structures. Physical simulation of tornado vortices, performed in facilities such as the tornado simulator at Texas Tech University, enhances the understanding of the turbulence and fluctuating pressure in tornado-like flows and enables the evaluation of their structural loading. In recent experiments, narrow-band components have been observed in simulations with higher swirl ratios and their frequency content is also dependent on the radial Reynolds number.

The multiple fan boundary layer wind tunnel at the University at Buffalo has a maximum length of 9 m and utilizes 64 individually controlled fans. The wind tunnel can accommodate vertical or horizontal structures. The maximum wind speed is 20 m/s, maximum wind speed change is 4 m/s in 0.3 s, and a maximum frequency response of 12 Hz. A deep reinforcement learning approach with RPM control is used to achieve target mean wind profiles and wind speed time histories. AI provides a promising tool for transient aerodynamic simulation.

Computational Wind Engineering Methodologies

Moderator: Forrest Masters, Professor and UF NHERI EF Associate Director

Speakers: Girma Bitsuamlak, Professor, Western University
Catherine Gorlé, Assistant Professor, Stanford University

Computational Wind Engineering (CWE) provides a complementary resource for experimental facilities. Computational Fluid Dynamics (CFD) simulations can capture a range of vortex and turbulence behaviors. CFD also enables high resolution investigation of simultaneous velocity and pressure fields and is capable of accurately reproducing building model RMS and peak pressure coefficients. Experimental data used for validation should include detailed measurements of boundary layer turbulence at the model location, including uncertainty. Extension of CFD approaches to full scale requires measured velocity fields for validation. Additionally, digital twins of experimental facilities (e.g., tornado simulators and boundary layer wind tunnels) can help plan experiments and further the understanding the bluff body aerodynamics and resulting wind loads through dense monitoring of the computational domain.

References

Catarelli, R.A., Fernández-Cabán, P.L., Masters, F.J., Bridge, J.A., Gurley, K.R., and Matyas, C.J. (2020). Automated terrain generation for precise atmospheric boundary layer simulation in the wind tunnel, *Journal of Wind Engineering and Industrial Aerodynamics*. 207(104276)

Catarelli, R.A., Fernández-Cabán, P.L., Phillips, B., Bridge, J.A., Masters, F.J., Gurley, K.R., Prevatt, D.O. (2020). Automation and New Capabilities in the University of Florida NHERI Boundary Layer Wind Tunnel, *Frontiers in Built Environment*. 6(166)

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Appendix: Session Presentations

National Science Foundation

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NHERI Experimental Facility at UF: Introductions and Overview

Boundary Layer Wind Tunnel Simulation of Transient and Non-Synoptic Wind Events

Jennifer A. Bridge, Ph.D., Kurt Gurley, Ph.D., Forrest Masters, Ph.D., Brian Phillips, Ph.D., Ryan Catarelli, Ph.D.

May 19, 2021

Goals

- Present transient simulation capabilities of UF NHERI Experimental Facility and discuss limitations
- Hear from experts on a range of topics related to transient and non-synoptic flow
- Discuss research community needs and how UF NHERI EF can meet them
  - Benchmark datasets
  - Experimental protocols
- Publish a workshop report on best practices in transient and non-synoptic event simulation and experimental design
- Generate interest in writing proposals that utilize the Flow Field Modulator

Agenda: Introduction & Overview (Morning)

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11:30 am – 11:50 am	Discussion
Break (11:50 am – 1:00 pm)	

Agenda: Science Themes (Afternoon)

Phenomenology → Target Boundary Layer Characteristics (1-2pm)

Kurt Gurley, Assoc. Director, UF NHERI EF

The Need for New and Revised Targets of Transient Winds
Frank Lombardo, Asst. Professor, University of Illinois, Urbana-Champaign

Measuring Engineering-Relevant Characteristics of Non-Stationary Wind (NSW) Events
John Schroeder, Professor, Texas Tech University

Bluff Body Aerodynamics: Kinematic and Dynamic Similitude (2-3pm)

Brian Phillips, Assoc. Director, UF NHERI EF

Scaling Concerns for Experimental Simulations of Tornado-Induced Wind Loading
Fred Haan, Professor, Calvin University

Gust Fronts, Vortical and Convective Systems, Rolls, and Intermittency: Changing Dynamic of Wind Fields
Ahsan Kareem, Professor, University of Notre Dame

Break (3:00 – 3:15 pm)

Physical Simulation Techniques (3:15-4:15 pm)

Forrest Masters, Assoc. Director, UF NHERI EF

Narrowband Components in Two-Celled Vortices Generated in a Tornado Simulator
Delong Zuo, Assoc. Professor, Texas Tech University

AI-Empowered Wind Tunnel for Transient Aerodynamics
Teng Wu, Assoc. Professor, University at Buffalo

Computational Wind Engineering Methodologies (4:15-5:15 pm)

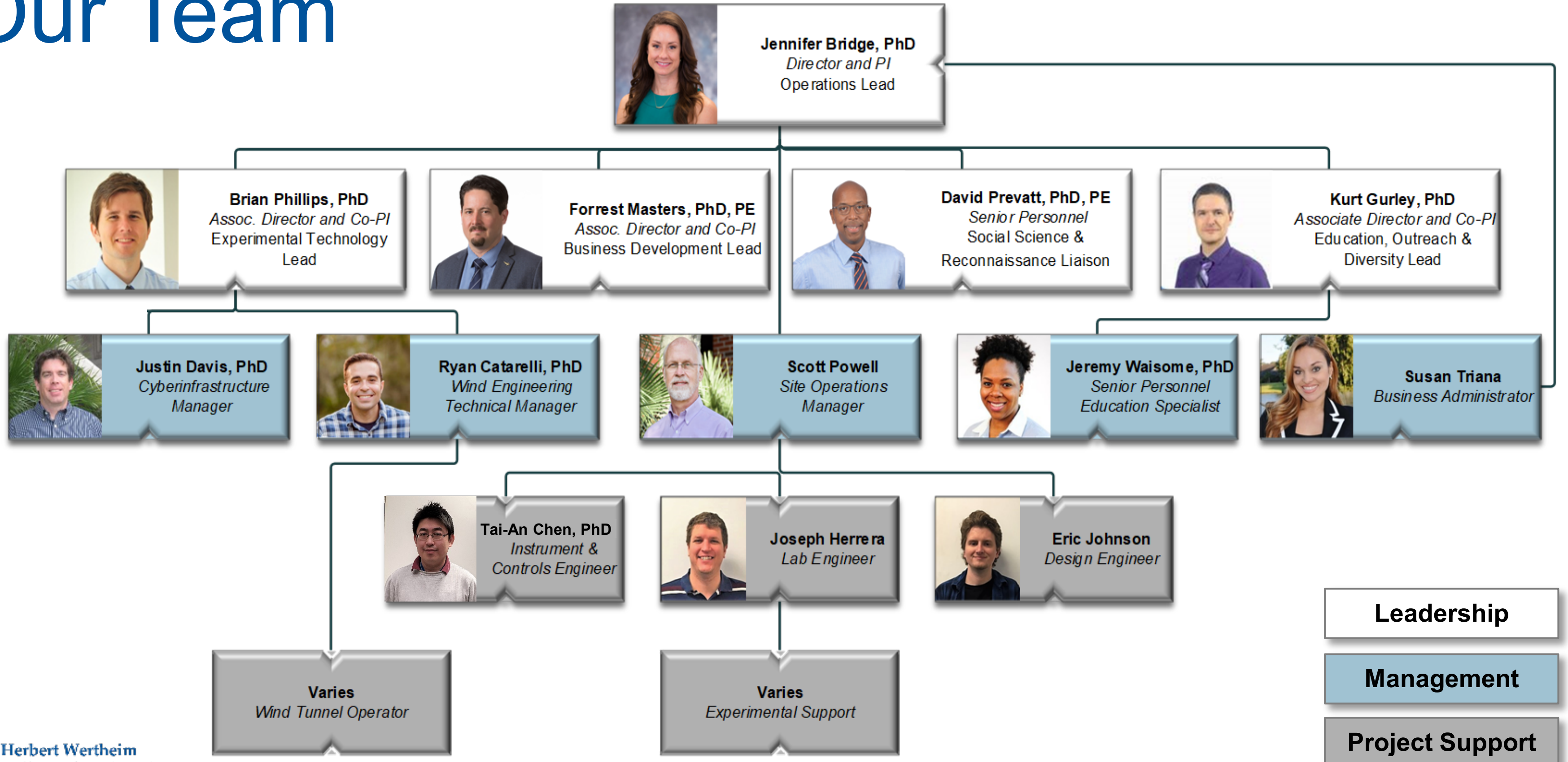
Forrest Masters, Assoc. Director, UF NHERI EF

Generation of Tornado-Like Vortices for Wind Engineering Applications
Girma Bitsuamlak, Professor, Western University

Sensitivity of Large-Eddy Simulation Peak Pressure Load Predictions to Boundary Layer Turbulence
Catherine Gorle, Asst. Professor, Stanford University

Workshop Wrap-up (5:15-5:30 pm)

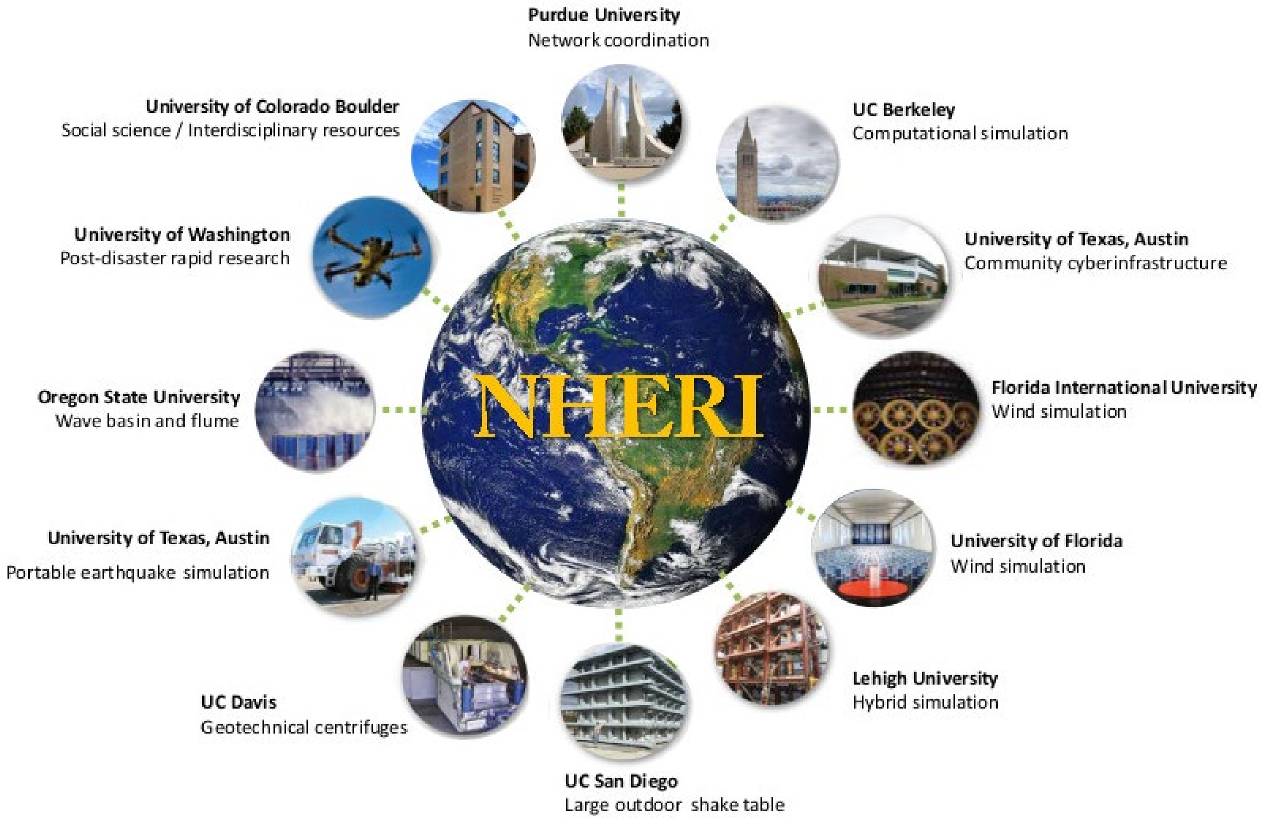
Our Team


Jennifer Bridge, PhD
Director and PI
Operations Lead
Brian Phillips, PhD
Assoc. Director and Co-PI
Experimental Technology Lead
Forrest Masters, PhD, PE
Assoc. Director and Co-PI
Business Development Lead
David Prevatt, PhD, PE
Senior Personnel
Social Science & Reconnaissance Liaison
Kurt Gurley, PhD
Associate Director and Co-PI
Education, Outreach & Diversity Lead
Justin Davis, PhD
Cyberinfrastructure Manager
Ryan Catarelli, PhD
Wind Engineering Technical Manager
Scott Powell
Site Operations Manager
Jeremy Waisome, PhD
Senior Personnel
Education Specialist
Susan Triana
Business Administrator
Tai-An Chen, PhD
Instrument & Controls Engineer
Joseph Herrera
Lab Engineer
Eric Johnson
Design Engineer
Varies
Wind Tunnel Operator
Varies
Experimental Support
Leadership
Management
Project Support

Participants

- Ph.D. students through senior faculty
- ~40 Universities/Organizations
  - US and International Universities
  - NIST and NOAA
- Participant goals:
  - Learn more about facility and explore opportunities to utilize it in research/proposals
  - Explore research combining UF EF capabilities with other experimental resources
  - Learn more about the topic of non-stationary wind
    - FSI, CFD, uncertainty quantification, simulation techniques

Natural Hazards Engineering Research Infrastructure



UF NHERI Experimental Facility

- Provide users access to **advanced wind engineering experimental research infrastructure**

- Support **transformative wind hazard research** through state-of-the-art experimental resources, seamless integration of high-performance computing, skilled personnel, and a culture of safety and collegiality

- **Expand and diversify** the wind engineering community to develop a **workforce** that serves society to create the hazard resilient infrastructure of the future

NSF Award 2037725

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Scientific Objectives: Grand Challenges

1. Reduce uncertainties in the wind loading chain

- Enable experimental rigor in boundary layer wind tunnel testing though advanced automation and control
- Provide flexibility and control to match desired flow characteristics to produce better composites of data

2. Advance physical modeling of complex flow fields to understand their impact

- Simulate nonstationary and non-neutral flow fields that are characteristic of thunderstorms and downbursts
- Quantify impacts of these flows on bluff body aerodynamics and building loads

3. Advance computational wind engineering to reduce reliance on physical testing

- Provide high-fidelity, repeatable datasets to inform computational modeling through advanced instrumentation and flow characterization

4. Advance automation and design of hazard resistant infrastructure

- Promote experiments to validate hazard resistance of emerging and automated design approaches
- Support cyberphysical wind tunnel testing, structural optimization, and machine learning to drive the future of engineering design

Fundamental Questions

High-resolution and high-throughput approach flow simulation and data collection

- How does variation in upwind fetch, simulated by high-resolution, random terrain fields, affect peak loads and higher-order effects in the inertial and roughness sublayers?
- What (big) data collection strategies will best inform computational wind engineering—e.g. CFD-LES, AI/ML prediction, FSI—to reduce our reliance on physical testing and advance numerical modeling (e.g., digital twin approaches)?

Non-synoptic wind simulation

- How do gust fronts impact structural loads and responses?
- What are the impacts of complex topographies and approach flow conditions on wind speed-up and resulting structural loads, particularly for nonstationary winds?
- Can a standard model for thunderstorm outflows and downbursts be developed and simulated in a BLWT?
- What are the scaling issues that will require correction or resolution when simulating non-synoptic winds in a BLWT?
- Is ASCE roughness regime sufficient to delineate load scenarios on low rise structures?


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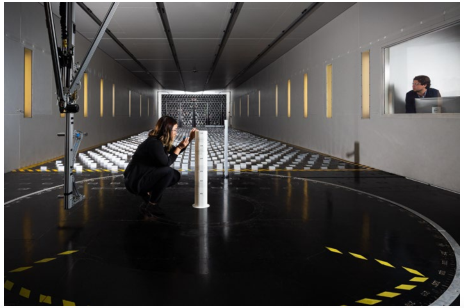
University of Florida East Campus

UF Experimental Facility

Self-Configuring Boundary Layer Wind Tunnel (**BLWT**)
NSF Award 2037725



Multi-Axis Wind Load Simulator (**MAWLS**)

High Airflow Pressure Loading Actuator (**HAPLA**)

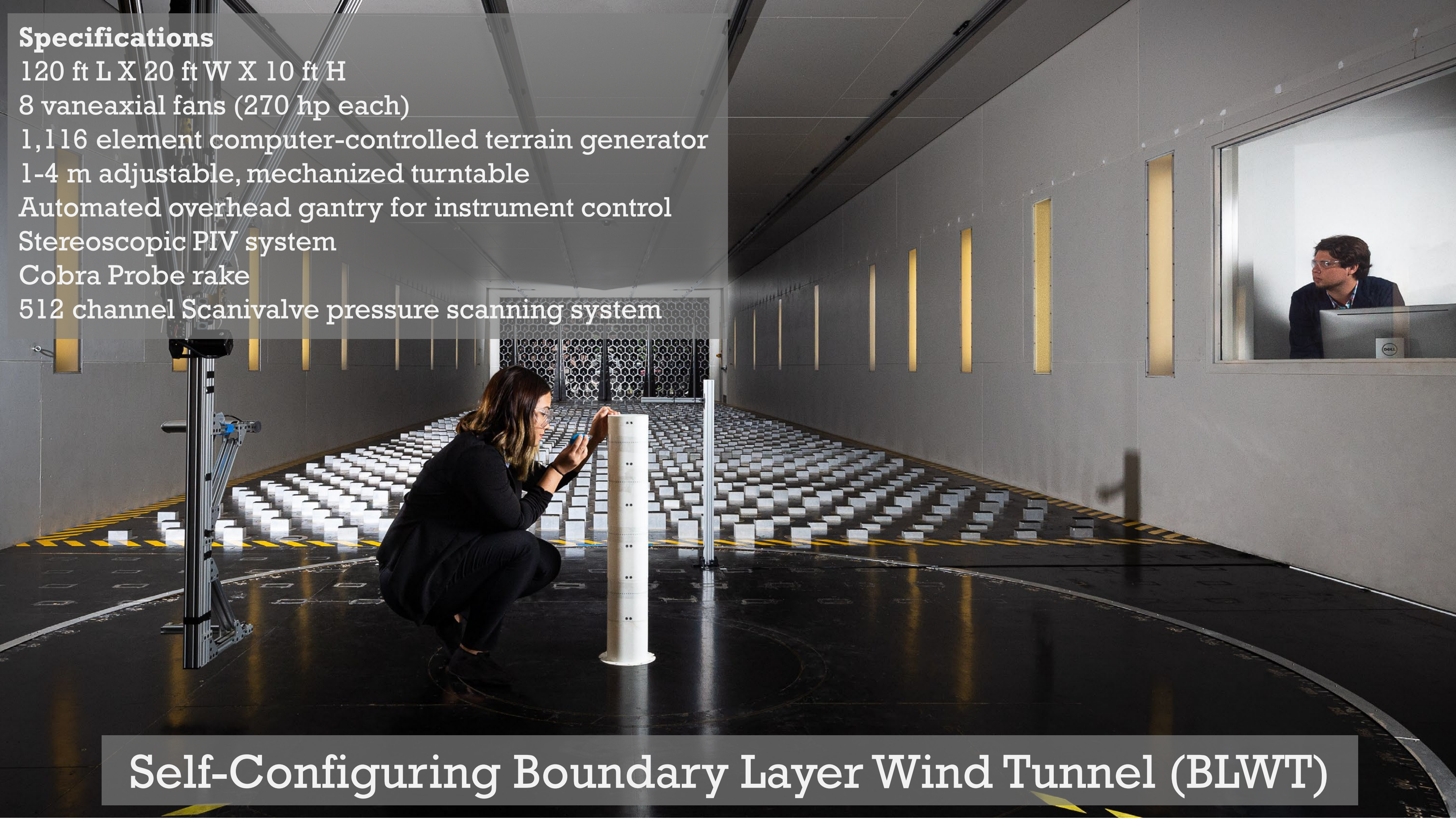
Dynamic Flow Simulator (**DFS**)

Spatiotemporal Pressure Loading Actuator (**SPLA**)

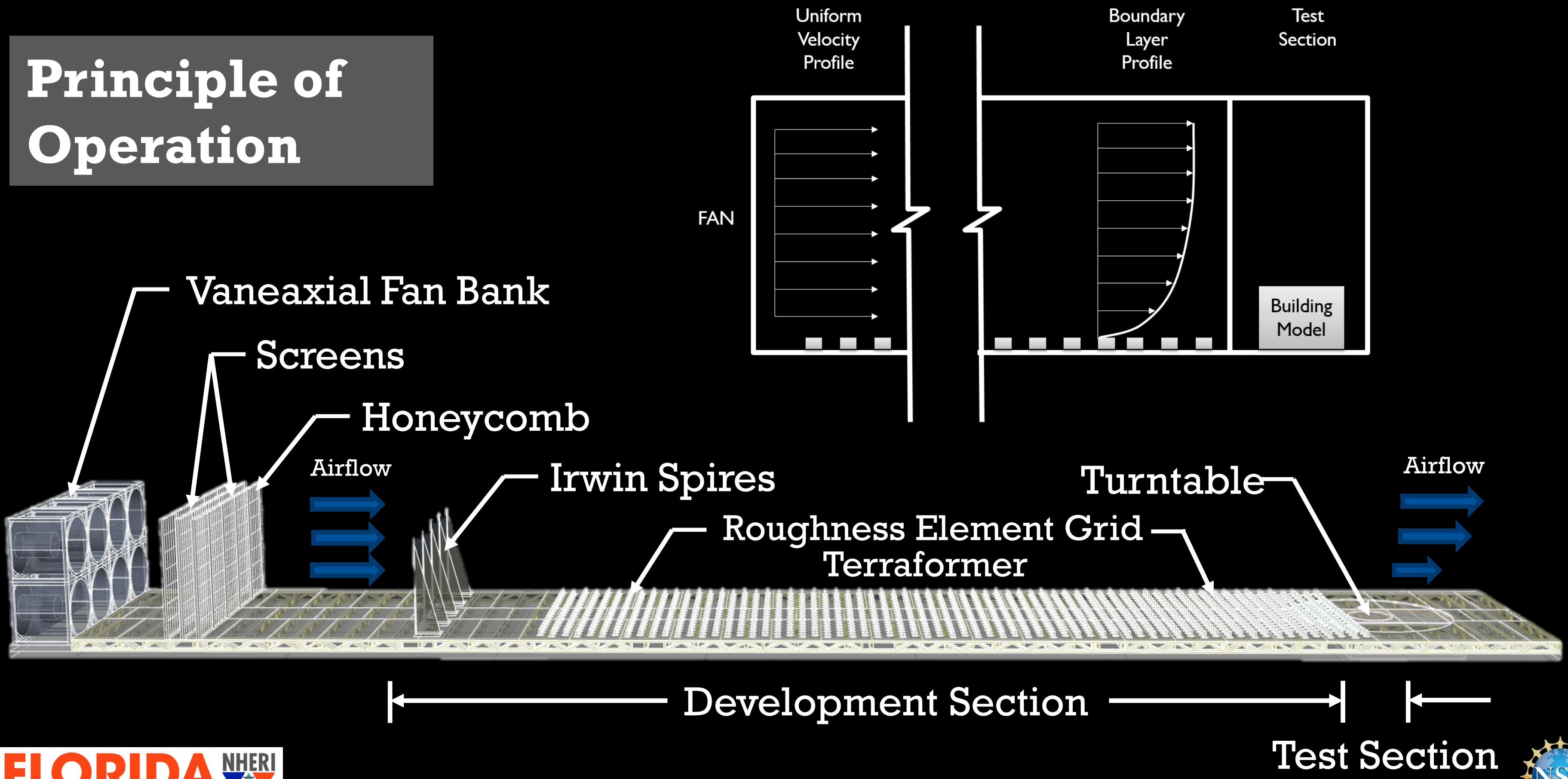
Self-Configuring Boundary Layer Wind Tunnel (BLWT)

Specifications

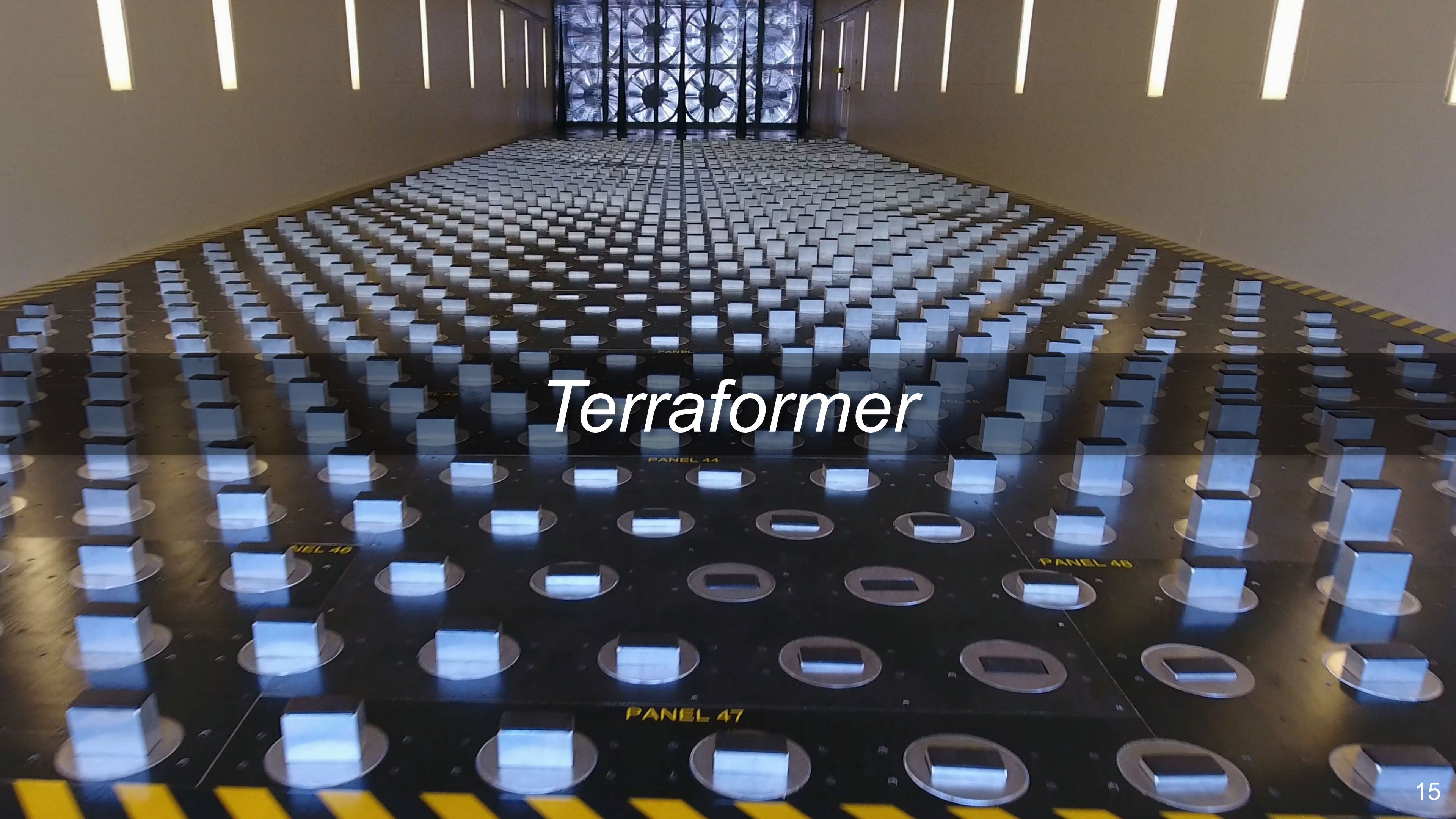
120 ft L X 20 ft W X 10 ft H
8 vaneaxial fans (270 hp each)
1,116 element computer-controlled terrain generator
1-4 m adjustable, mechanized turntable
Automated overhead gantry for instrument control
Stereoscopic PIV system
Cobra Probe rake
512 channel Scanivalve pressure scanning system



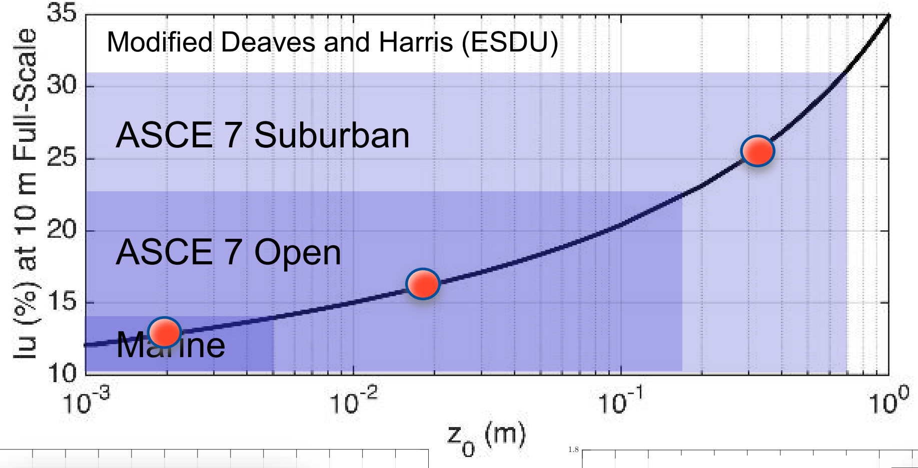
Principle of Operation

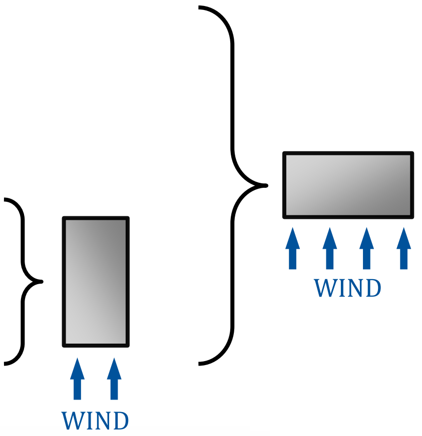


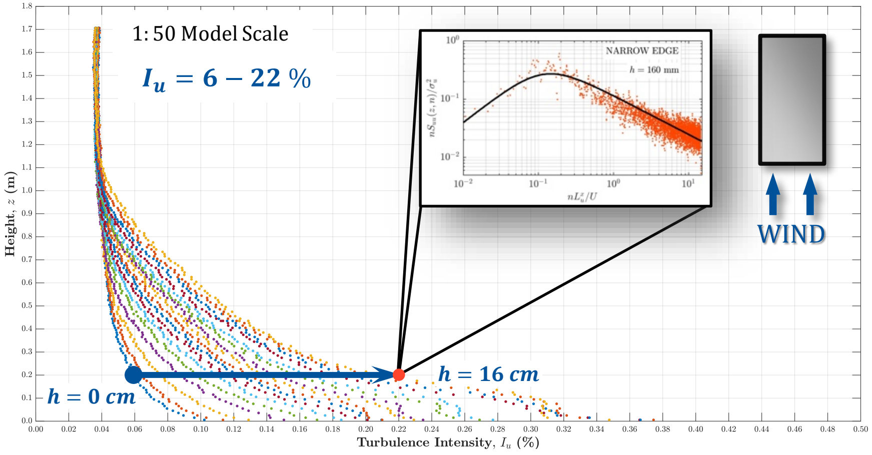
Terraformer



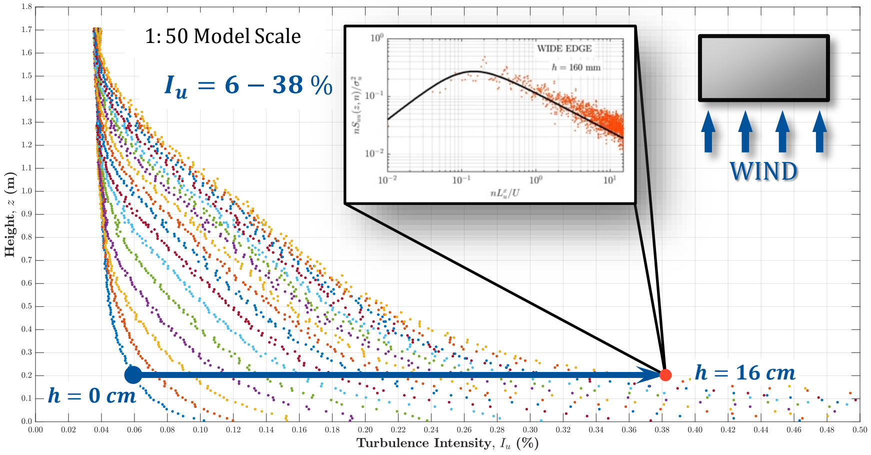
Continuum of Terrain Conditions







$I_v/I_u = 0.71 - 0.79$ $I_w/I_u = 0.59 - 0.63$



$I_v/I_u = 0.69 - 0.77$ $I_w/I_u = 0.56 - 0.62$

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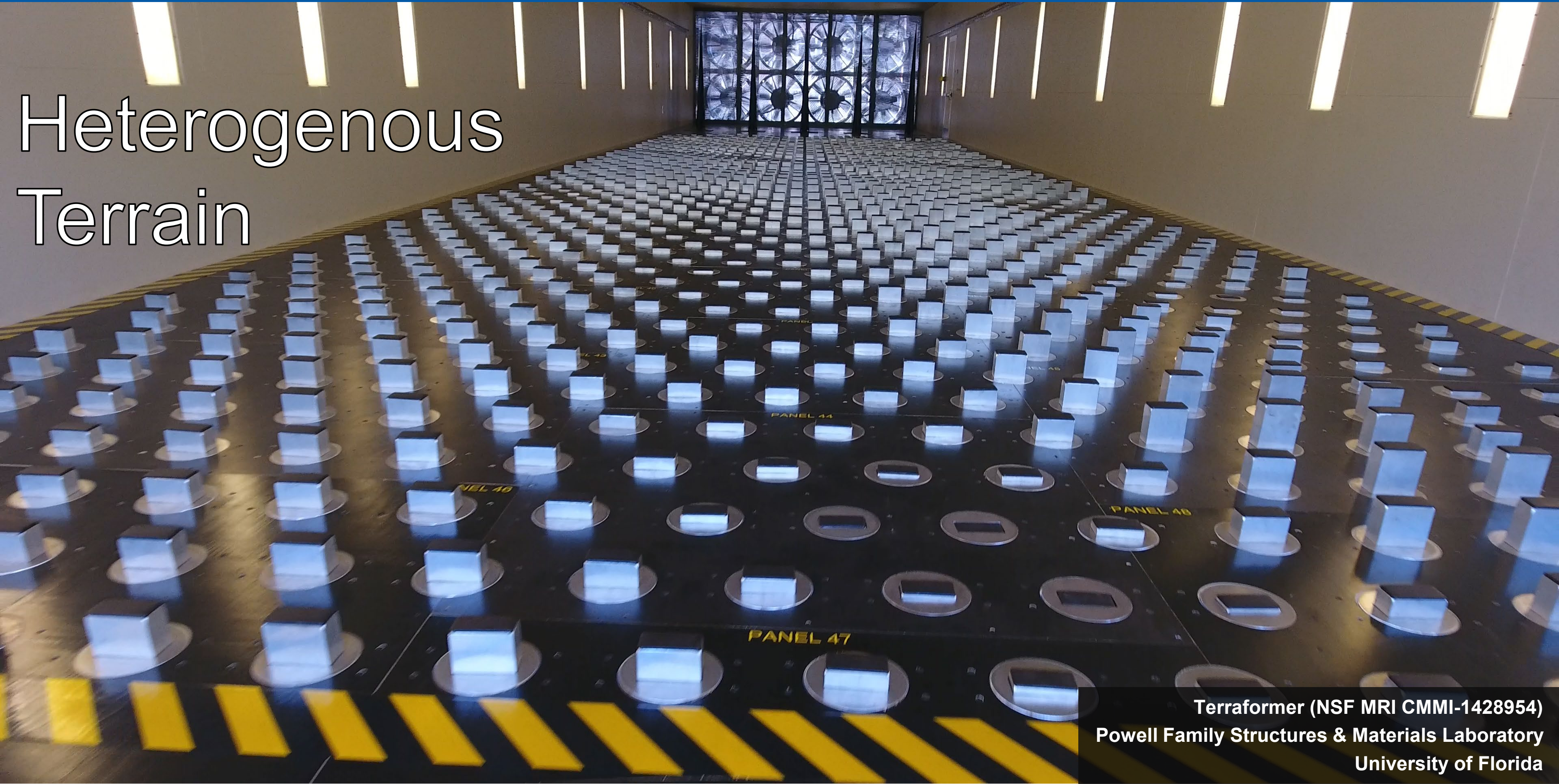
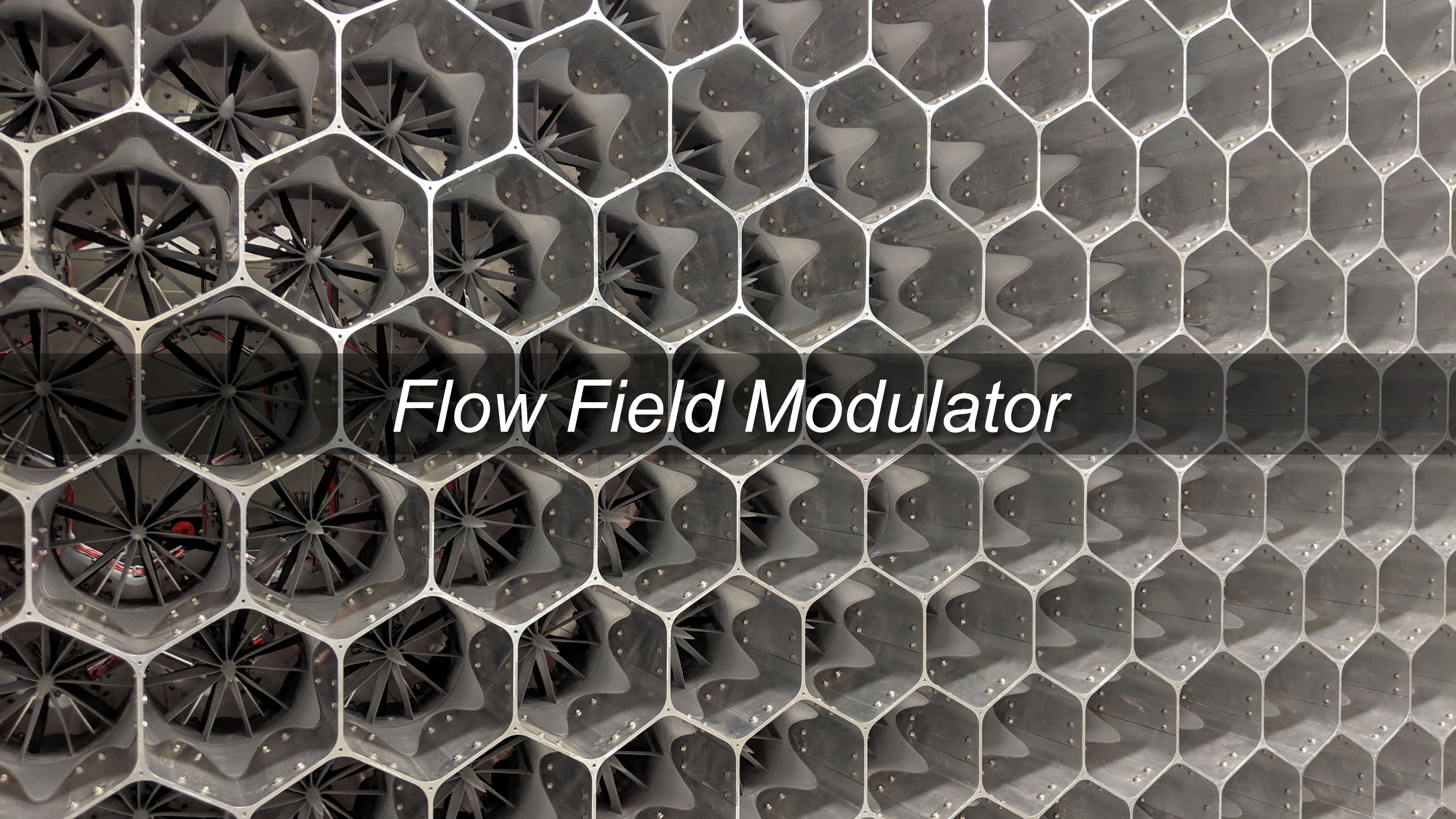
Heterogenous Terrain

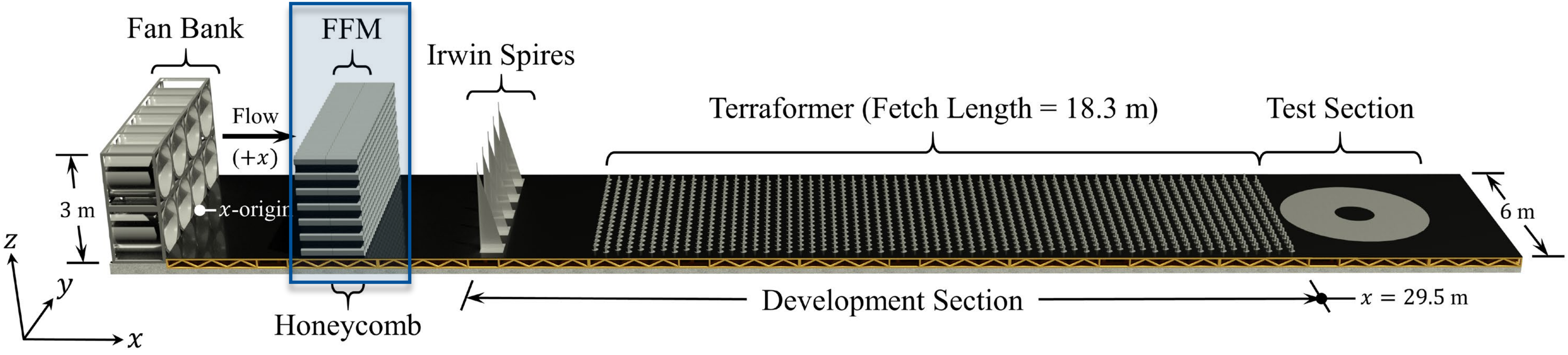


Terraformer (NSF MRI CMMI-1428954)
Powell Family Structures & Materials Laboratory
University of Florida


Flow Field Modulator

Flow Field Modulator

Optional Active Flow Control: Mean Velocity and Turbulence Generator

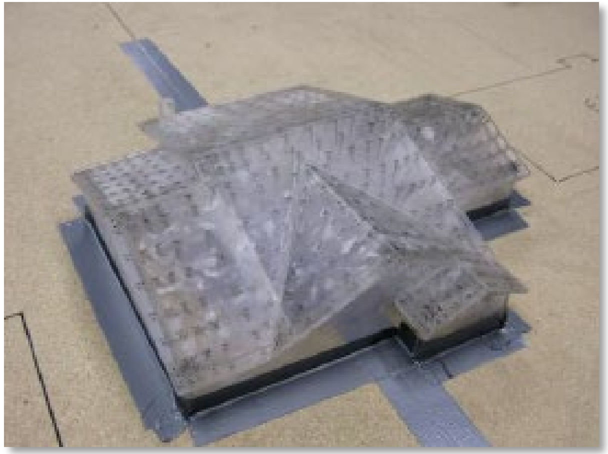


MRI (NSF Award 1428954)

Instrumentation

Model Instrumentation

- Scanivalve pressure scanning system
  - 512 pressure taps can be measured simultaneously from eight ZOC33 modules
  - Max sampling rate = 625 Hz
- 6-axis force balance sensors
- Displacement sensors
- Accelerometers



Flexible tubes inside model connects pressure ‘taps’ to pressure scanning modules

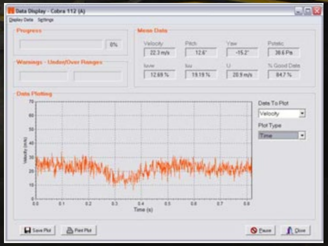
Wind Profile Measurements

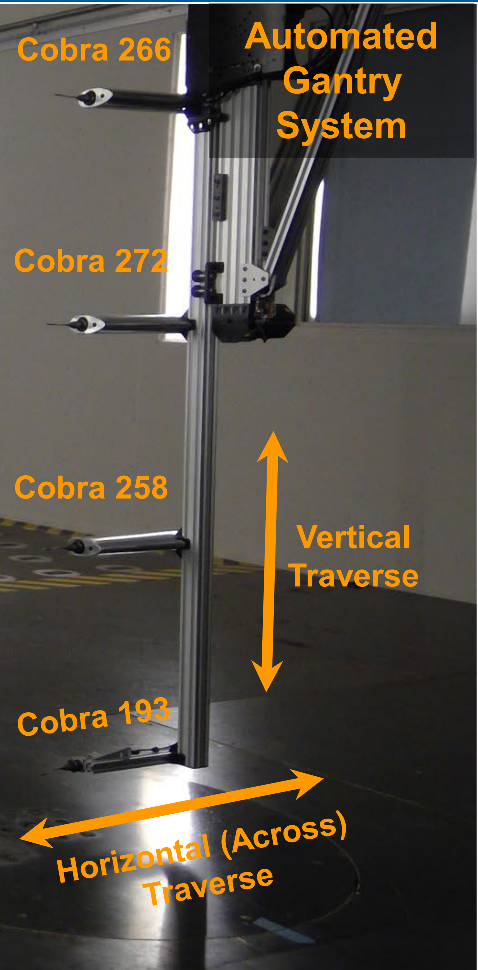
Series 100 Cobra Velocity Probes

Turbulent Flow Instrumentation

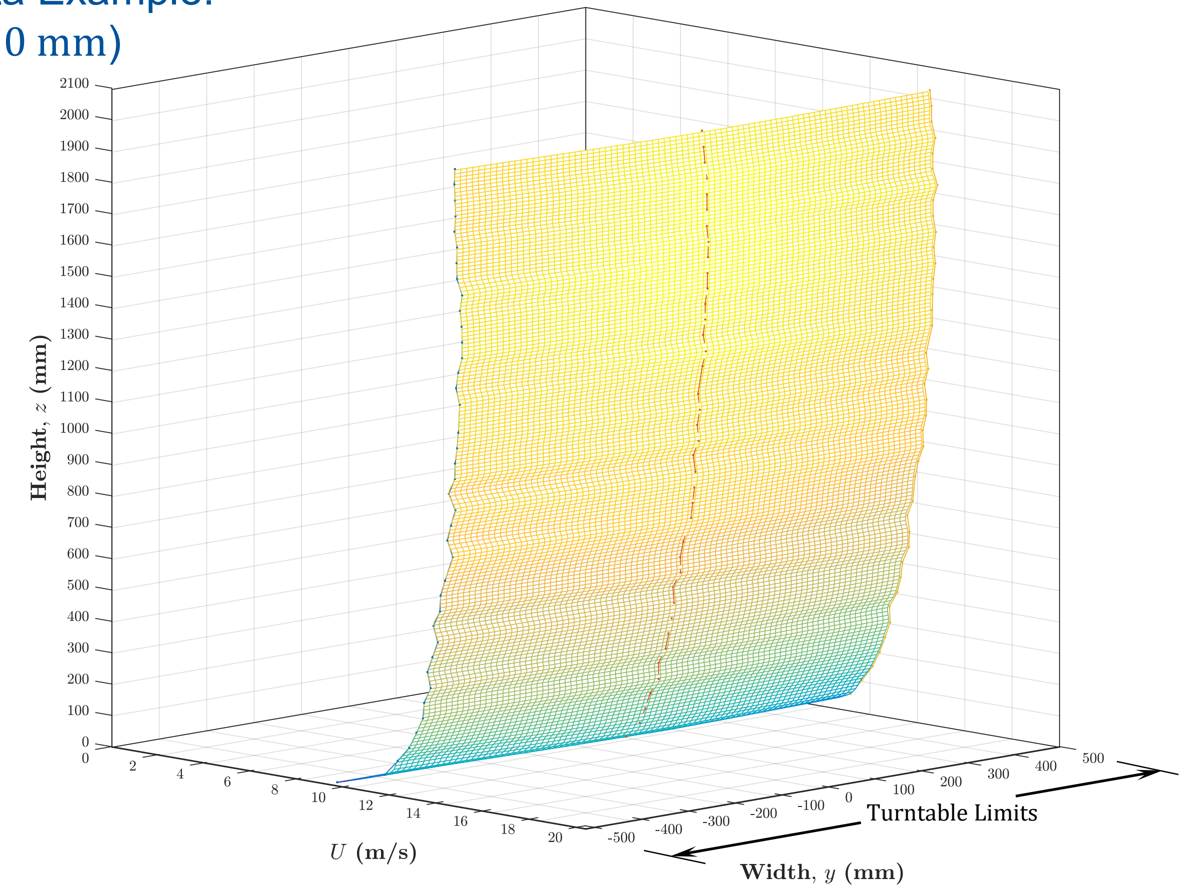
TurbulentFlow Instrumentation

- Measure u, v, and w velocity components and static pressure
- Acceptance cone: ±45°
- Maximum frequency response: 2 kHz
- Sensing range: 2-65 m/s

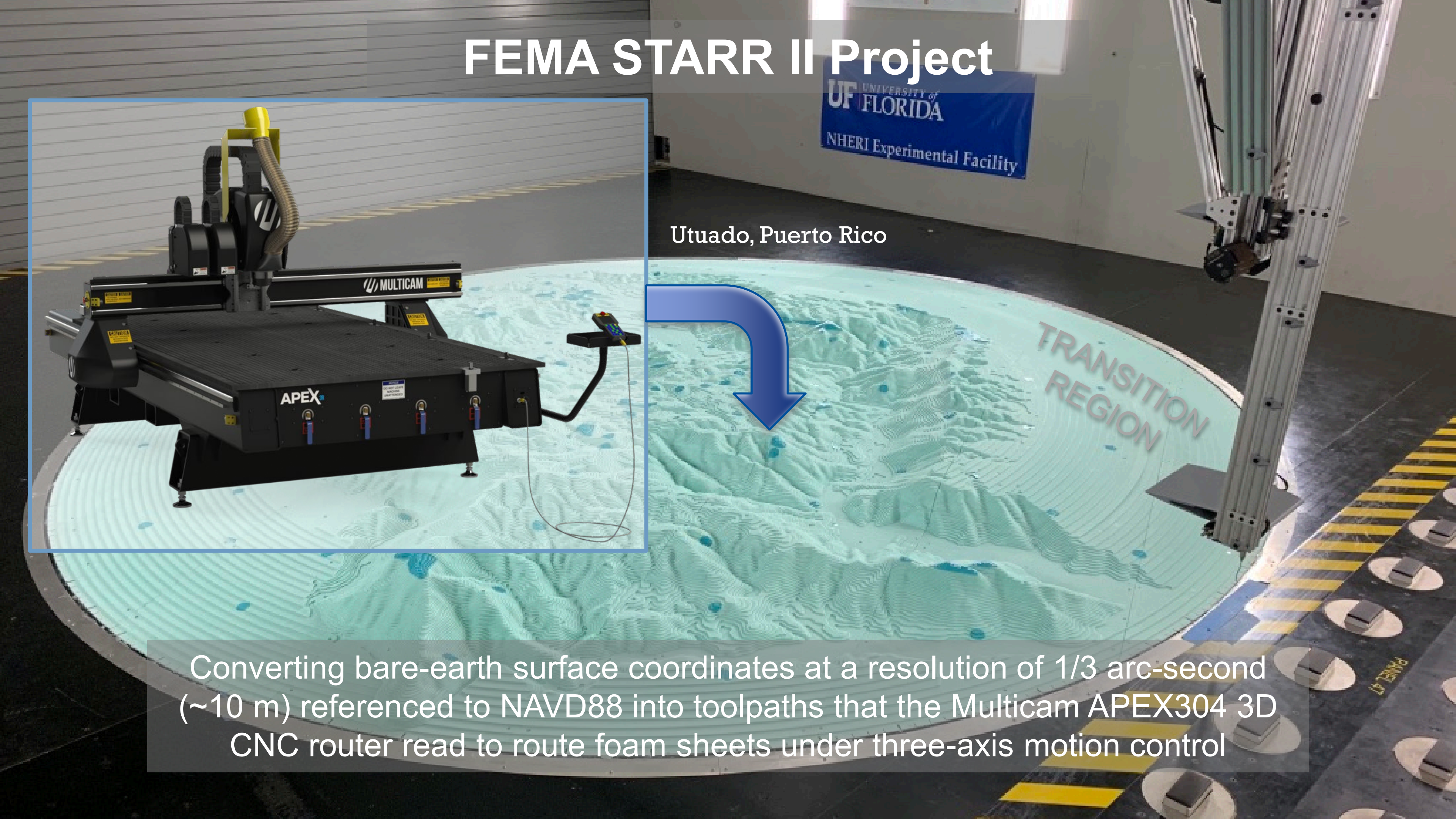




Cobra Probe Data Example: Flush Case ($h = 0$ mm)



FEMA STARR II Project



Converting bare-earth surface coordinates at a resolution of 1/3 arc-second (~10 m) referenced to NAVD88 into toolpaths that the Multicam APEX304 3D CNC router read to route foam sheets under three-axis motion control

FEMA STARR II Project

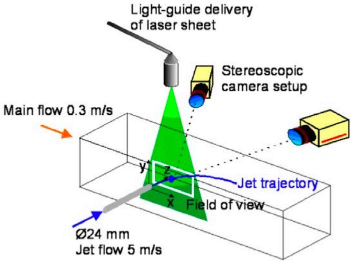
3D instrument control of the Cobra Probe Rake for precision measurement of surface flows

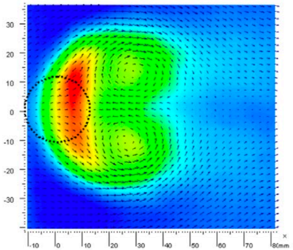
(a) Cobra Probe installed in instrument traverse

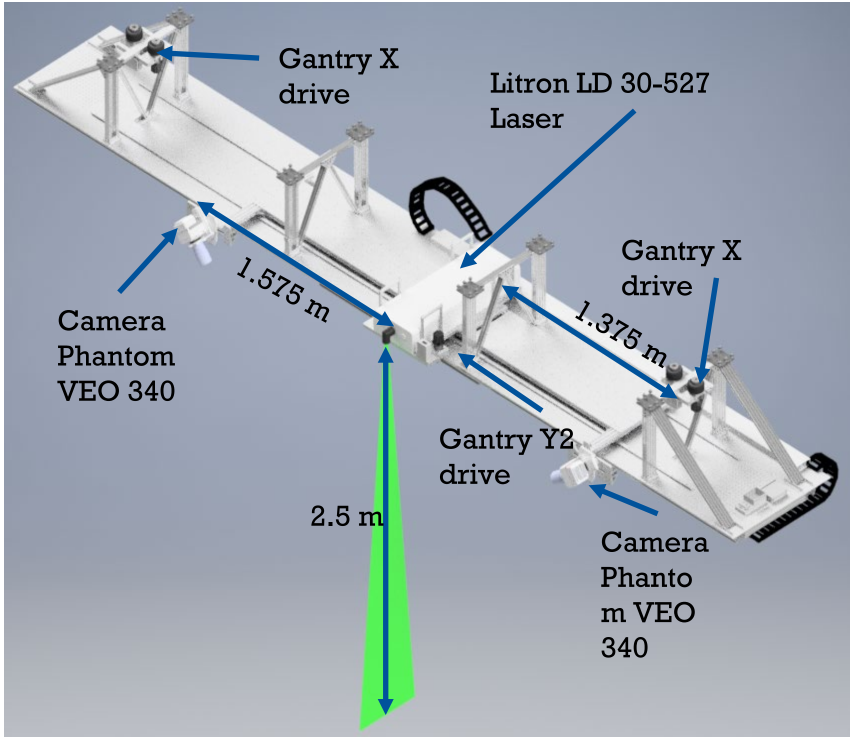
(b) Zoomed in view of the Cobra Probe over the topographic model surface

Particle Image Velocimetry (PIV)

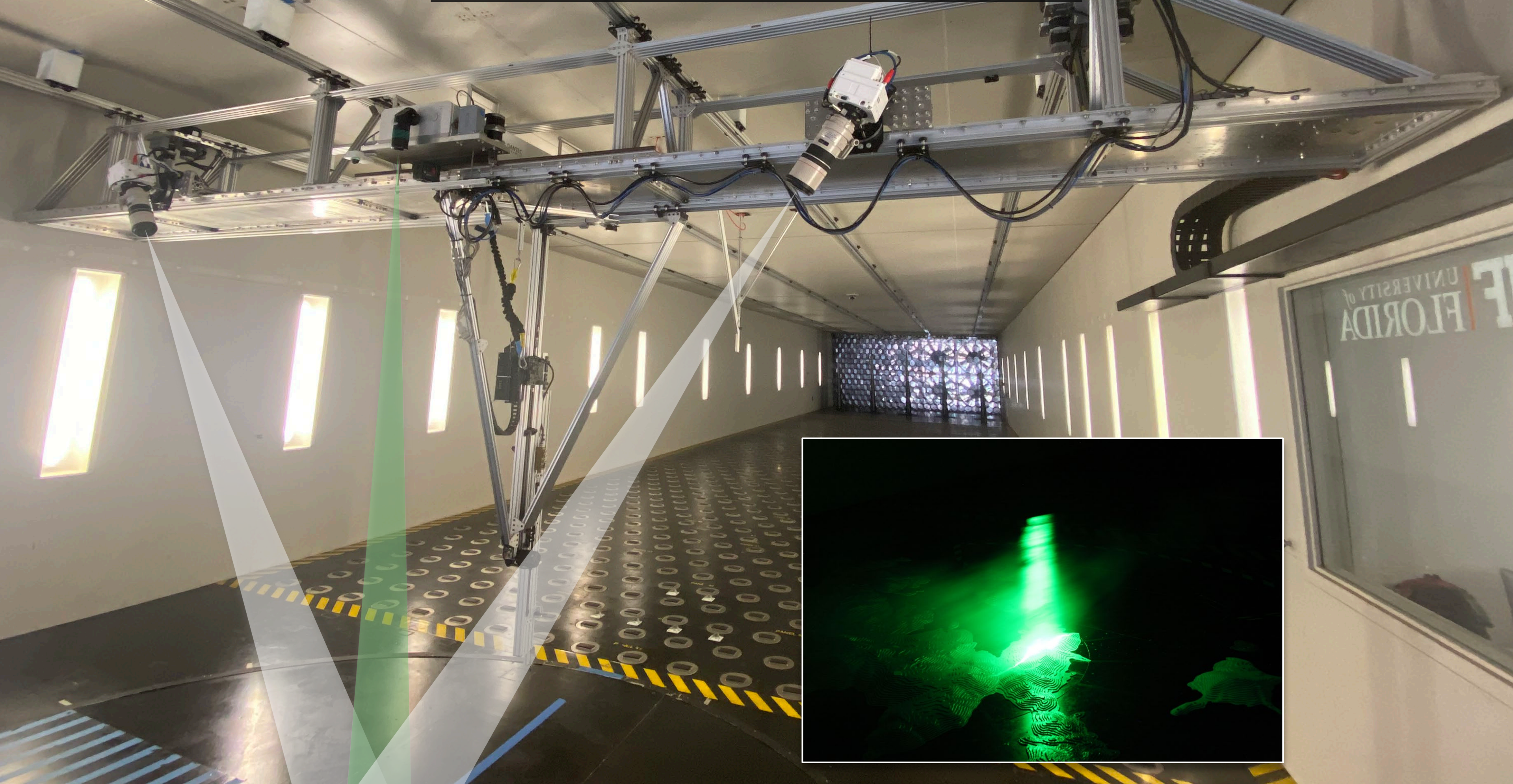
- Dantec Dynamics PIV system
  - DualPower 30-1000 laser (2 X 30 mJ at 1000 Hz; 527 nm)
  - SpeedSense VEO 340 camera that can record up to 72 GB of data at 4MP and 800 fps
  - Camera is equipped with a 10 Gb interface to enable rapid transfer of data







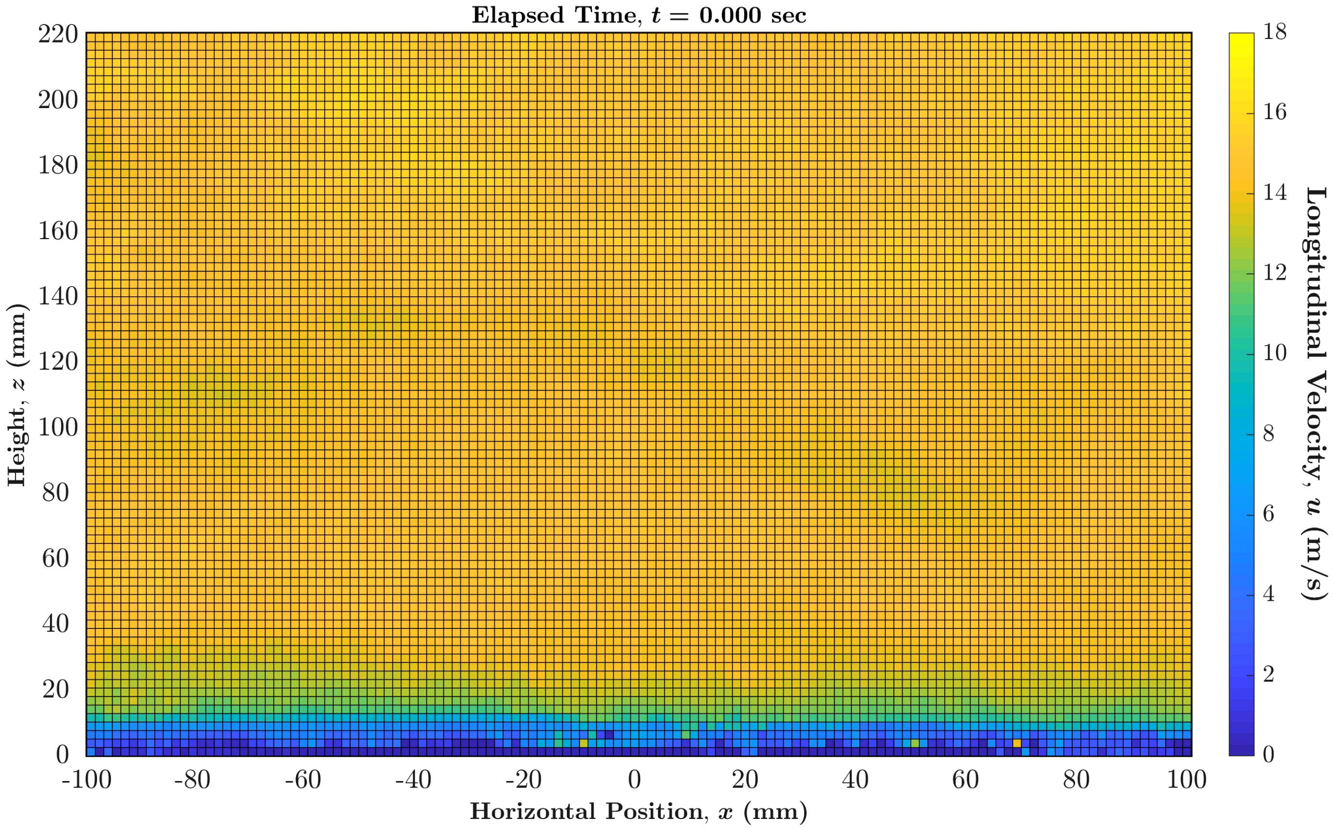
Particle Image Velocimetry (PIV)

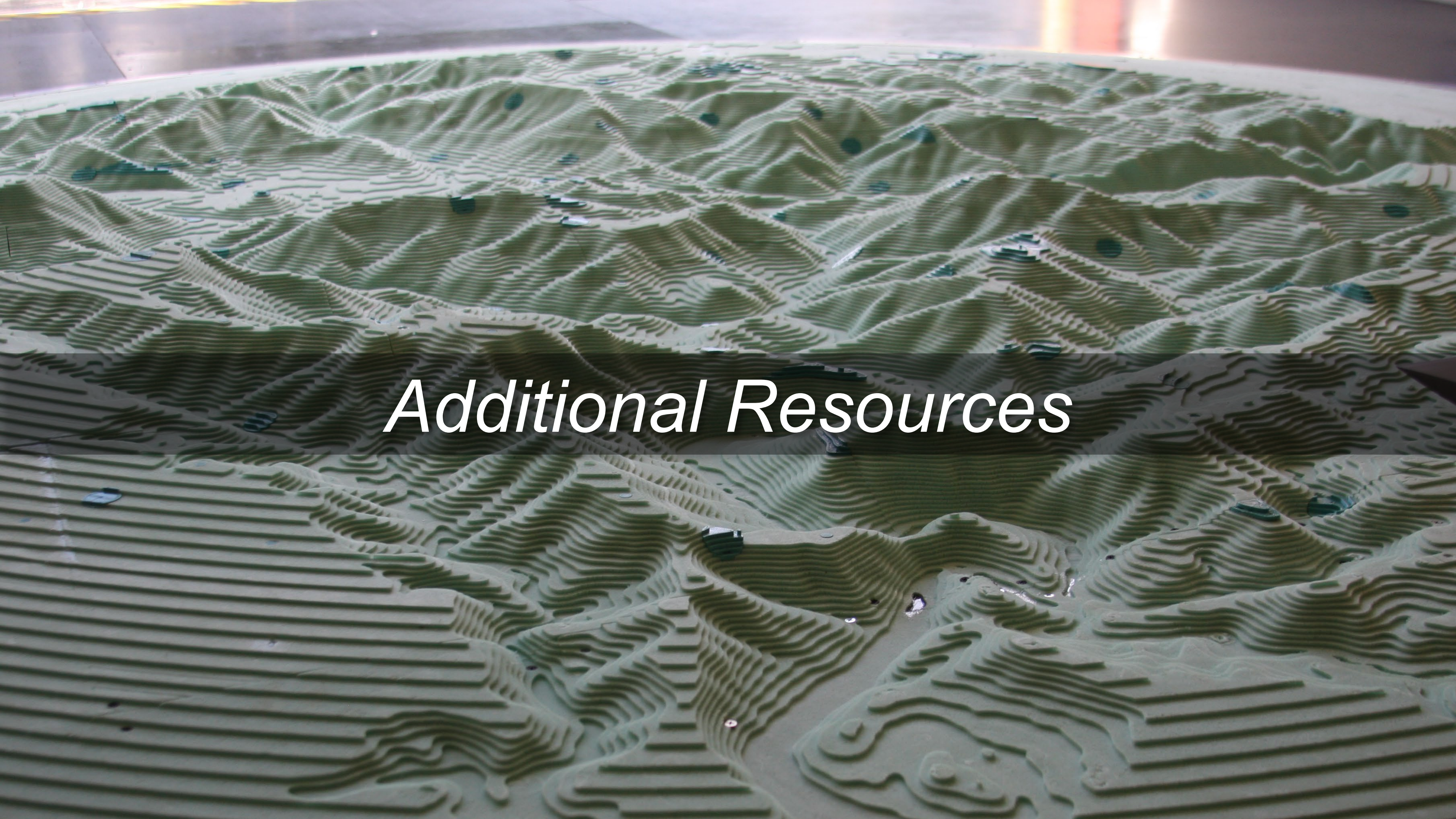


PIV Setup

- Designed and built seeders in house
  - Produce particles of the correct size (1-2 micron)
  - Evenly and sufficiently distribute particles in PIV window
  - Use safe and inexpensive fluid

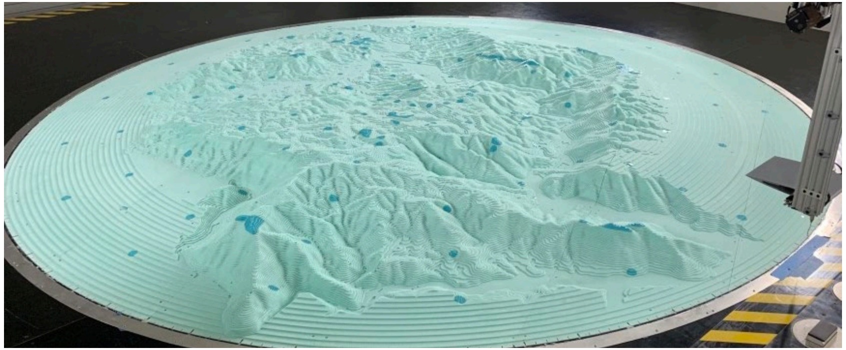
Time-resolved Longitudinal Velocity from PIV





Additional Resources

In-House Fabrication



- 3-axis CNC router
  - Fully programmable MultiCam APEX3R CNC Router for routing foam, wood, plastics, and aluminum model components
  - 1.5m x 3m
- 3D printers
  - Three Formlabs Form 2 stereolithography 3D printers for high-resolution rigid pressure-tapped models
  - Five LulzBot TAZ 6 Fused Filament Fabrication 3D printers for production of larger lower resolution model components
- Machine shop and skilled design/fabrication staff

Working with UF NHERI

- NSF subsidizes testing in NHERI Experimental Facilities (EFs)
  - Some or all experimental testing is paid for by NSF

- Two paths to working with UF NHERI with NSF subsidy:

New NSF Project

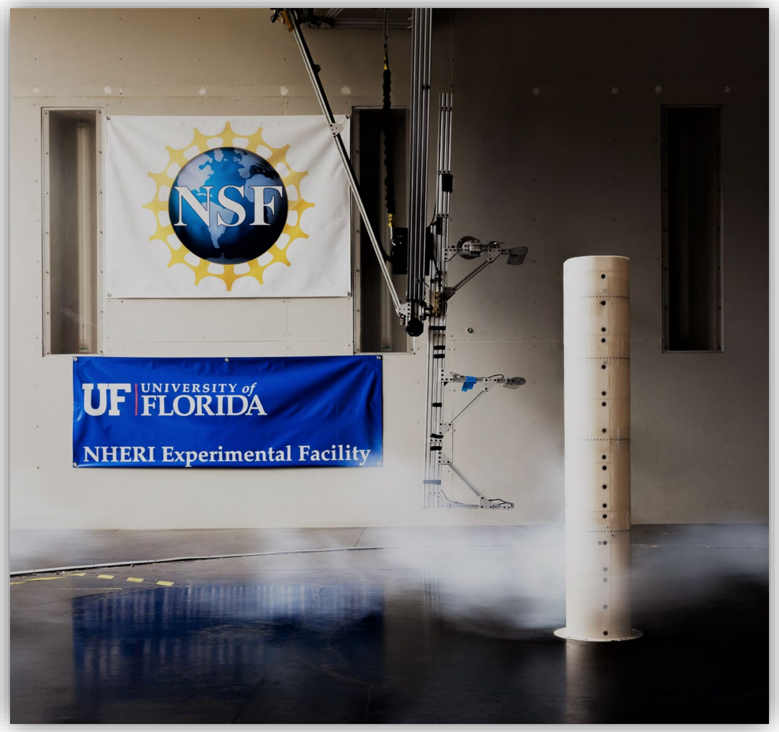
- Work with EF to generate scope of work to be completed in EF
- Include a letter of collaboration from EF
- Testing within standard usage does not need to be included in project budget
- Testing above standard usage will receive estimate from EF and must be included in project budget

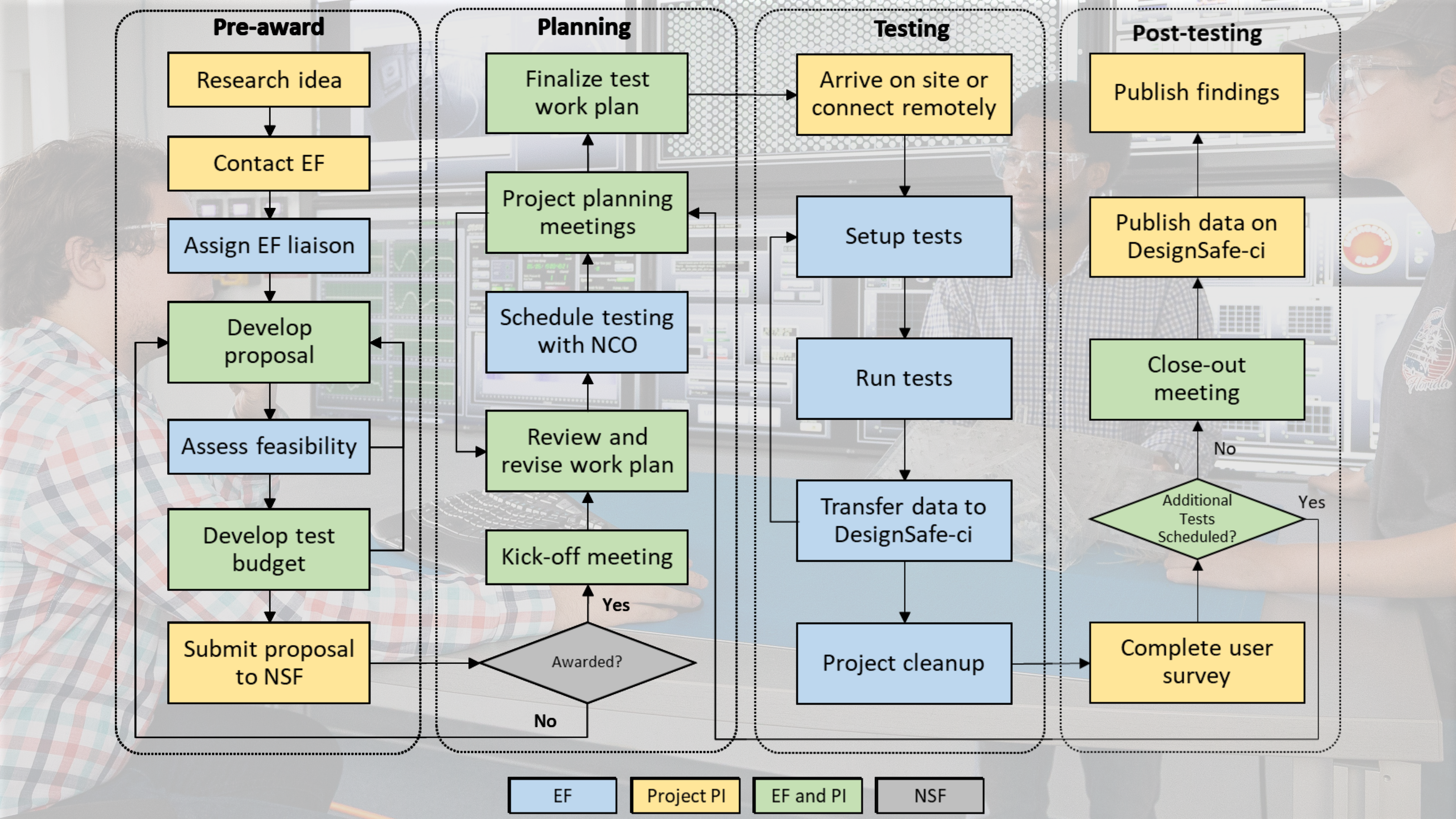
NSF Enhancement Project

- Enhance the research of an existing NSF project
- Work with EF to generate scope of work to be completed in EF
- Testing within standard usage does will not receive an invoice
- Testing above standard usage will be invoiced

What does NSF pay for?

- Standard BLWT usage: **24 days** of setup/operation/clean-up
  - With or without FFM or PIV
- Standard usage includes
  - Access to highly trained staff
  - Test planning and consultation
  - Standard instrumentation and data acquisition
  - Automatic data/metadata archiving
  - Set up and tear down
  - Operation of all equipment
  - Dedicated workspace for users
- **Model fabrication not included**



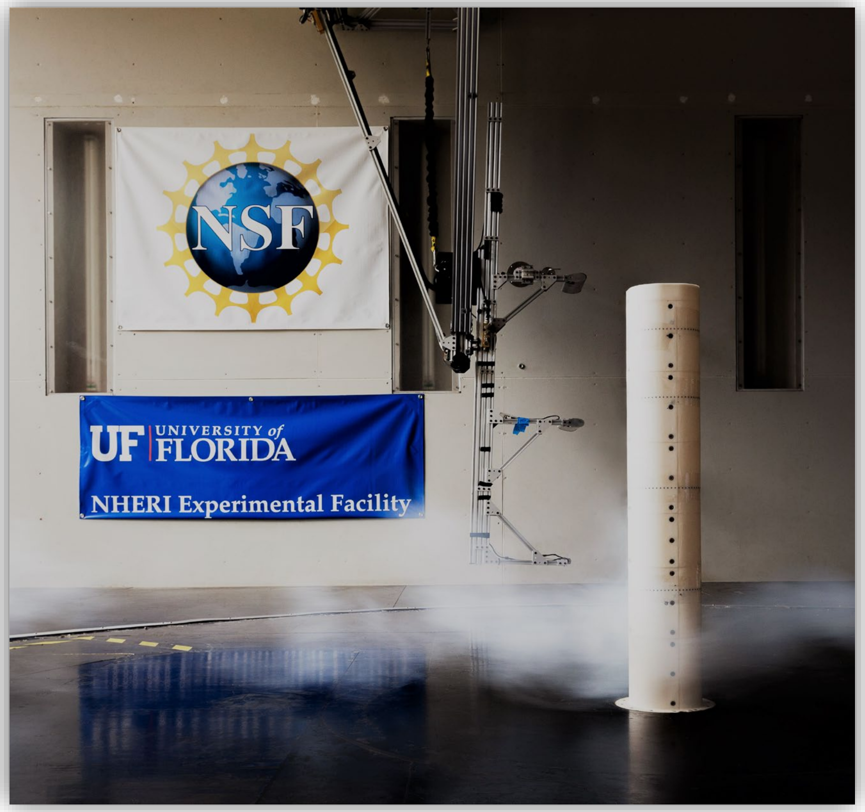

Pre-award
Research idea
Contact EF
Assign EF liaison
Develop proposal
Assess feasibility
Develop test budget
Submit proposal to NSF
Planning
Finalize test work plan
Project planning meetings
Schedule testing with NCO
Review and revise work plan
Kick-off meeting
Yes
Awarded?
No
Testing
Arrive on site or connect remotely
Setup tests
Run tests
Transfer data to DesignSafe-ci
Project cleanup
Post-testing
Publish findings
Publish data on DesignSafe-ci
Close-out meeting
No
Additional Tests Scheduled?
Yes
Complete user survey
EF
Project PI
EF and PI
NSF

Data Publication & Reuse

- NHERI provides a repository of curated data related to natural hazards experimental research
- DesignSafe: designsafe-ci.org
  - University of Texas provides cyberinfrastructure support for NHERI
  - DesignSafe accounts available through TACC
- Data curated in DesignSafe receives a DOI for citation

How do I learn more?

- https://ufl.designsafe-ci.org
  - Virtual tour
  - Workshop announcements
- **Contact one of the PI team**
  - Jennifer Bridge, jennifer.bridge@essie.ufl.edu
  - Forrest Masters, masters@ce.ufl.edu
  - Kurt Gurley, kgurl@ce.ufl.edu
  - Brian Phillips, brian.phillips@essie.ufl.edu



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NHERI

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Flow Field Modulator: Theory of Operation

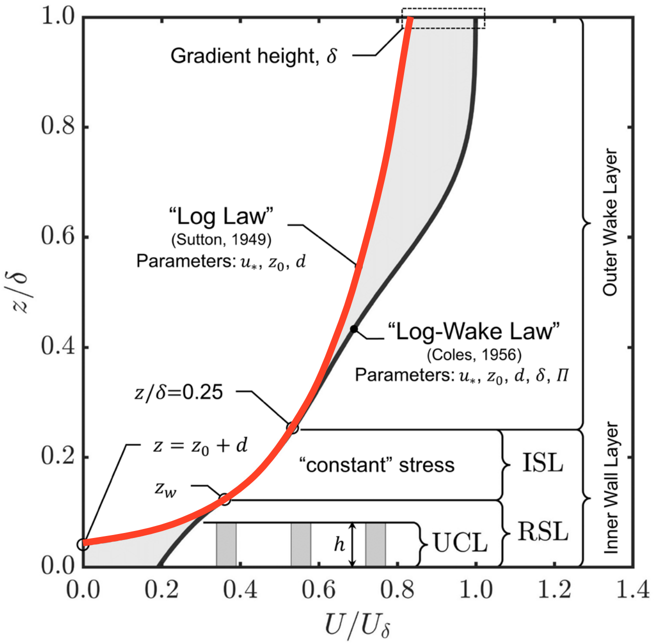
Jennifer A. Bridge, Ph.D., Kurt Gurley, Ph.D., Forrest Masters, Ph.D., Brian Phillips, Ph.D., Ryan Catarelli, Ph.D.

Boundary Layer Wind Tunnel Simulation of Transient and Non-Synoptic Wind Events

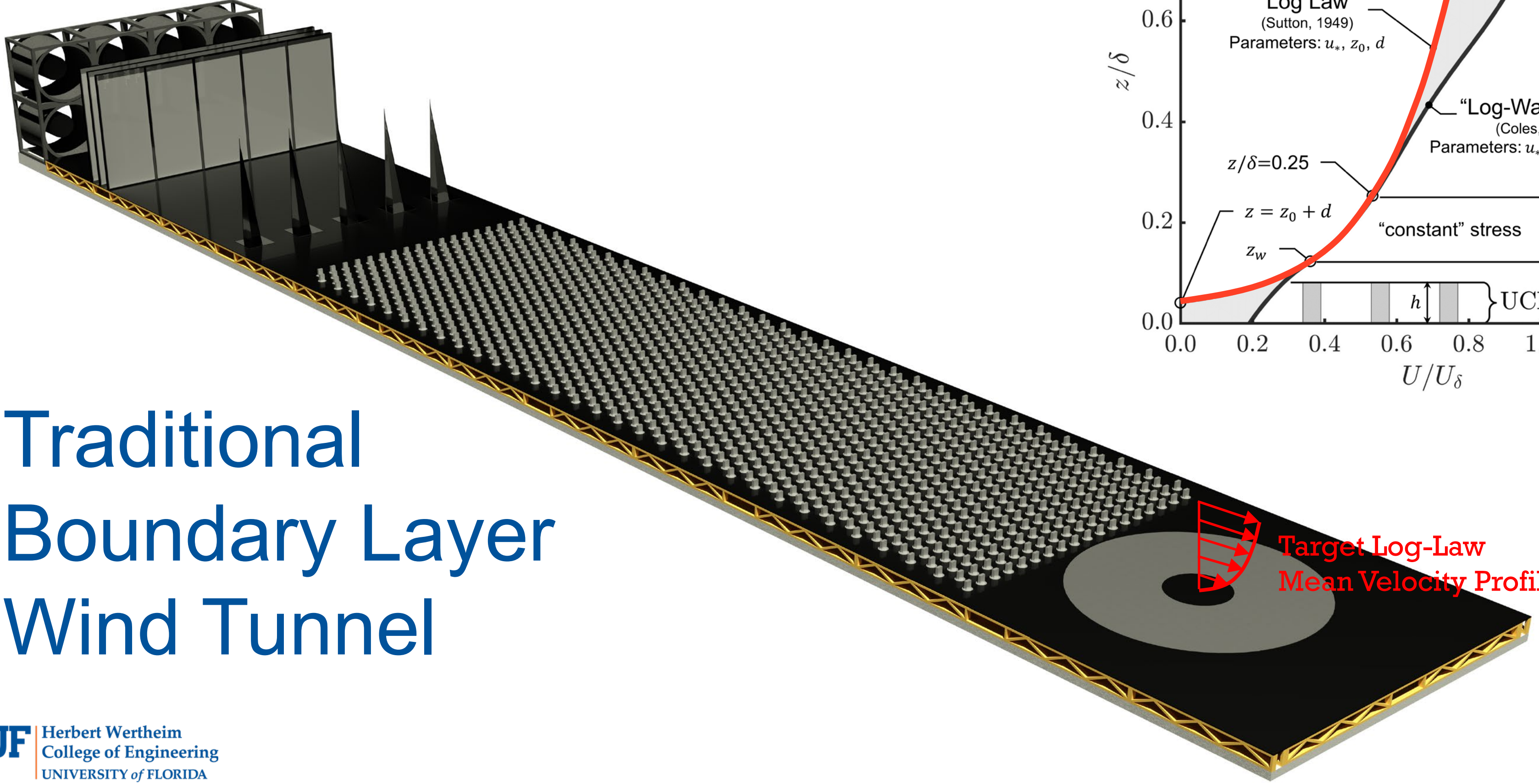
May 19, 2021

NSF Award# 2037725

Boundary Layer
Mean Velocity Profile



Traditional Boundary Layer Wind Tunnel



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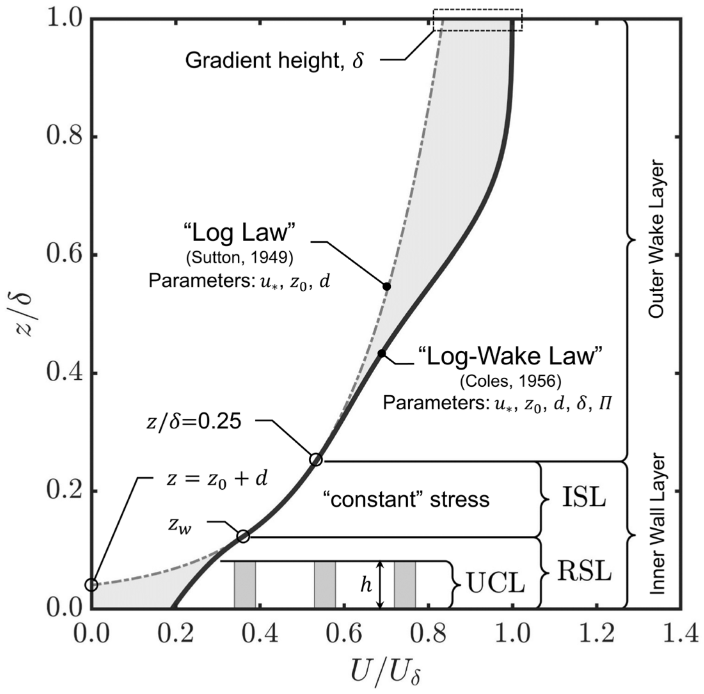
UNIVERSITY of FLORIDA

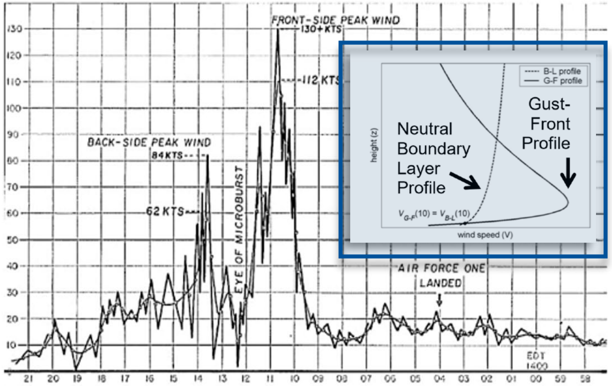
Limitations of Traditional BLWT

- Boundary layer generated by mechanical turbulence
  - Difficult to create non-monotonic profiles
  - Difficult to freely scale regions of boundary layer
  - Difficult to adjust turbulence frequency and intensity – relies on energy cascade
  - Difficult to generate non-stationary/transient flow
- Flow control is primarily in the longitudinal direction



Example Open Questions

- Non-Neutral & Nonstationary Flows
  - Gust fronts associated with thunderstorms characterized by non-stationary amplitude and frequency components (e.g., Kwon and Kareem, 2009) and others
  - May significantly alter primary load paths engaged and thus structural vulnerability and habitability (Kijewski-Correa and Bentz, 2011)
- Influence of Complex Topography on Wind Loads
  - Guidance exists for isolated topographic features such escarpments, 3-D axisymmetric hills, or 2D ridge (e.g., ASCE 7-16), but no guidance currently exists for complex topography
  - Influence of topography on wind speed must be experimentally determined on a case-by-case basis



Example of a nonstationary velocity record measured during a downburst at Andrews Air Force Base (Fajita, 1985). Mean velocity profiles (Kwon and Kareem, 2009).

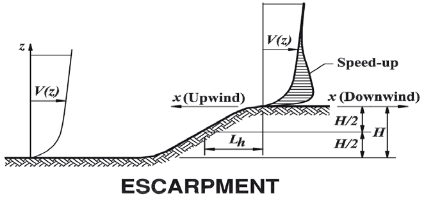
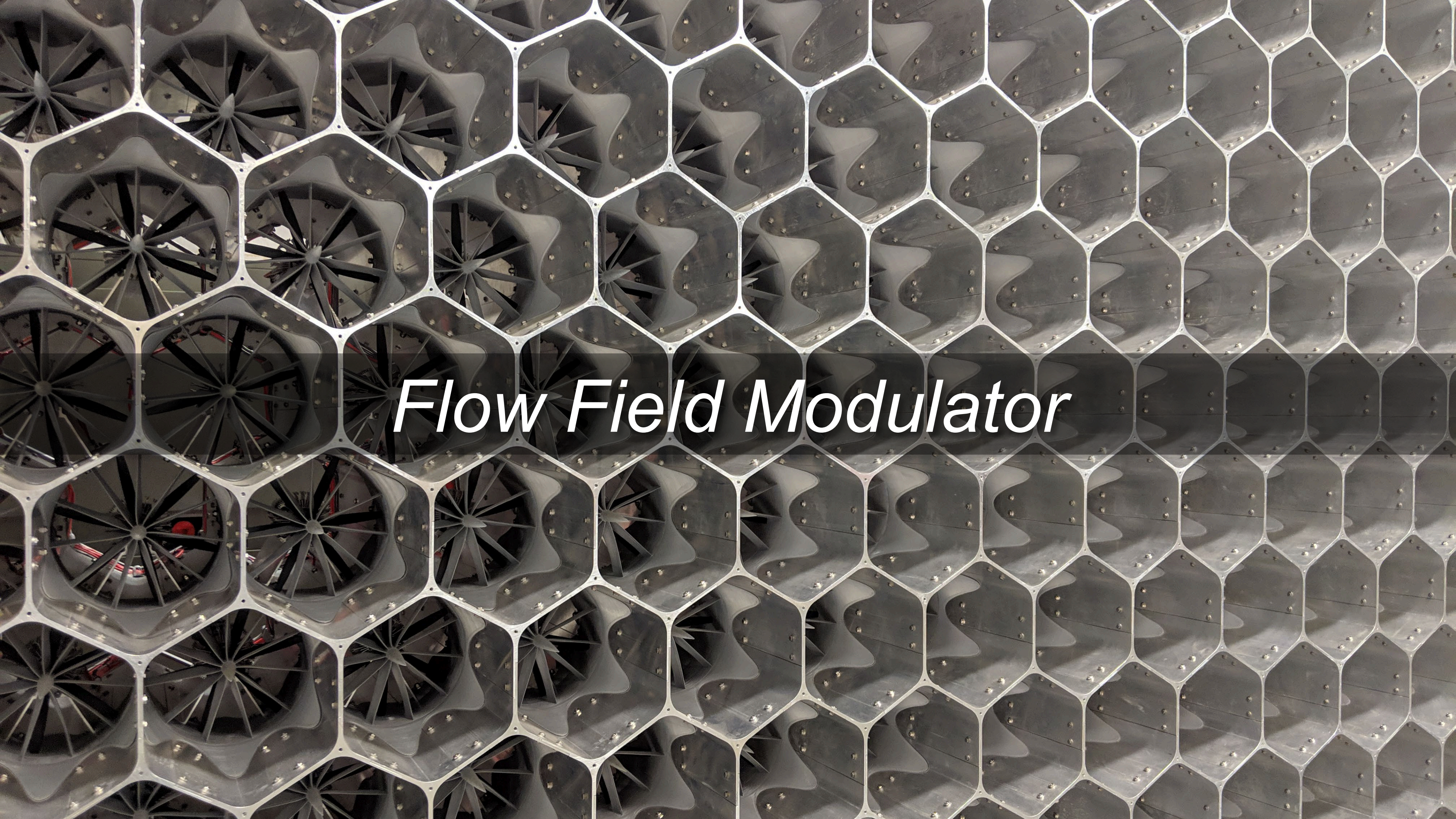
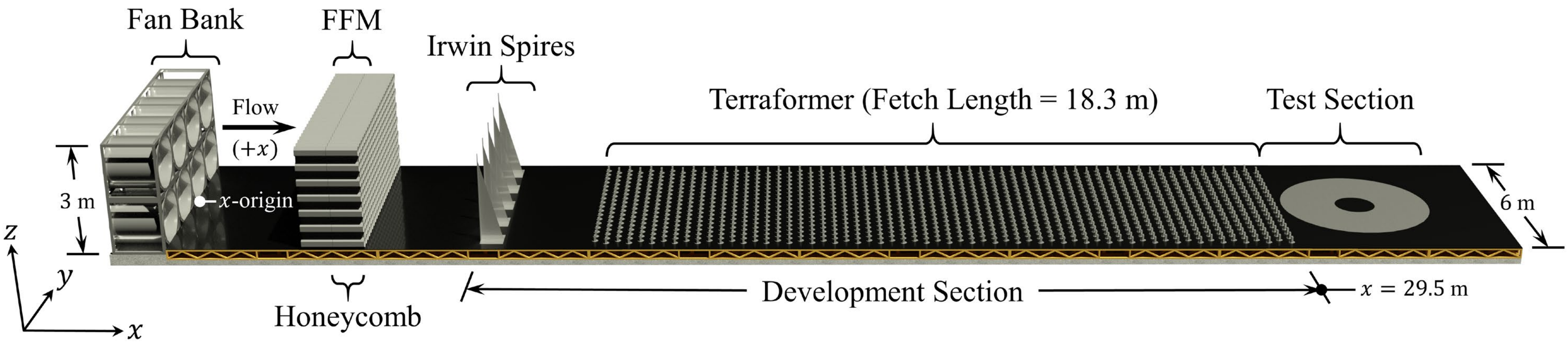


Diagram for topographic speedup factor, K_{zt} (ASCE 7-16)


Flow Field Modulator

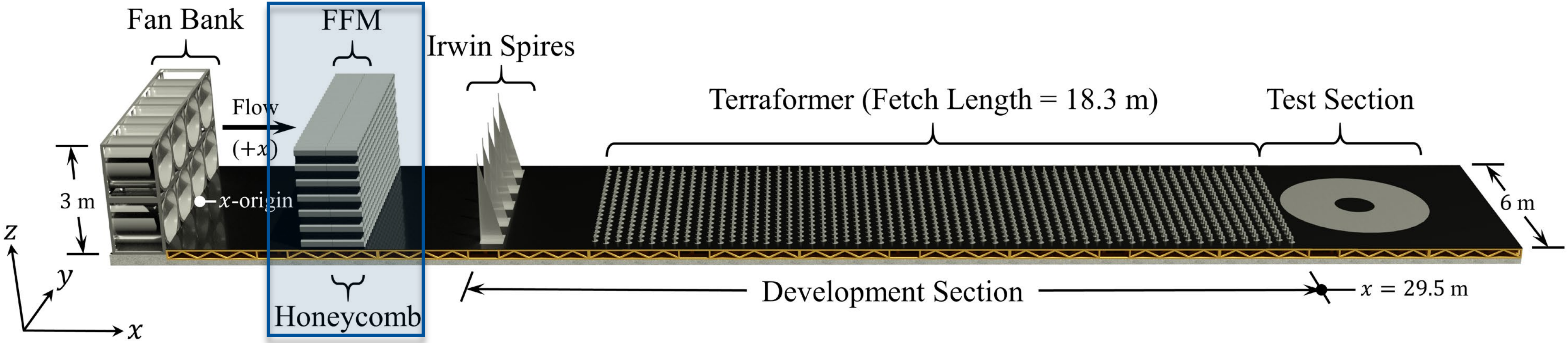
University of Florida BLWT

Open Circuit Low-Speed Wind Tunnel



Flow Field Modulator

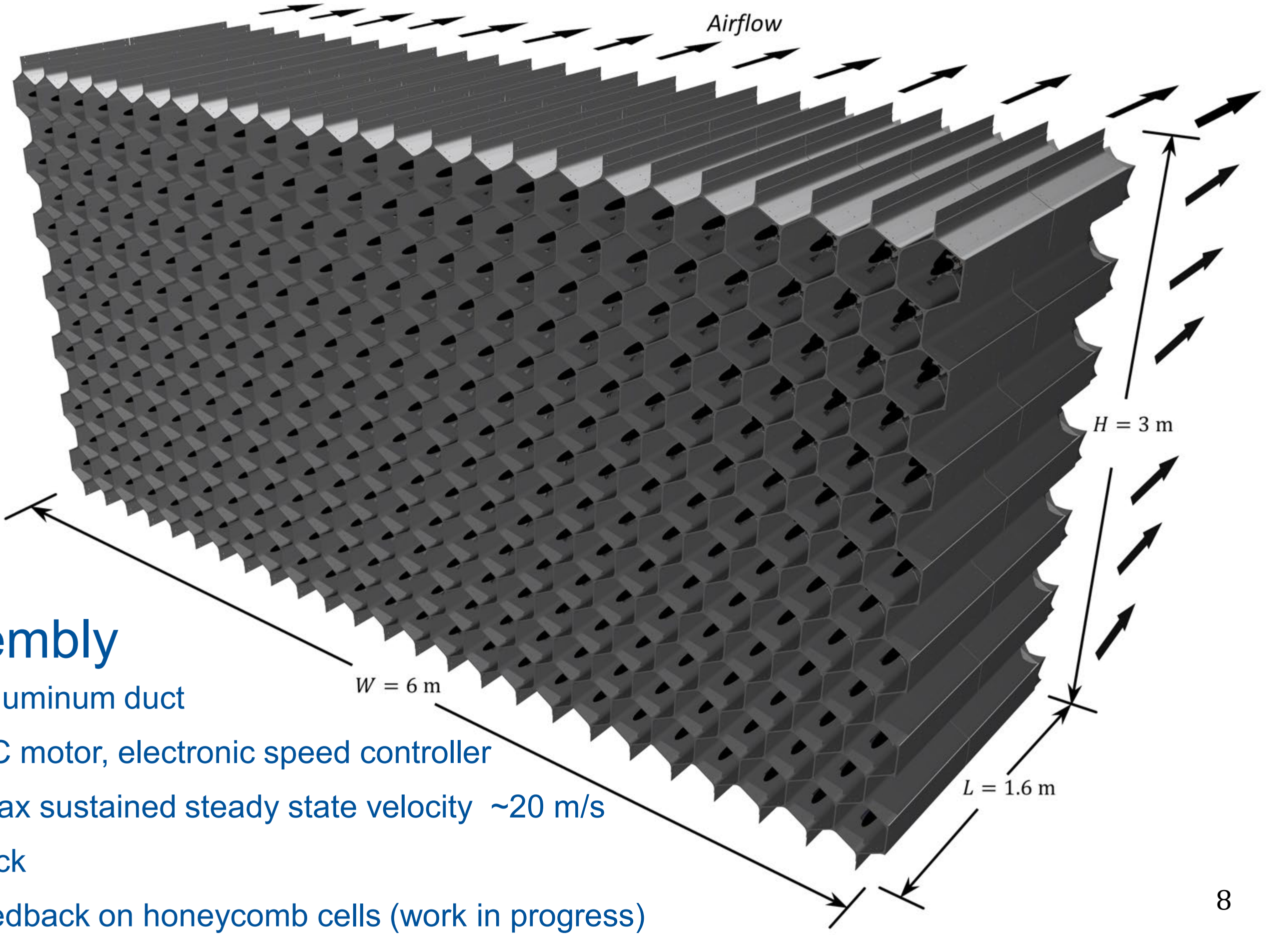
Mean Velocity and Turbulence Generator



MRI (NSF Award 1428954)

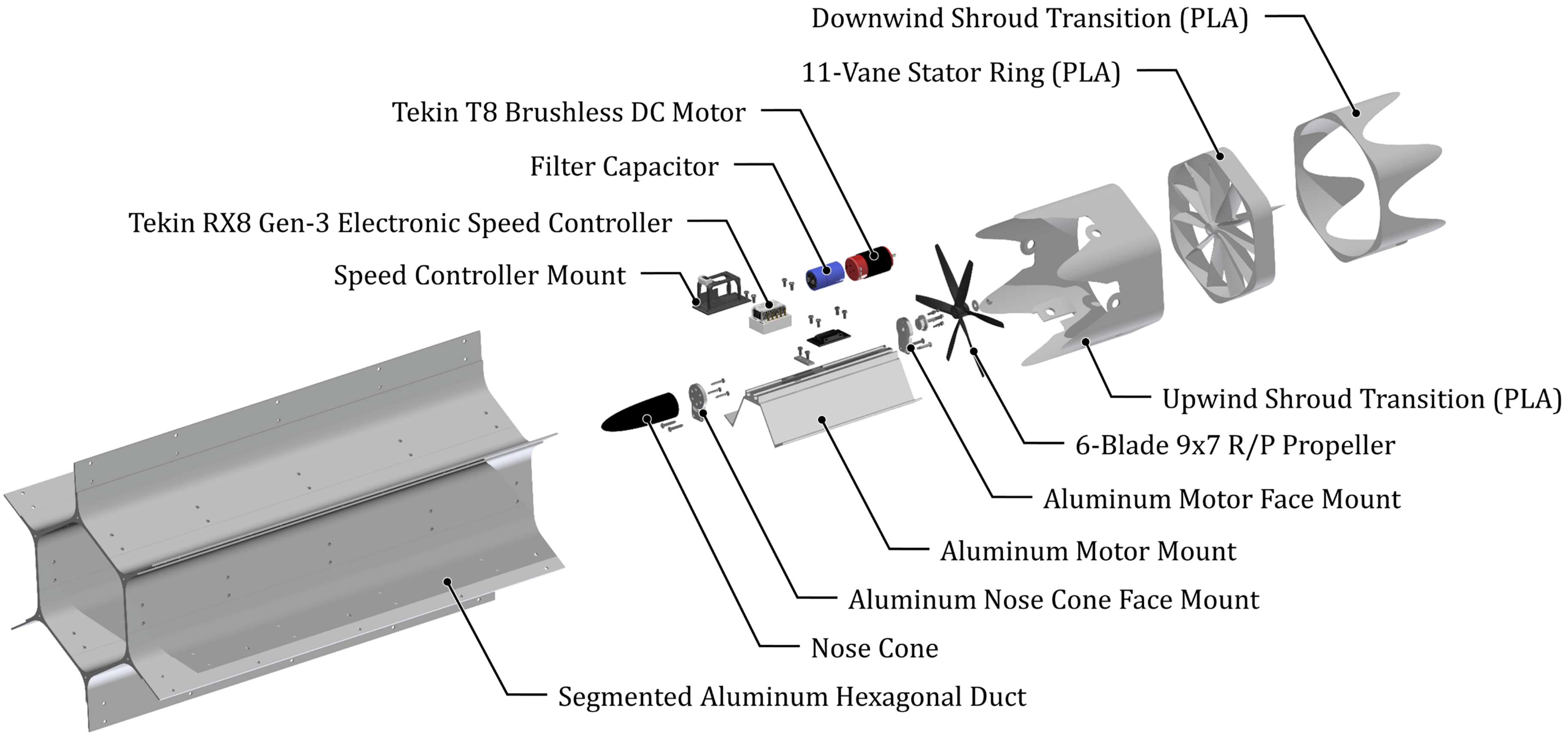
Flow Field Modulator

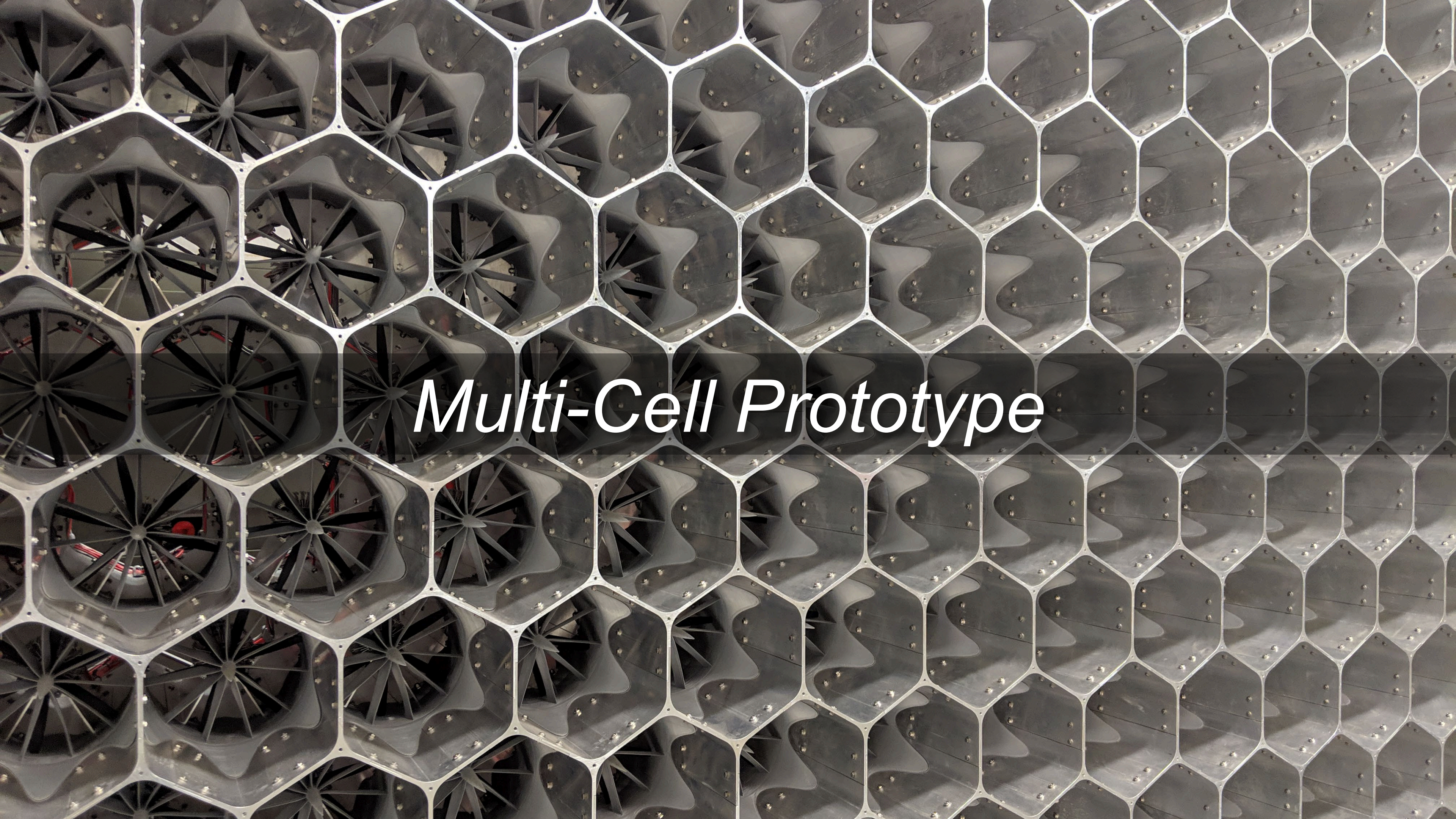
- Based on research by Cao et al. (2002), Smith et al. (2012), Xu et al. (2014), etc.
- 319 ducted fan assemblies
- Capable of reproducing user-specified non-monotonic and nonstationary flows
- Velocity profiles produced along the height of the tunnel by varying row fan speeds
- Individual fan speeds can fluctuate to achieve target turbulence properties



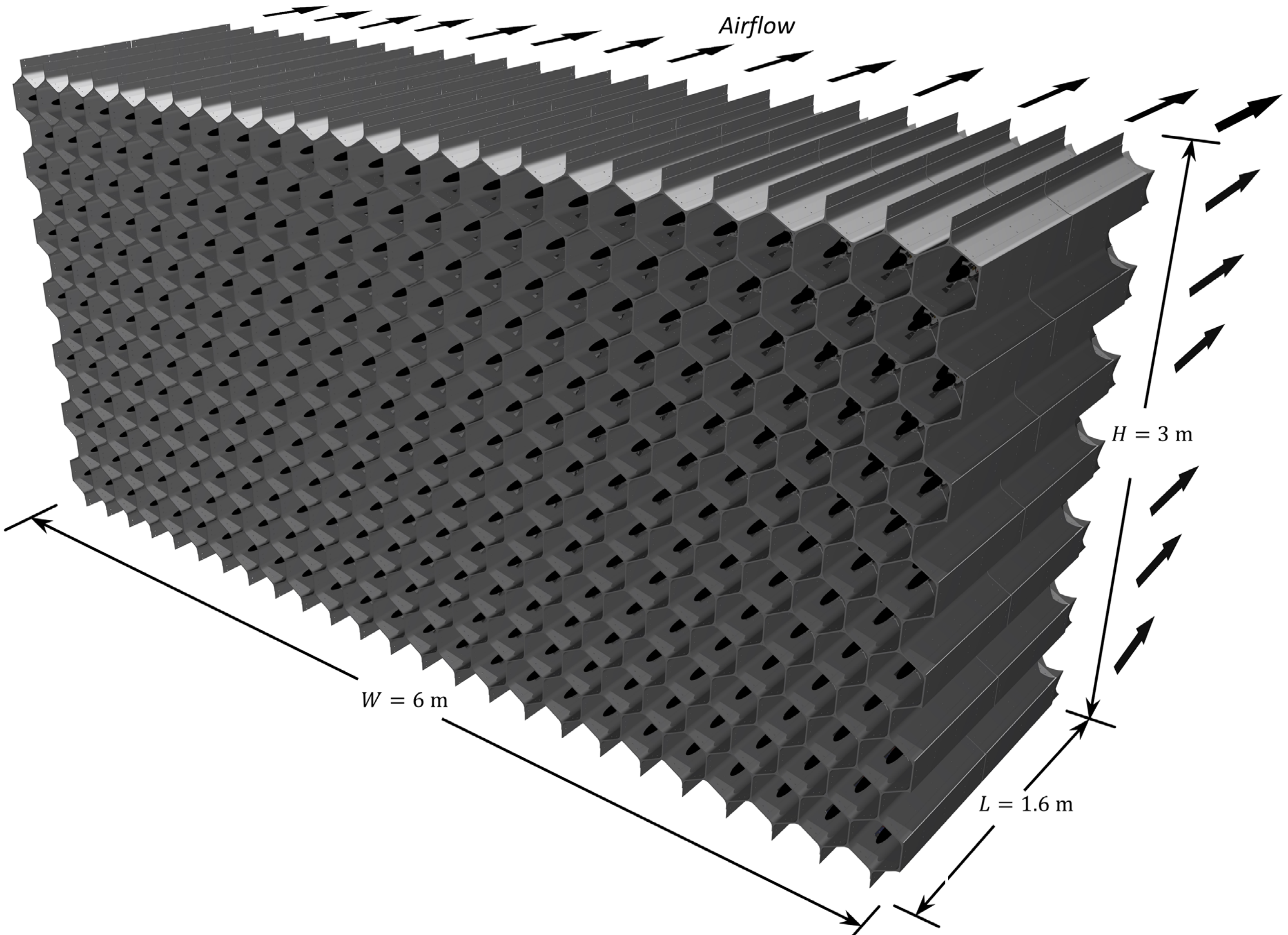
Cell Assembly

- Hexagonal aluminum duct
- Brushless DC motor, electronic speed controller
- Single cell max sustained steady state velocity ~20 m/s
- RPM feedback
- Pitot tube feedback on honeycomb cells (work in progress)

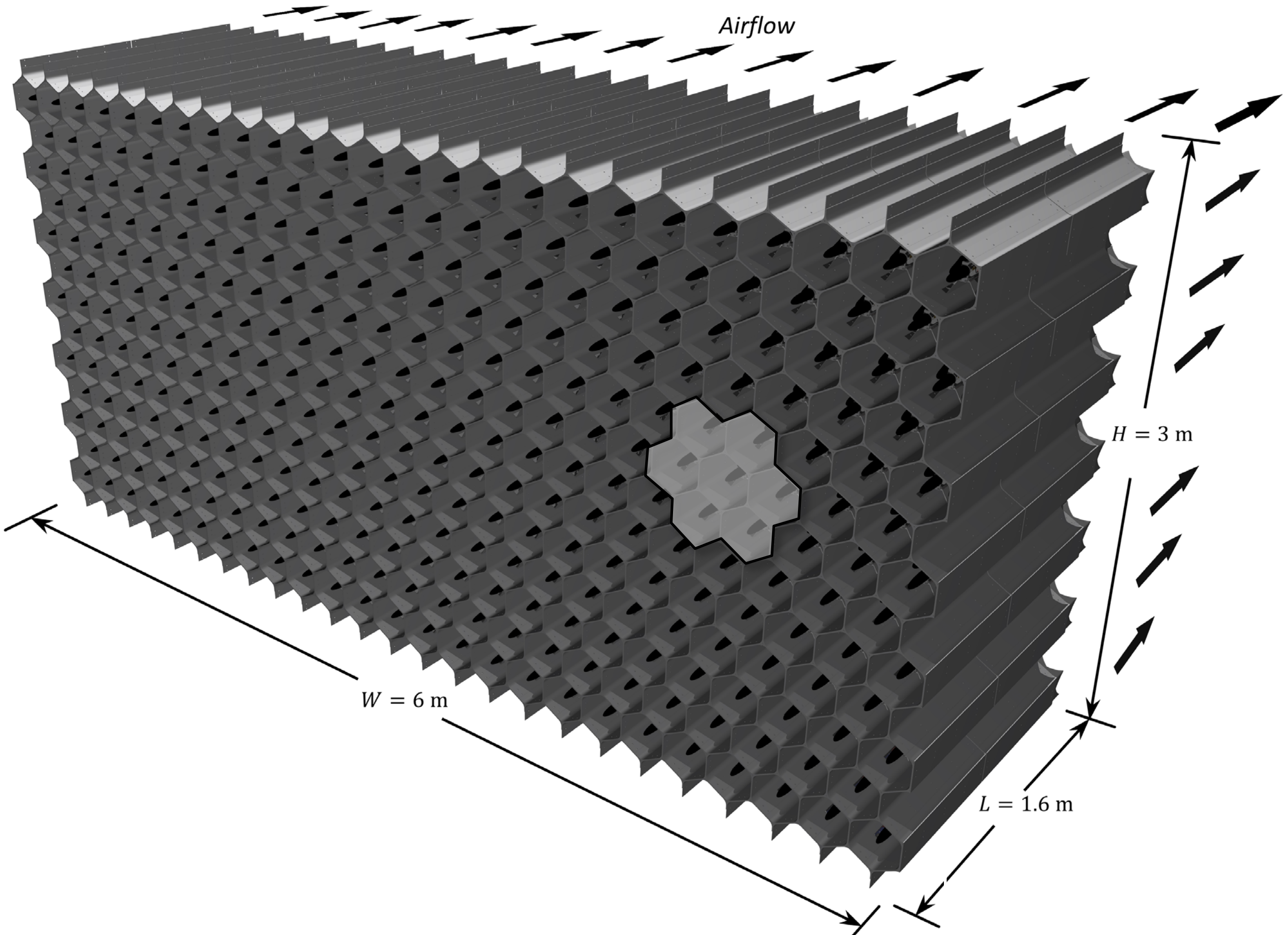

Downwind Shroud Transition (PLA)
11-Vane Stator Ring (PLA)
Tekin T8 Brushless DC Motor
Filter Capacitor
Tekin RX8 Gen-3 Electronic Speed Controller
Speed Controller Mount
Upwind Shroud Transition (PLA)
6-Blade 9x7 R/P Propeller
Aluminum Motor Face Mount
Aluminum Motor Mount
Aluminum Nose Cone Face Mount
Nose Cone
Segmented Aluminum Hexagonal Duct


Multi-Cell Prototype

7-Cell Prototype



7-Cell Prototype



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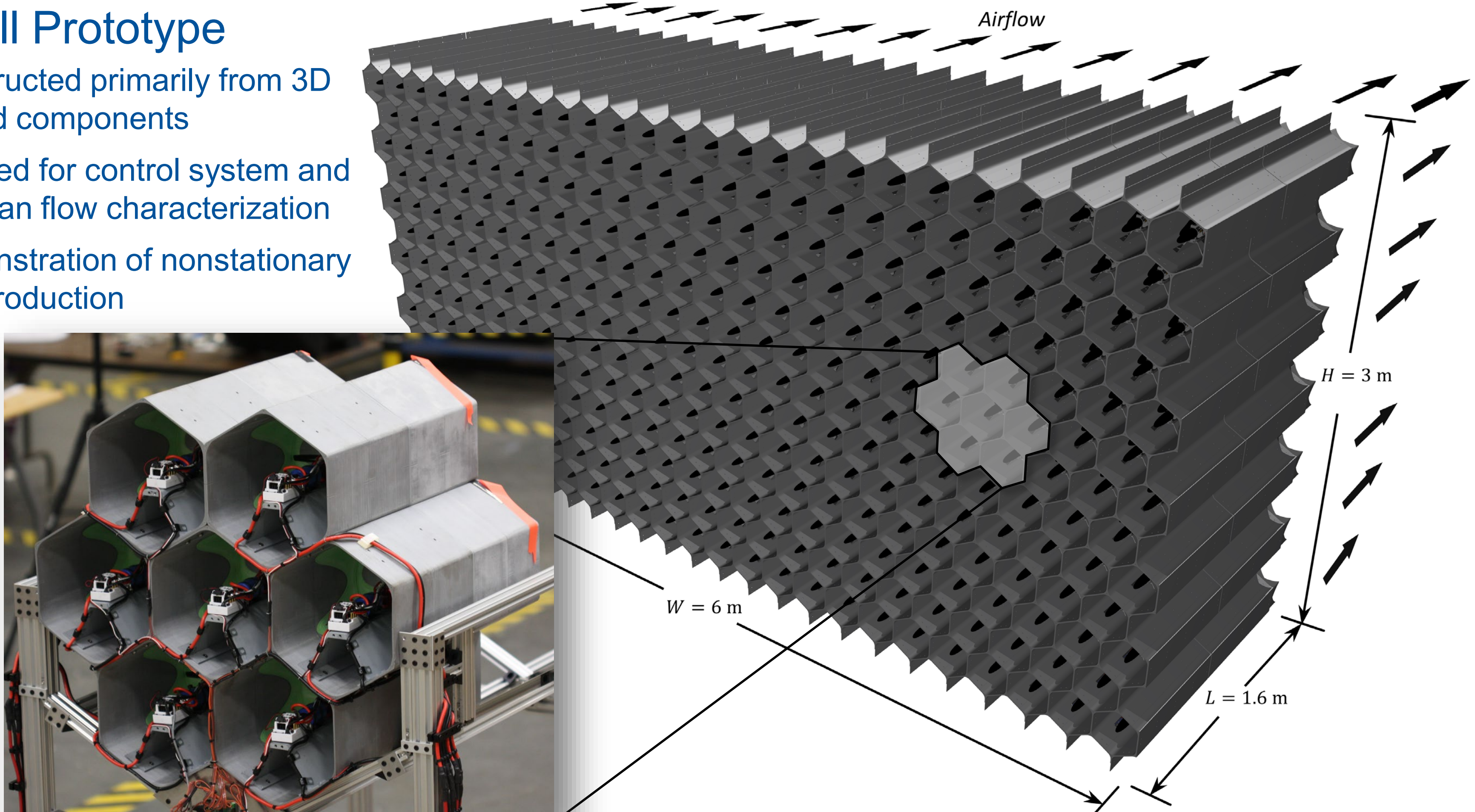
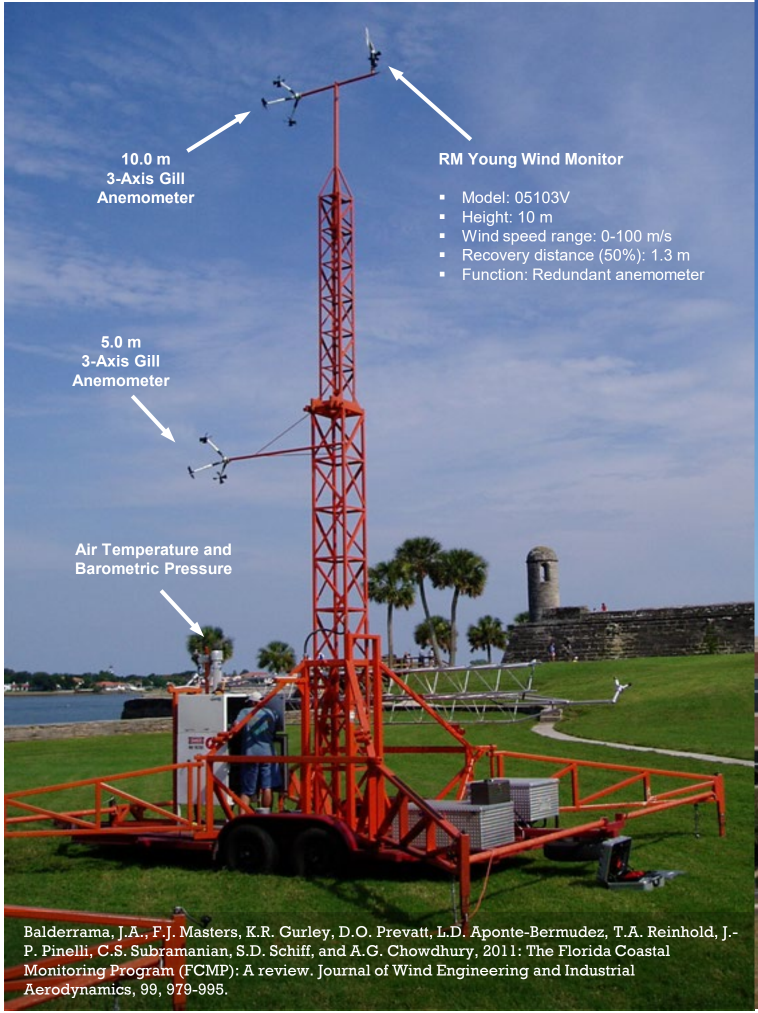
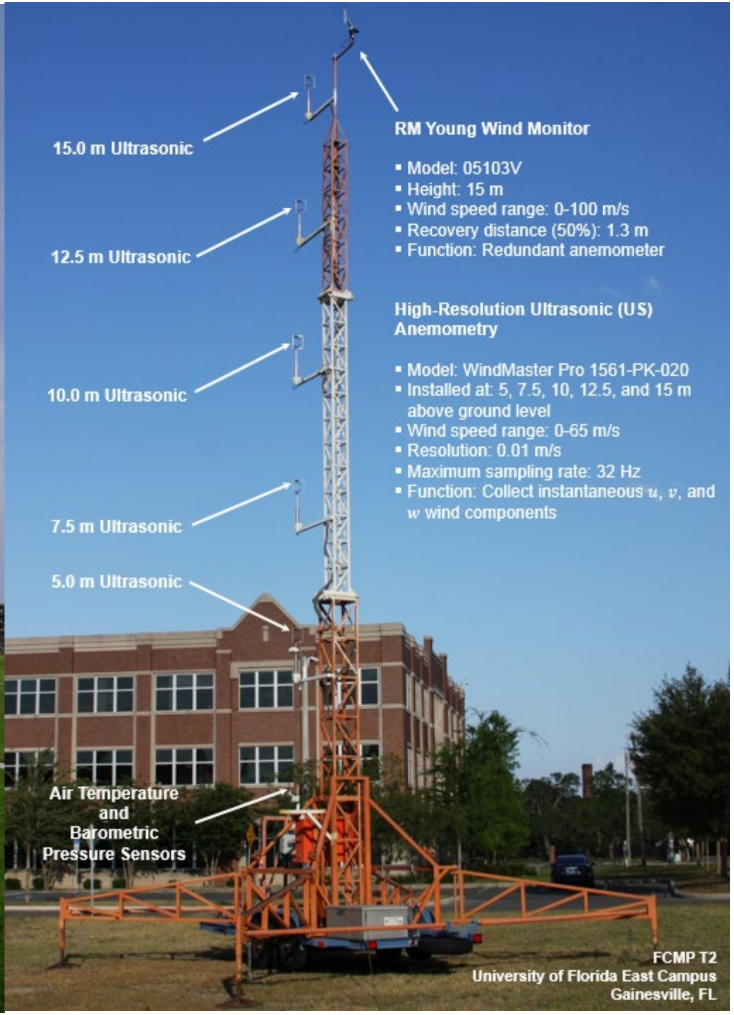
7-Cell Prototype

- Constructed primarily from 3D printed components
- Test bed for control system and multi-fan flow characterization
- Demonstration of nonstationary flow production



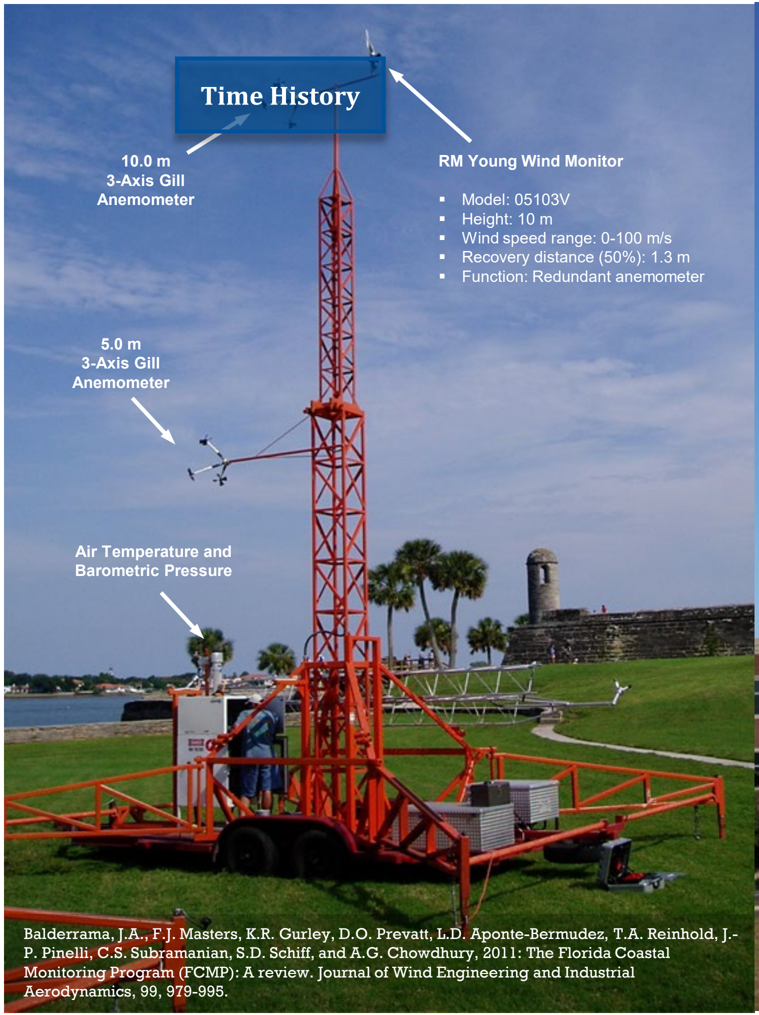
10-m Towers



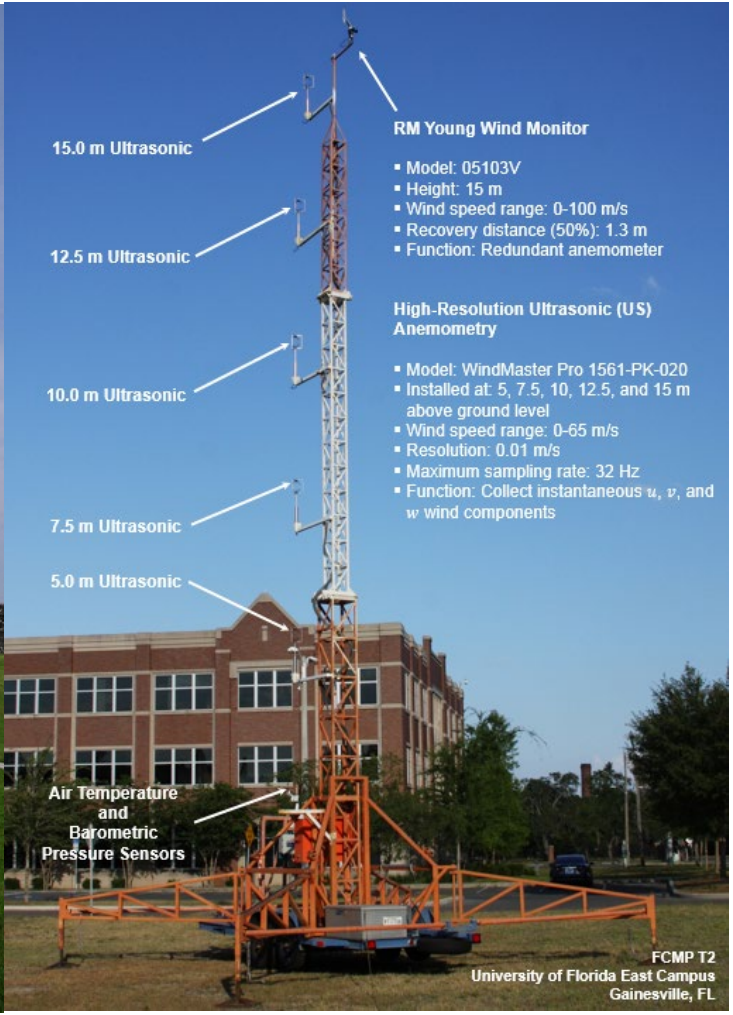


15-m Towers

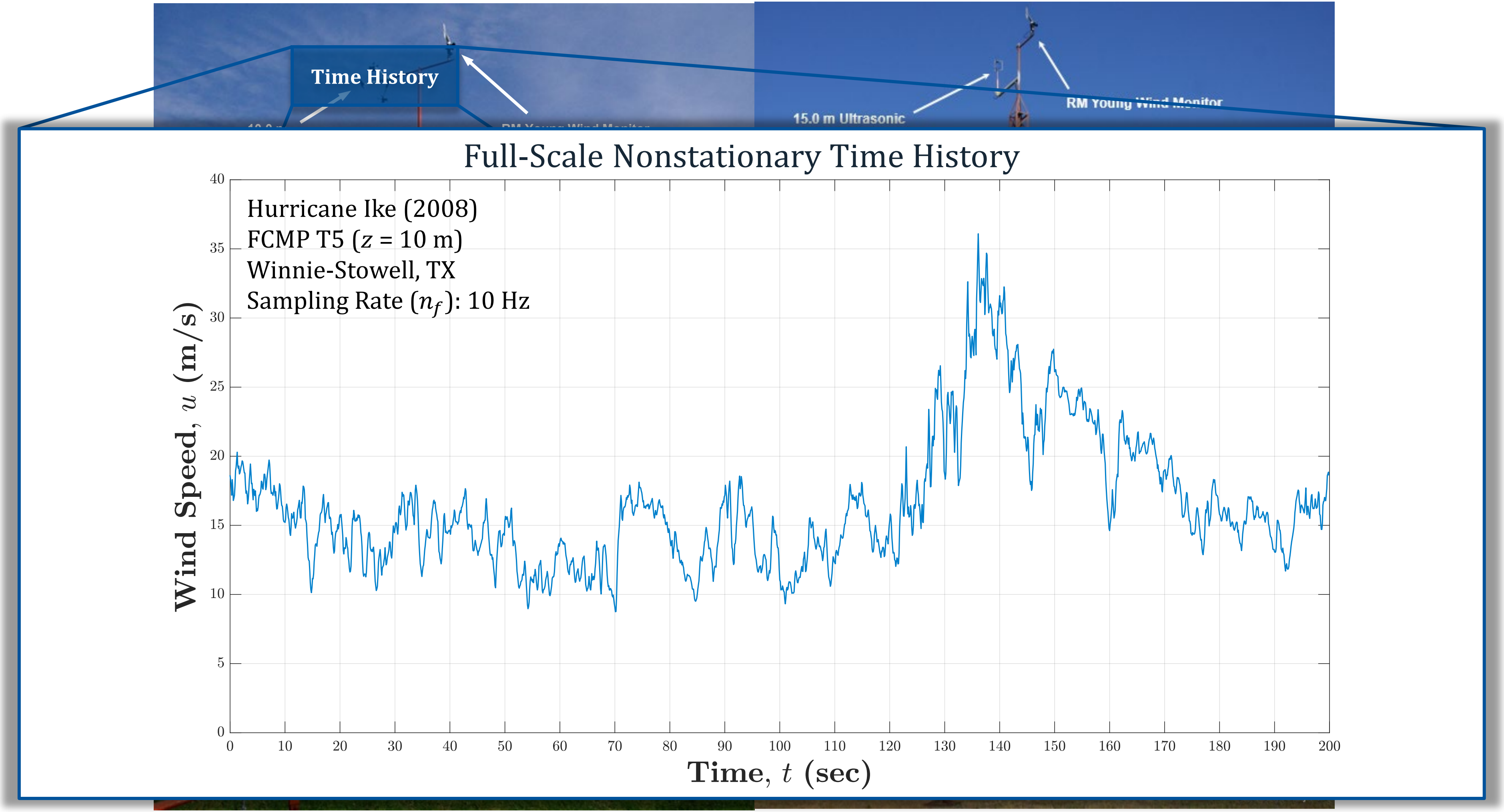
10-m Towers

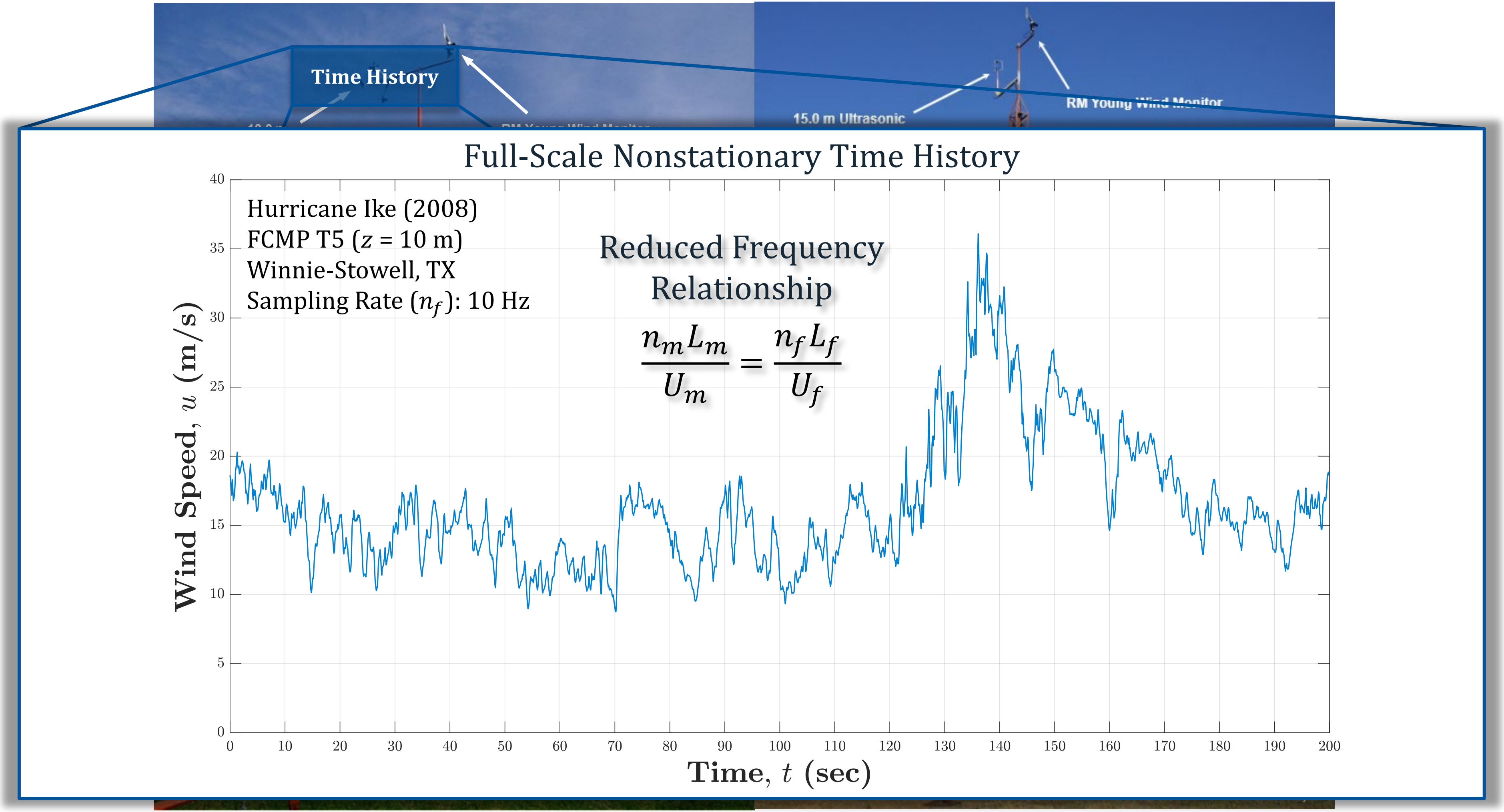


Balderrama, J.A., F.J. Masters, K.R. Gurley, D.O. Prevatt, L.D. Aponte-Bermudez, T.A. Reinhold, J.-P. Pinelli, C.S. Subramanian, S.D. Schiff, and A.G. Chowdhury, 2011: The Florida Coastal Monitoring Program (FCMP): A review. Journal of Wind Engineering and Industrial Aerodynamics, 99, 979-995.

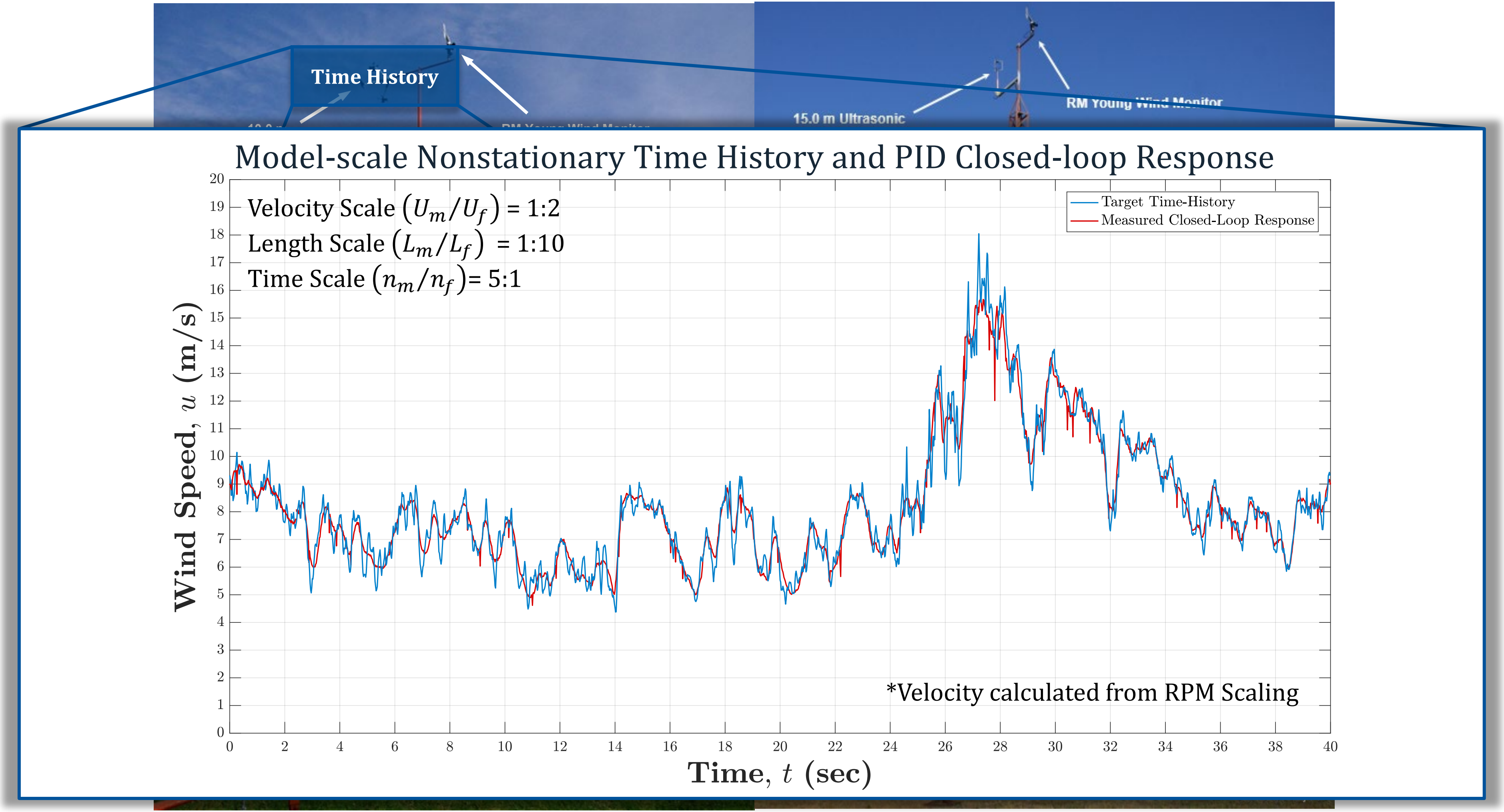


15-m Towers

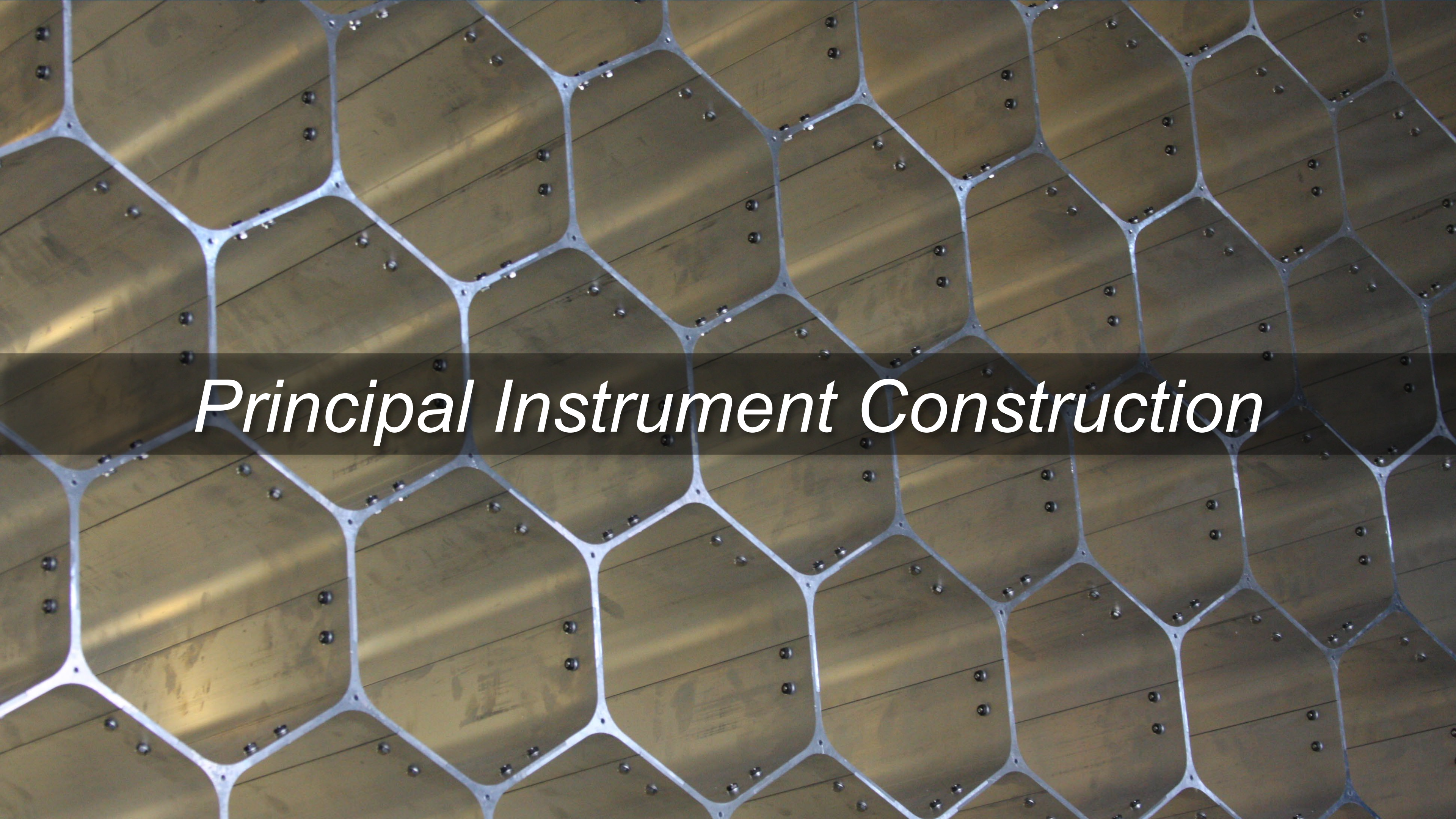

Time History
15.0 m Ultrasonic
RM Young Wind Monitor
Full-Scale Nonstationary Time History
Hurricane Ike (2008)
FCMP T5 (z = 10 m)
Winnie-Stowell, TX
Sampling Rate (n_f): 10 Hz
Wind Speed, u (m/s)
Time, t (sec)
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200



Time History
15.0 m Ultrasonic
RM Young Wind Monitor
Full-Scale Nonstationary Time History
Hurricane Ike (2008)
FCMP T5 (z = 10 m)
Winnie-Stowell, TX
Sampling Rate (n_f): 10 Hz
Reduced Frequency Relationship
$$\frac{n_m L_m}{U_m} = \frac{n_f L_f}{U_f}$$
Wind Speed, u (m/s)
Time, t (sec)


Time History
15.0 m Ultrasonic
RM Young Wind Monitor
Model-scale Nonstationary Time History and PID Closed-loop Response
Velocity Scale (U_m/U_f) = 1:2
Length Scale (L_m/L_f) = 1:10
Time Scale (n_m/n_f)= 5:1
Target Time-History
Measured Closed-Loop Response
*Velocity calculated from RPM Scaling
Wind Speed, u (m/s)
Time, t (sec)

Principal Instrument Construction



Flow Field Conditioner (FFC)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida

Flow Field Conditioner (FFC)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida


Flow Field Conditioner (FFC)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida


Flow Field Modulator (FFM)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida


Flow Field Conditioner (FFC)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
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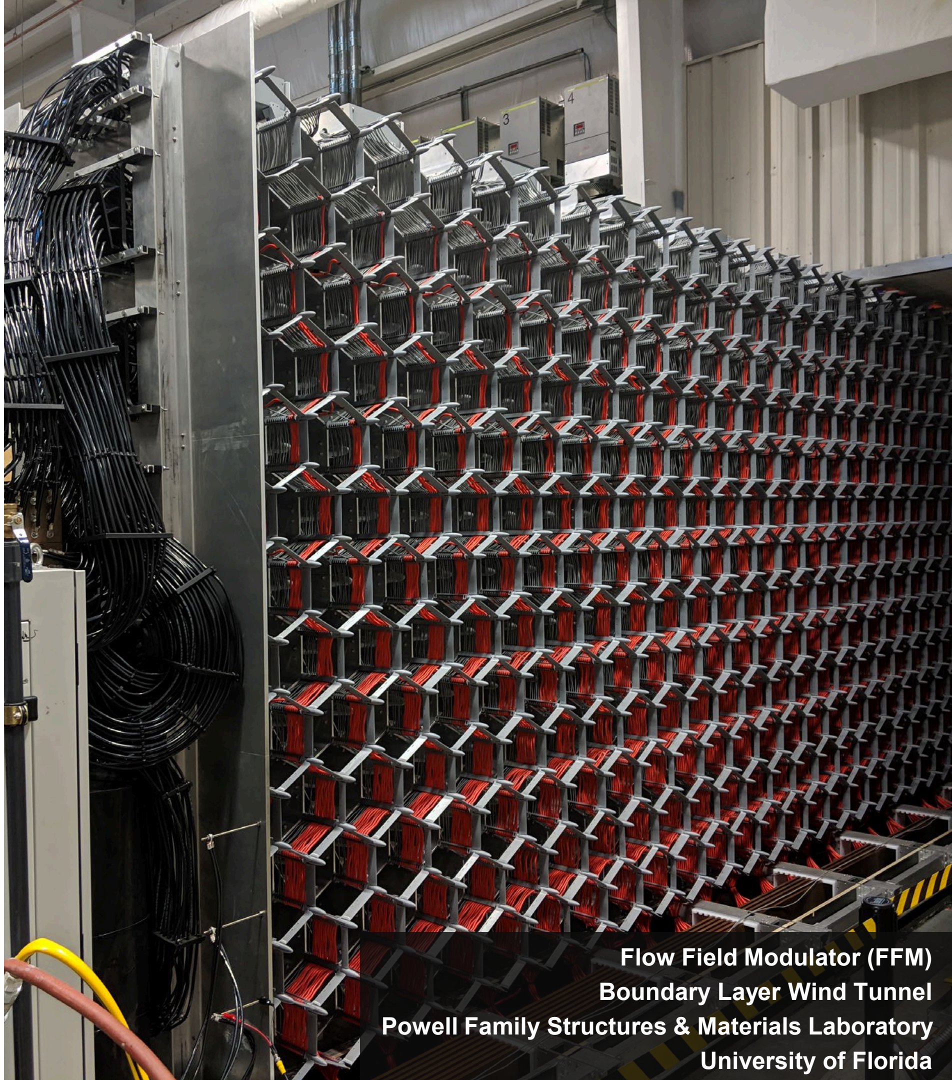
Flow Field Modulator (FFM)
Boundary Layer Wind Tunnel
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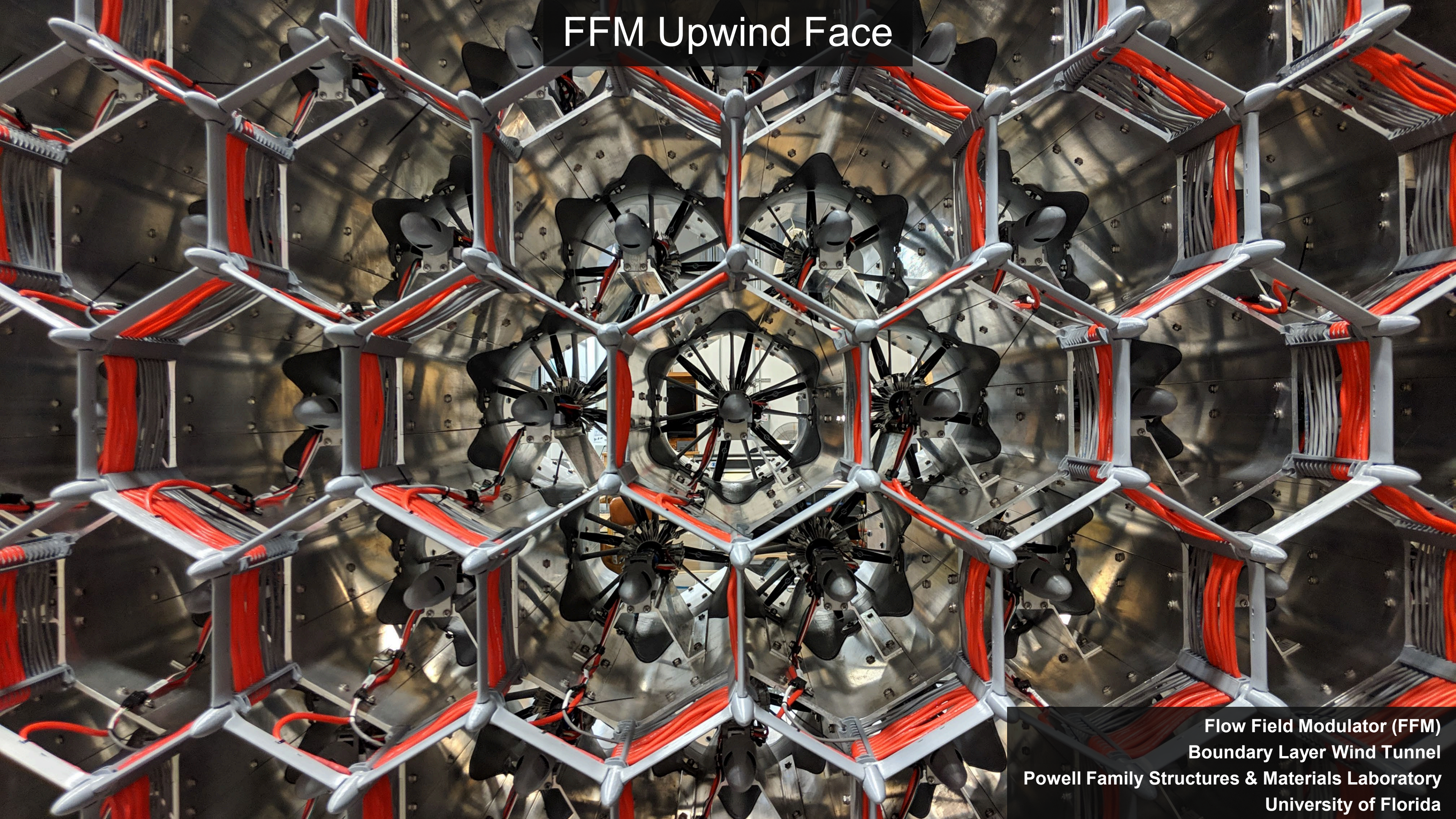
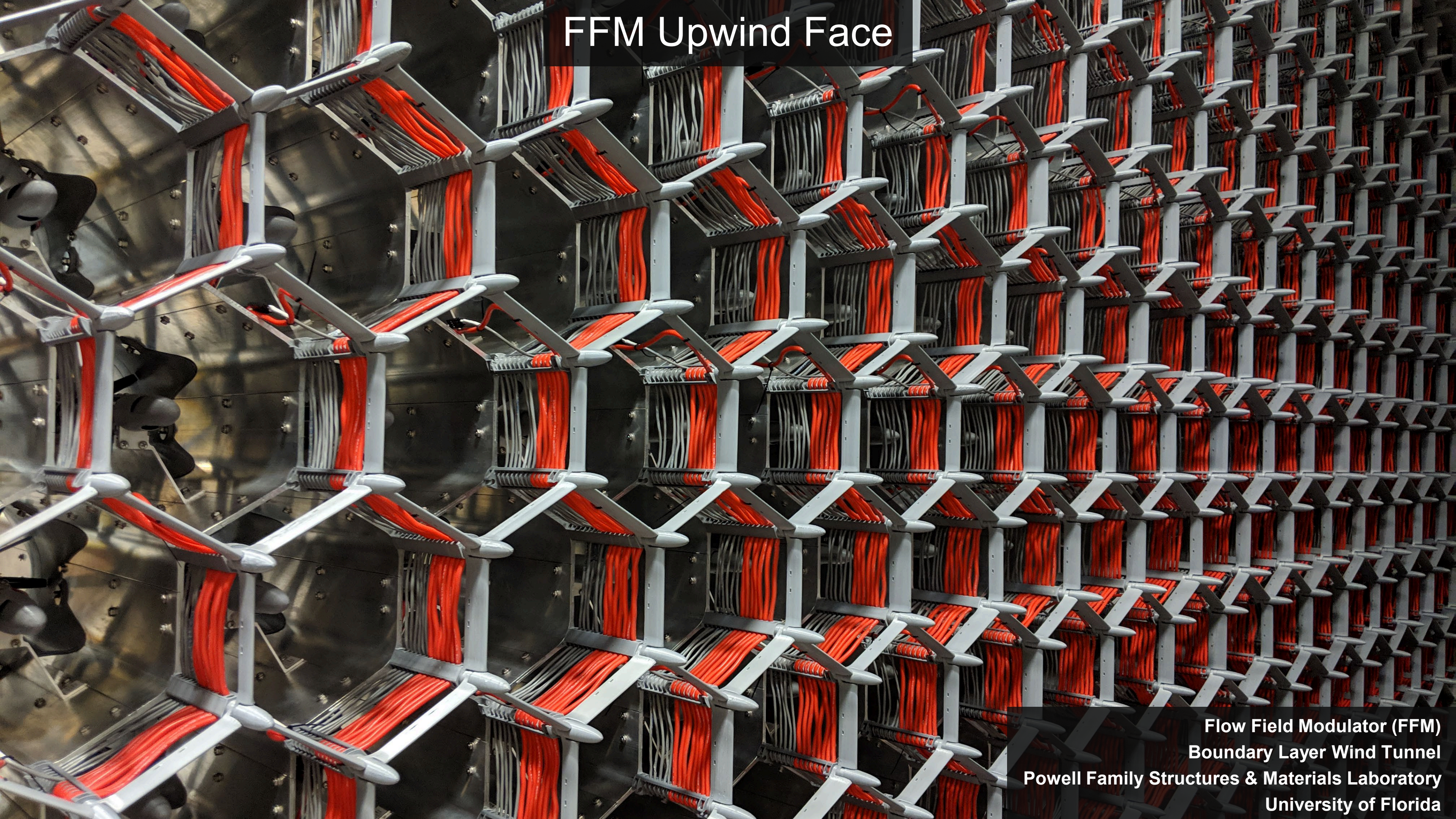
FFM Downwind Face
Flow Field Modulator (FFM)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida


FFM Upwind Face
Flow Field Modulator (FFM)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida

FFM Upwind Face



Flow Field Modulator (FFM)
Boundary Layer Wind Tunnel
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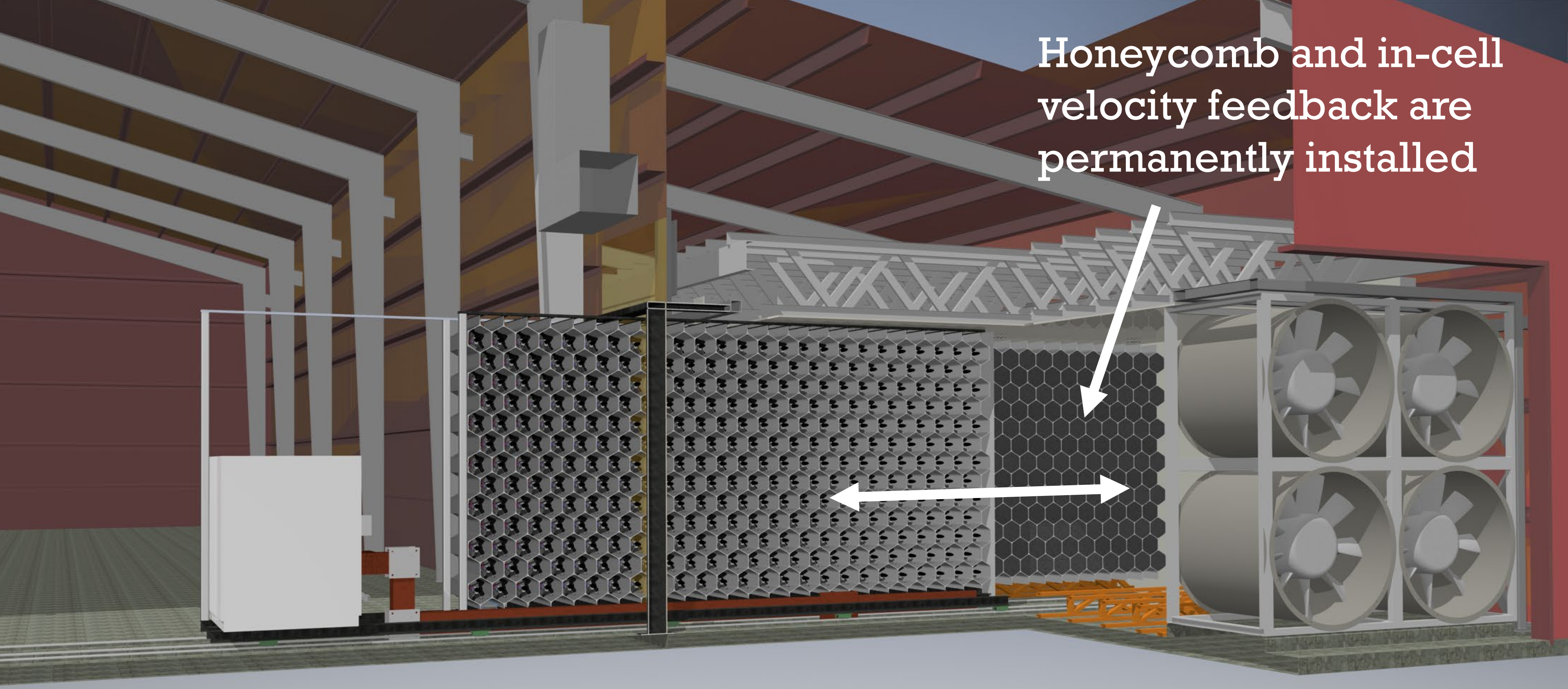


The FFM **slides into** the wind tunnel to provide active flow control or **slides out** for conventional BLWT operation

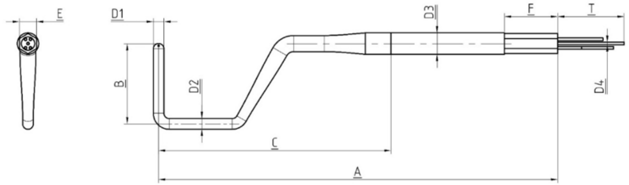

FFM Downwind Face


FFM Upwind Face
UF BOUNDARY LAYER WIND TUNNEL
Flow Field Modulator (FFM)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida

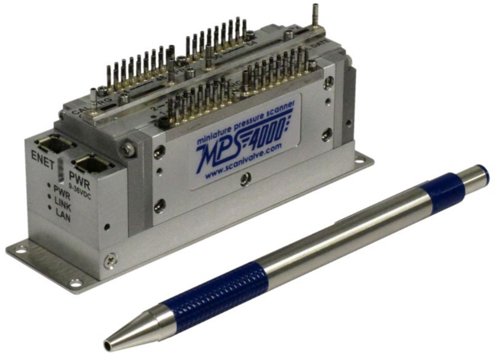
FFM Support Resources

Time-correlated Velocity Profiles

- How to capture entire velocity profile with time-correlated measurements?
  - Investigating 12-probe probe rake combining: Vectoflow multi-hole cobra probes, Scanivalve 64-channel miniature pressure scanner, and automated gantry



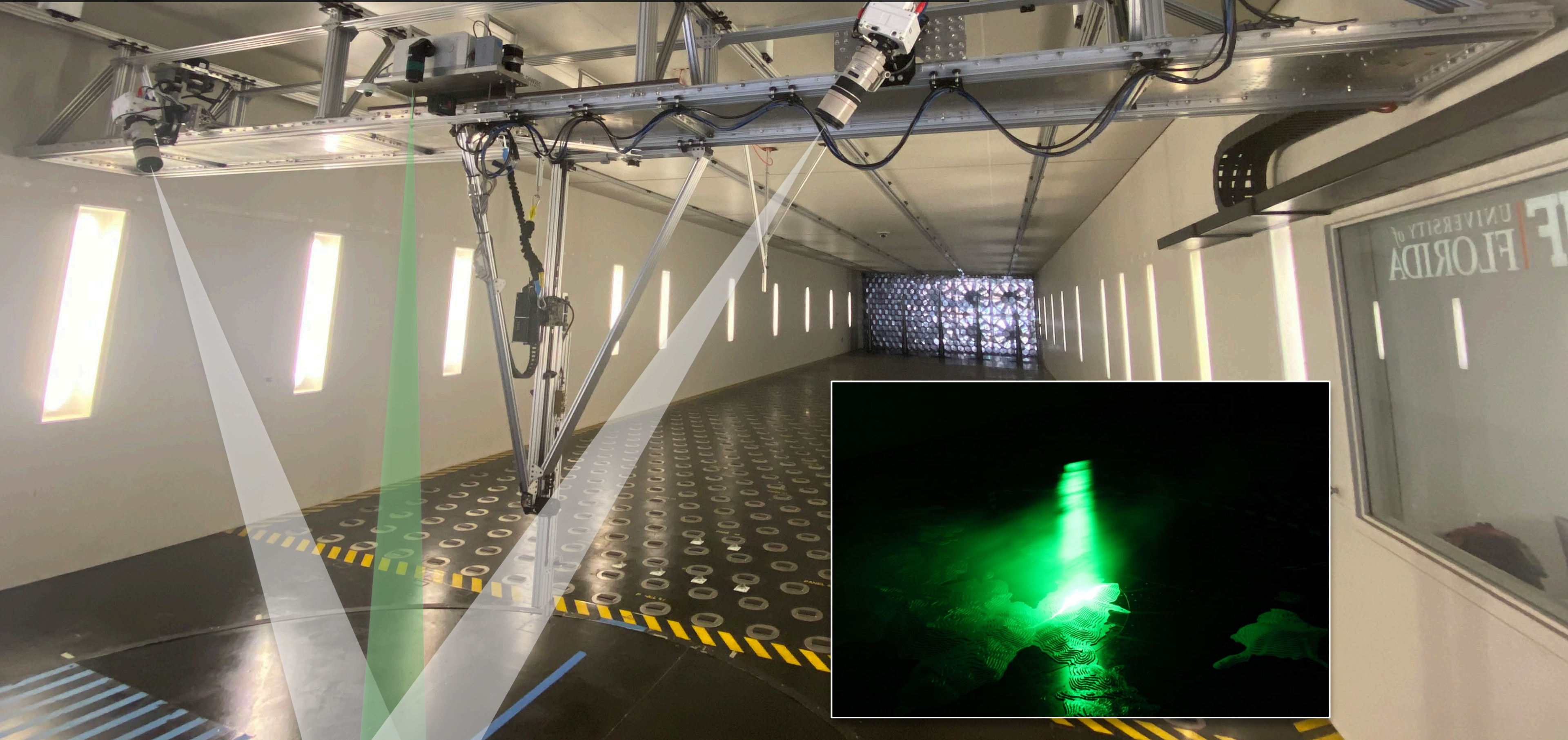
Vectoflow 5-hole Cobra Probe (x12)



Scanivalve MPS4000

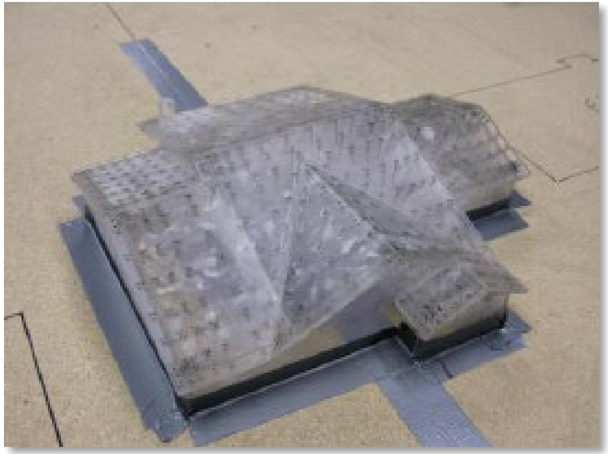
Time-correlated Velocity Profiles

Particle Image Velocimetry (PIV)



Capturing the Structural Response

- What features of transient and non-synoptic flows influence structural response?
- Model instrumentation
  - Scanivalve pressure scanning system
  - 6-axis force balance sensors
  - Displacement sensors
  - Accelerometers



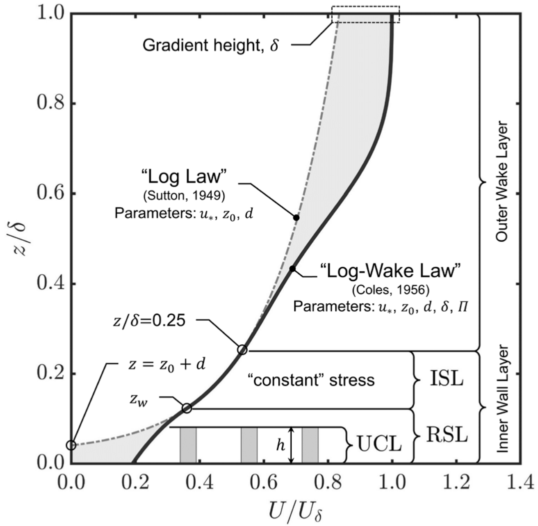
Pressure-tapped Model

Simulation Targets

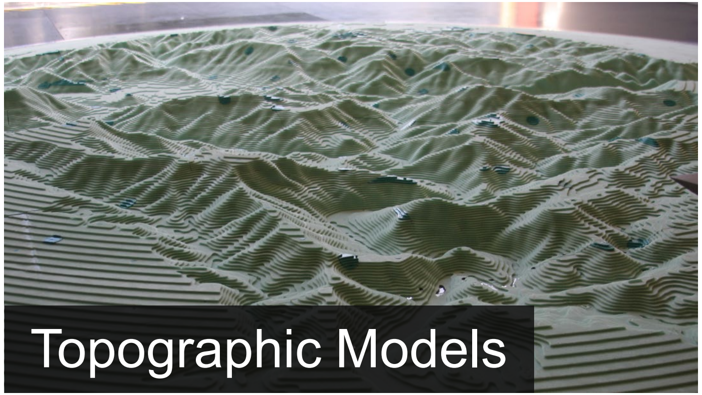
- Permanent/Mobile Towers
  - Hurricane wind traces
  - Thunderstorms and downbursts
- Remote Sensing (Radar, LiDAR, etc.)
  - Larger flow structures

Simulation Targets

- CWE Simulations
  - Comprehensive data
- Analytical Models
  - Gust front mean velocity profiles, turbulence, and transitions
  - Dive into the urban canopy
- Topographic Models
  - Topographic speedup effects



Boundary Layer Models



High-performance Computing

- Users have access to UF's HiPerGator supercomputer and data center
  - 150 teraflop supercomputer with 16,284 CPUs and 2.88 Petabytes of shared disk space
  - Run real-time scripts (in MATLAB, Python, etc.) to process data, including PIV, on the fly

- UF recently acquired two NVIDIA DGX™ A100 GPU systems — the world's most advanced AI system
  - Built on NVIDIA A100 Tensor Core GPU
  - 5 petaFLOPS per unit

HiPerGator

DGX™ A100

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Powell Family Structures and Materials Laboratory

UF UNIVERSITY of FLORIDA

UFLORIDA NHERI
Powell Family Structures and Materials Laboratory

NSF NHERI User Workshop | May 19th, 2021

FFM Capabilities & Benchmarking

PI: Jennifer A. Bridge, Ph.D.

Co-PIs: Kurt Gurley, Ph.D., Forrest Masters, Ph.D., Brian Phillips, Ph.D.

Senior Personnel: Jeremy Waisome, Ph.D., David Prevatt, Ph.D.

Presented by: Ryan A. Catarelli, Ph.D.
Research Assistant Scientist / Wind Engineering Technical Manager

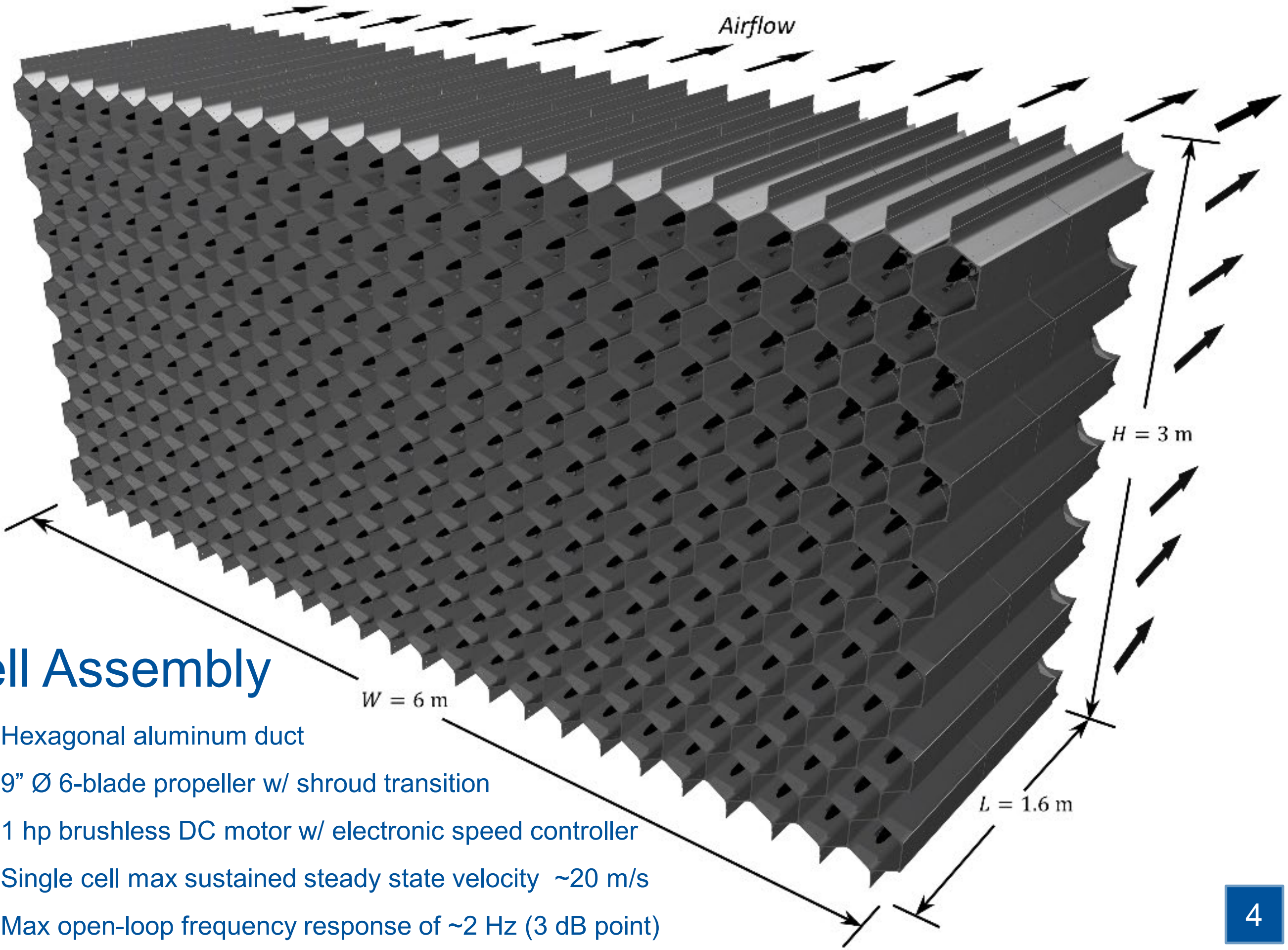
Overview

- Operational Limits
  - Single Fan Flow Characteristics
  - Fan Acceleration & Open-Loop Frequency Response
- Full System Capability Demonstration
  - Nonstationary Flow Simulation
  - User-Specified Stationary Mean Velocity Profiles
  - Flow Transition of Stationary Mean Velocity Profiles
  - Turbulence Modulation
- FFM Status Updates


FFM Operational Limits

Flow Field Modulator

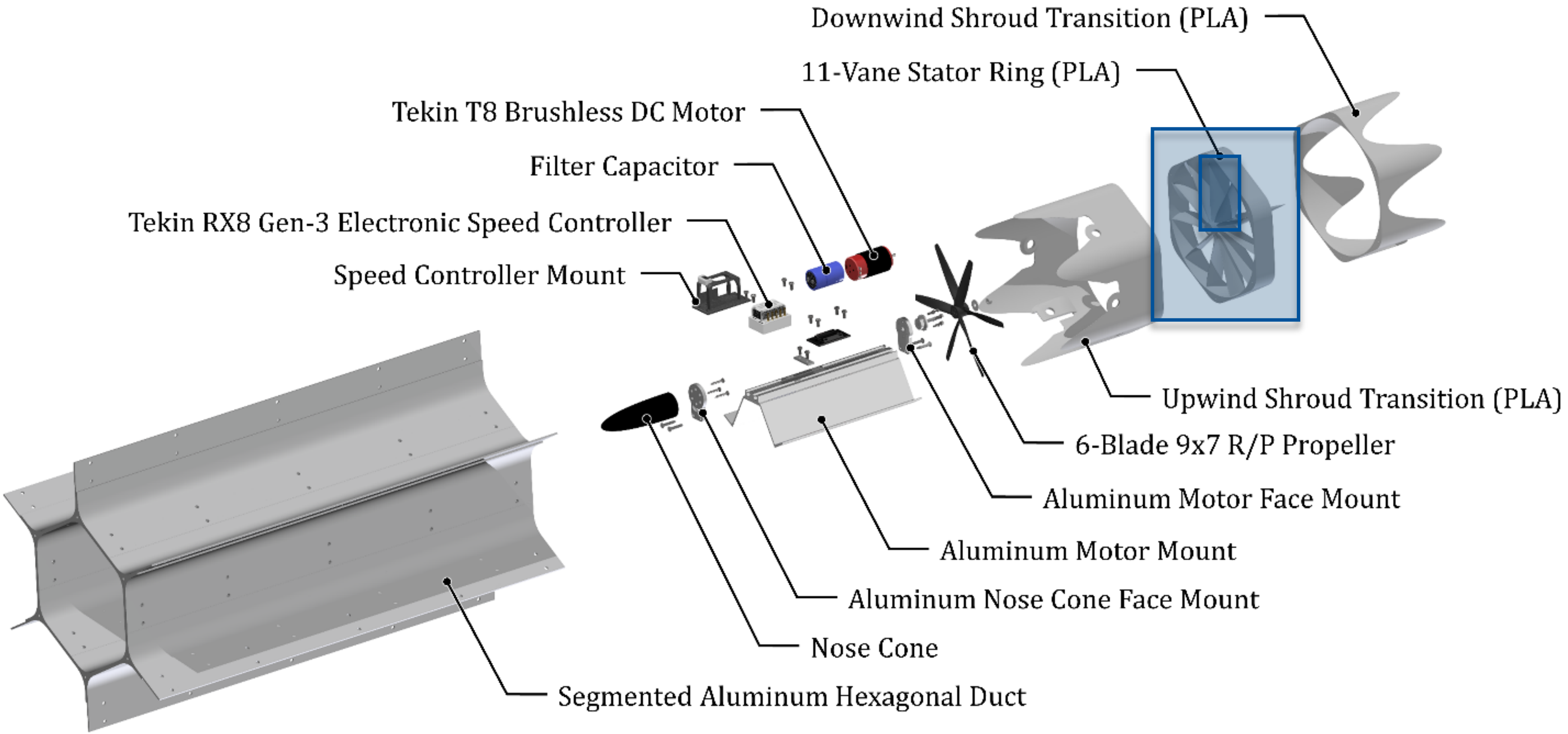
- Computer controlled mean velocity profiler and turbulence generator
- Based on research by Cao et al. (2002), Smith et al. (2012), Xu et al. (2014), etc.
- 319 ducted fan assemblies
- Capable of reproducing user-specified non-monotonic and/or spatiotemporally nonstationary flows
- Mean velocity profiles produced along the height of the tunnel by varying the mean rotational speeds of fan rows
- Individual instantaneous fan speeds fluctuate to achieve target turbulence properties



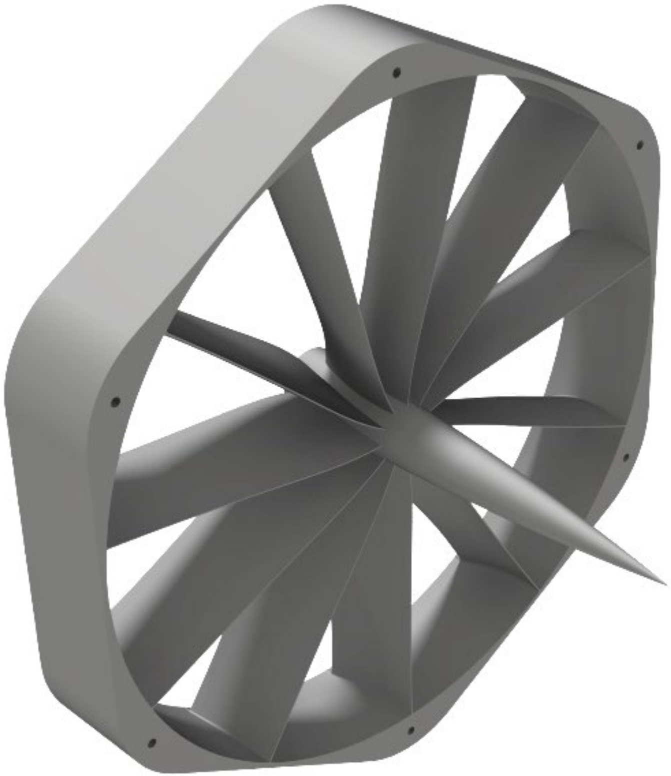
Cell Assembly

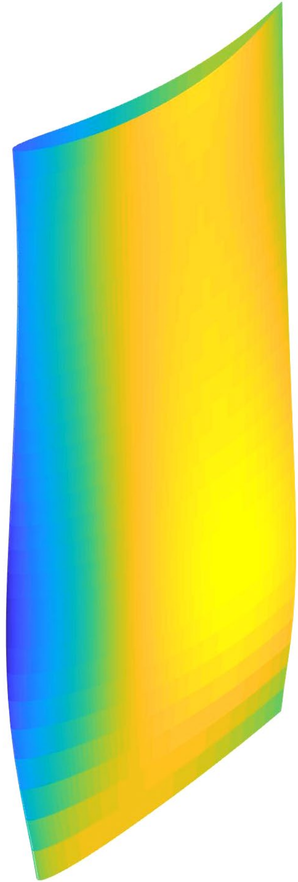
- Hexagonal aluminum duct
- 9” Ø 6-blade propeller w/ shroud transition
- 1 hp brushless DC motor w/ electronic speed controller
- Single cell max sustained steady state velocity ~20 m/s
- Max open-loop frequency response of ~2 Hz (3 dB point)

FFM Single Fan Flow Characteristics

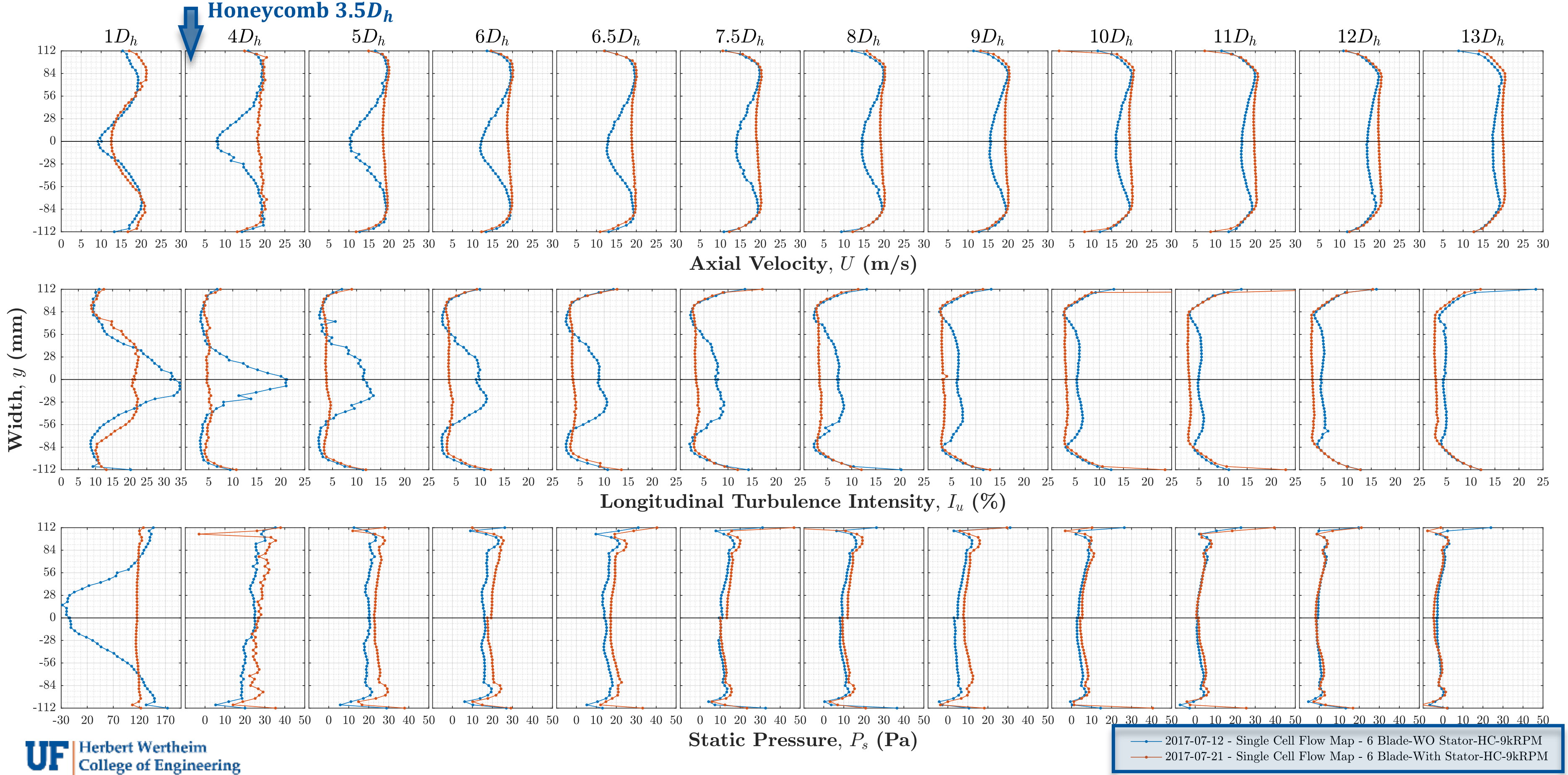


11-Vane Stator Ring & Stator Vane Design





Single Cell: 6 Blade w/o Stator VS 6 Blade w/ Stator



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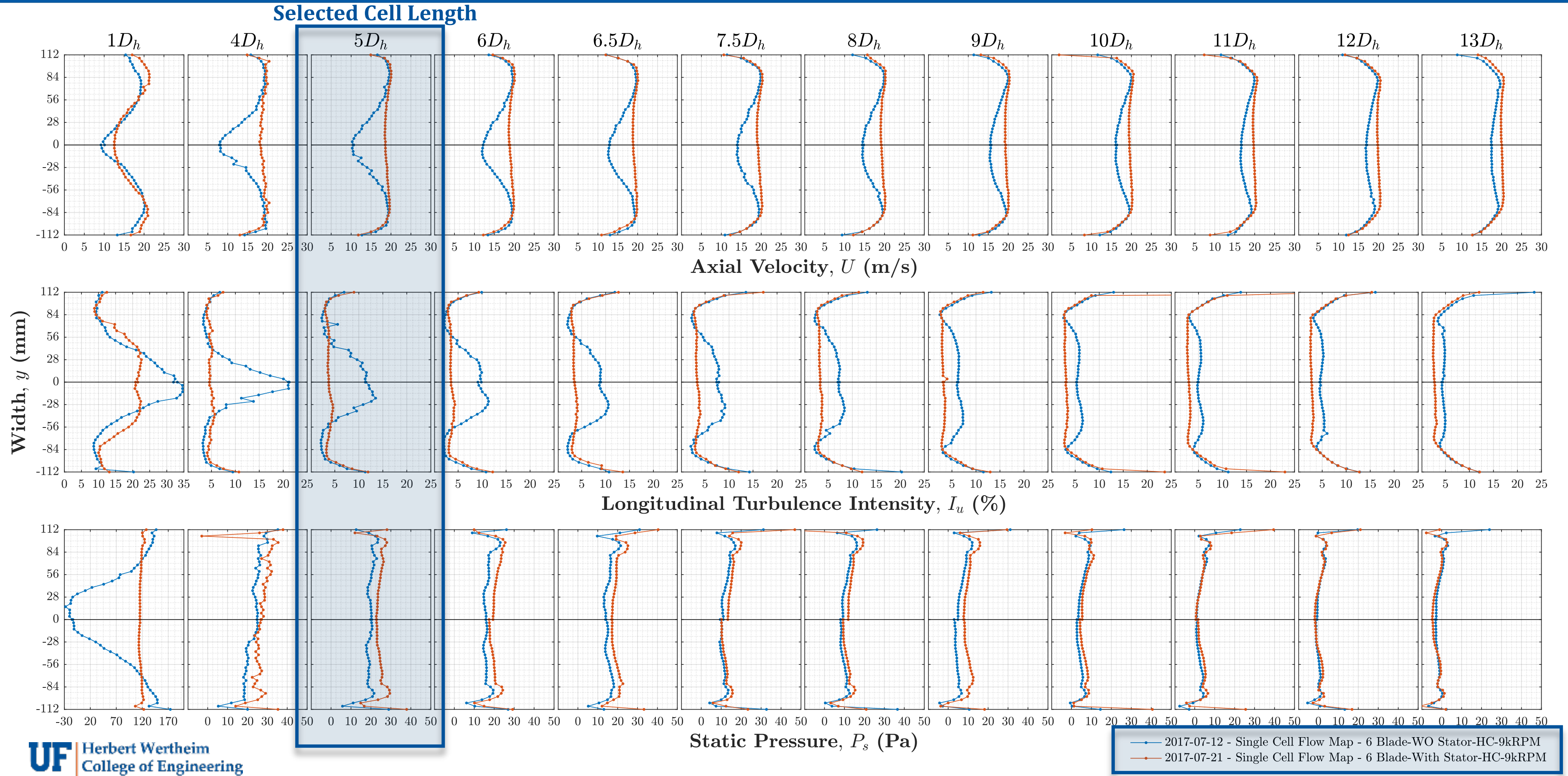
Single Cell: 6 Blade w/o Stator VS 6 Blade w/ Stator



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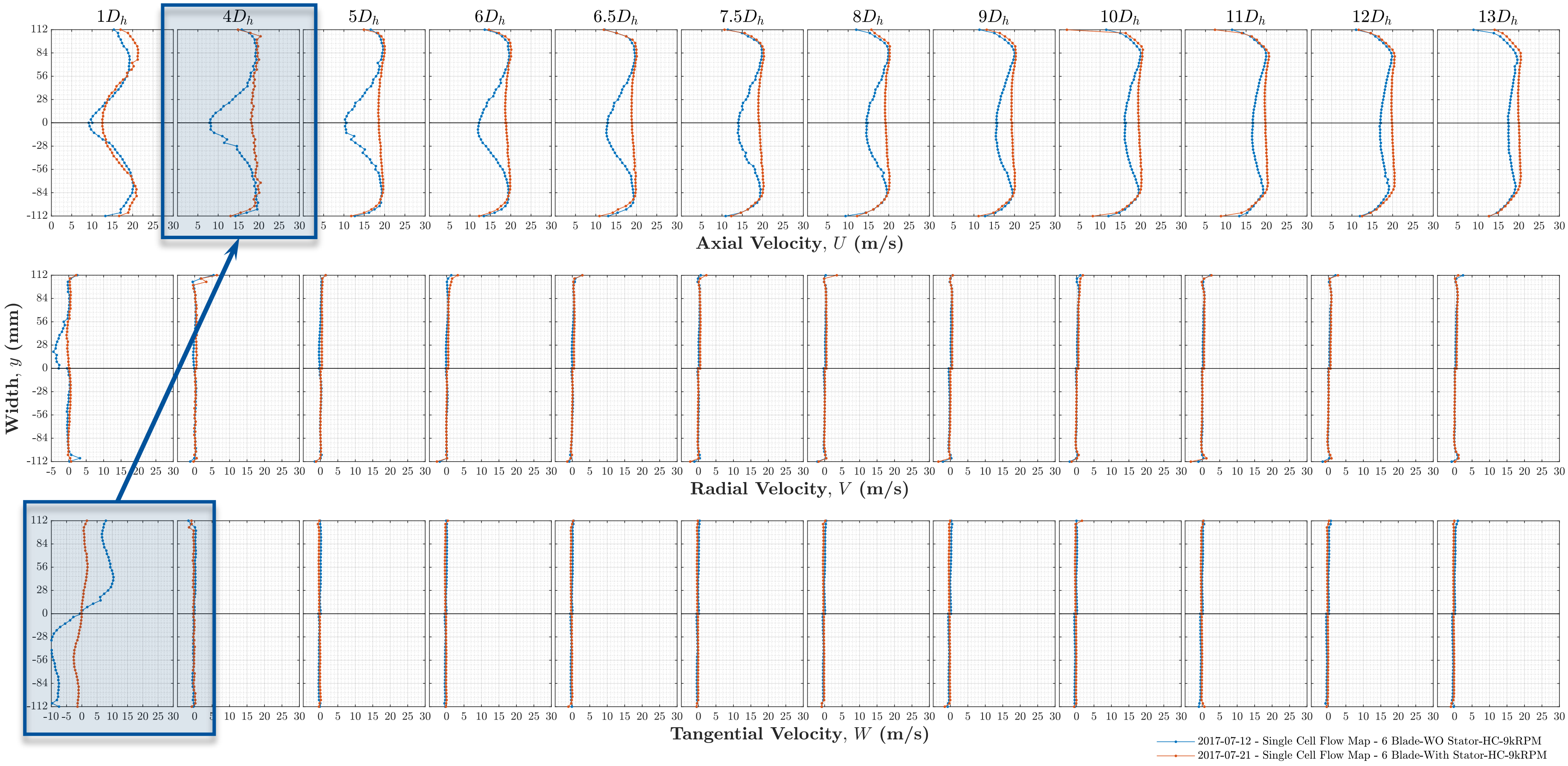
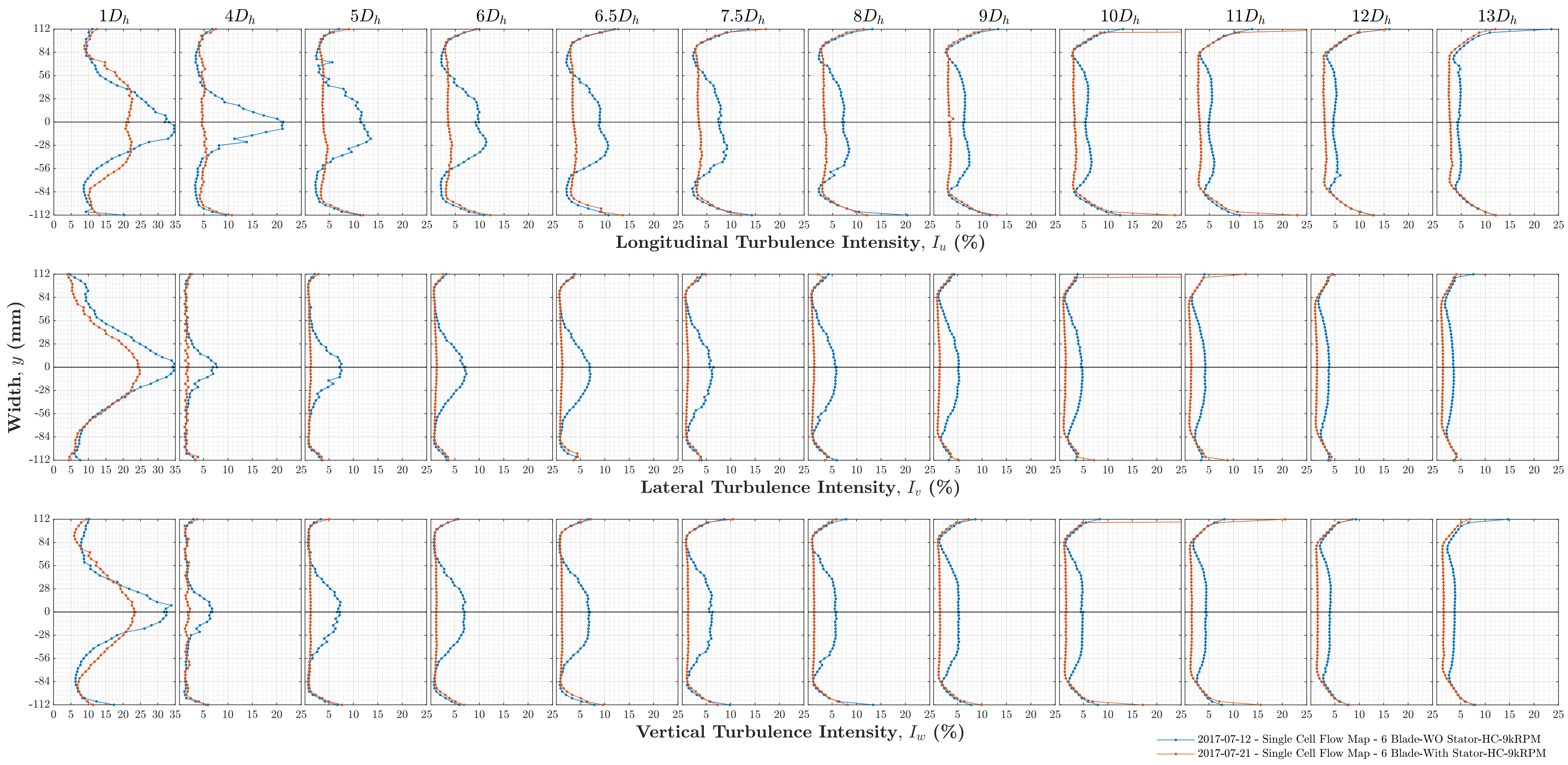
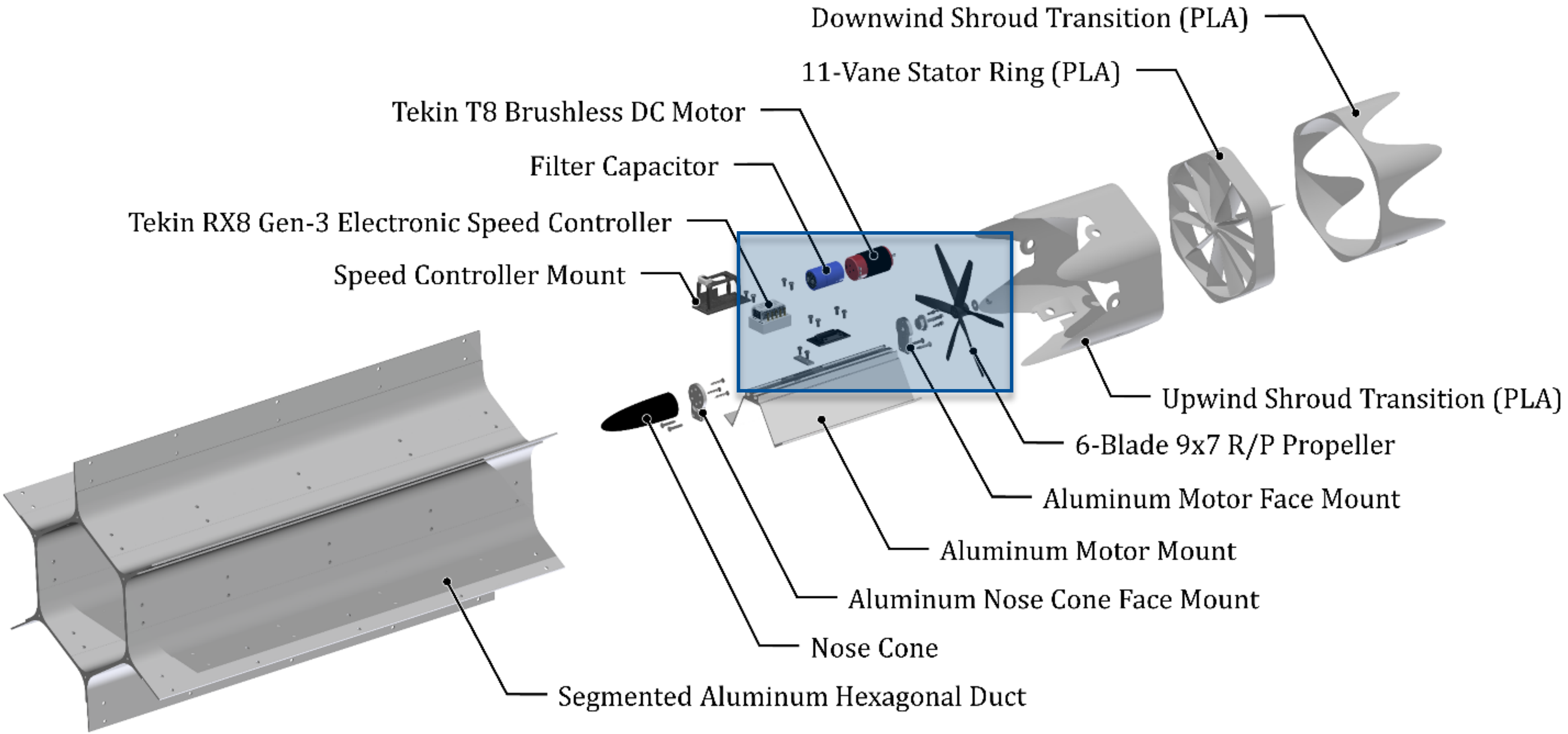
Single Cell: 6 Blade w/o Stator VS 6 Blade w/ Stator



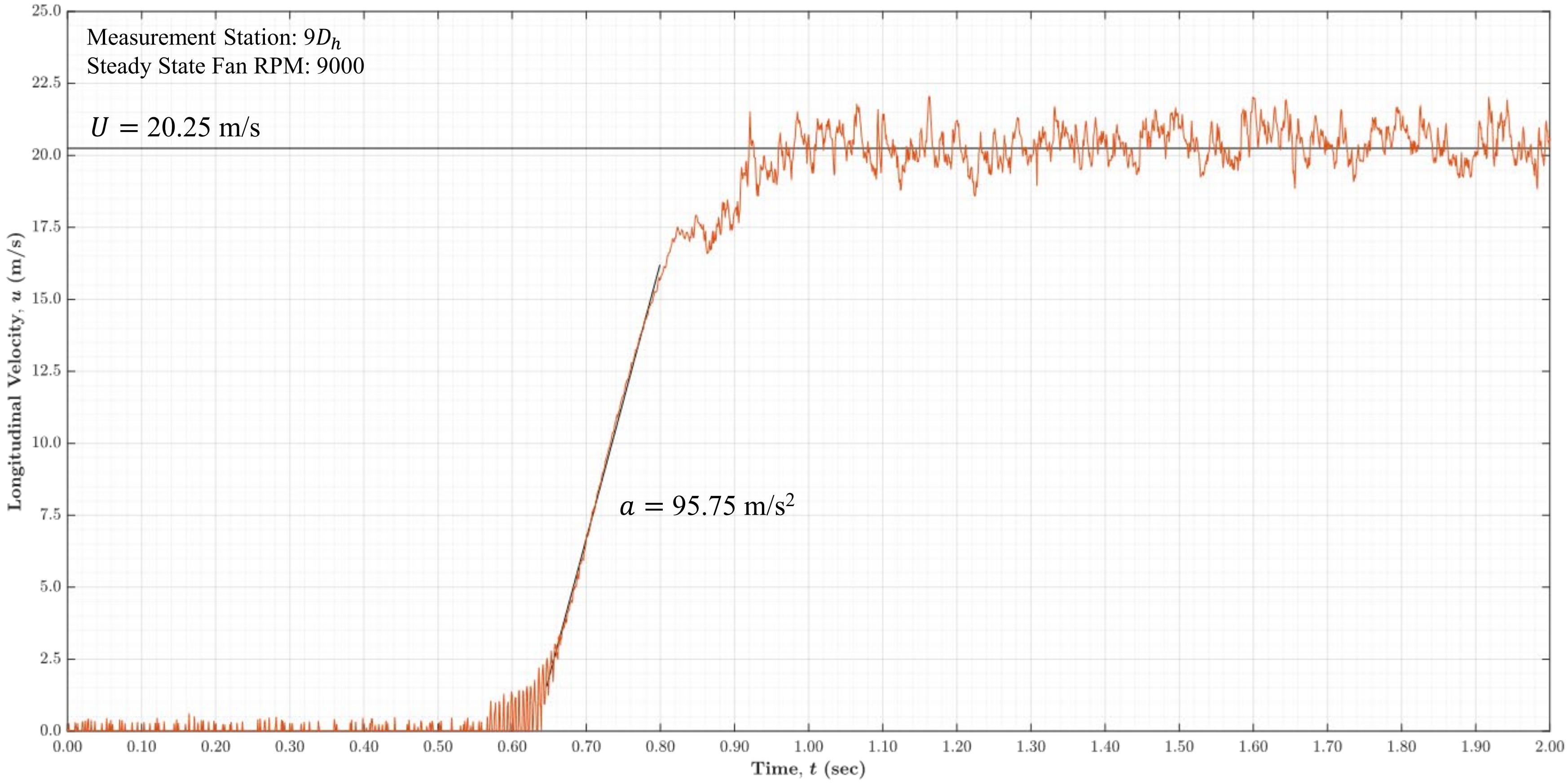
Single Cell: 6 Blade w/o Stator VS 6 Blade w/ Stator



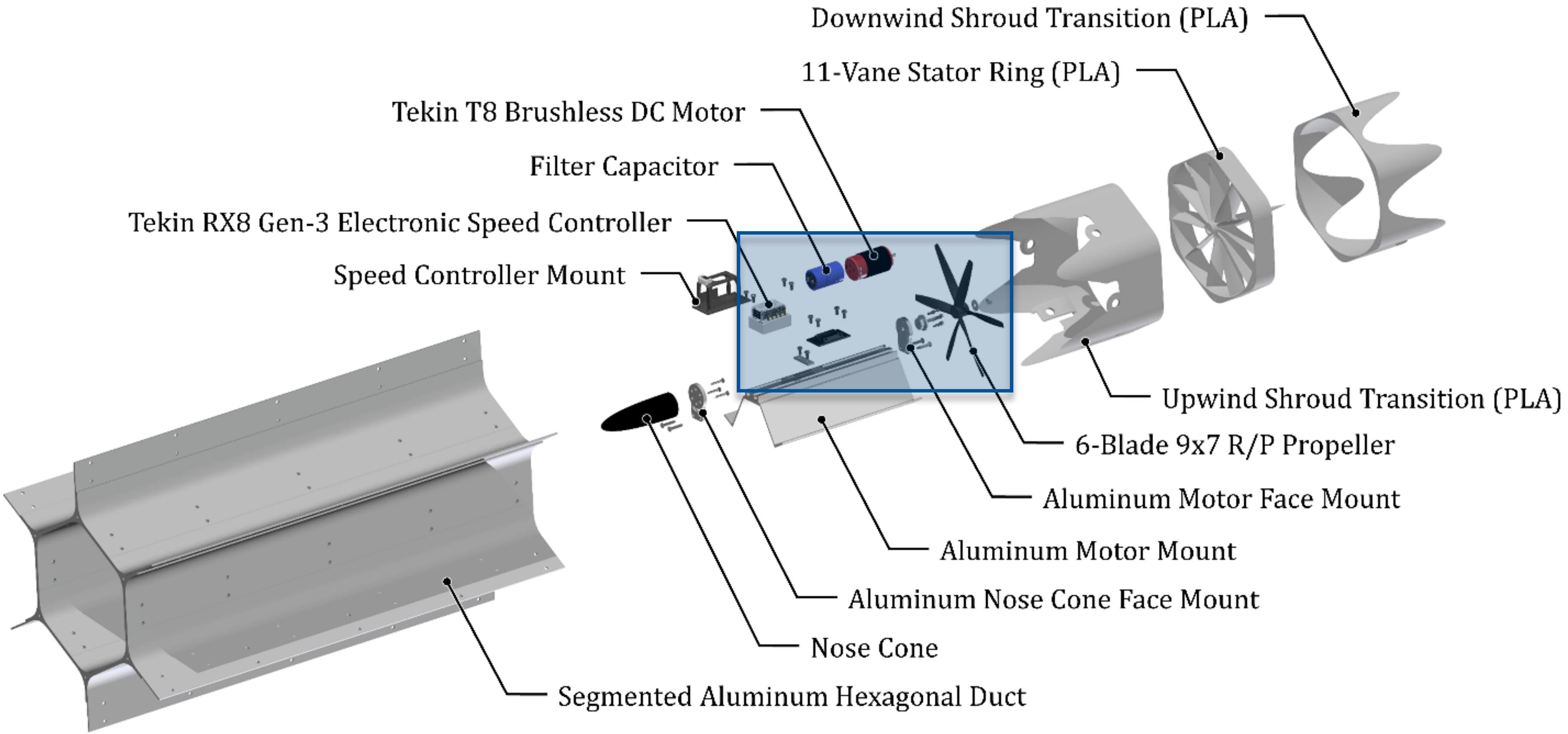
FFM Single Fan Acceleration Characteristics



FFM Single Fan Acceleration Characteristics

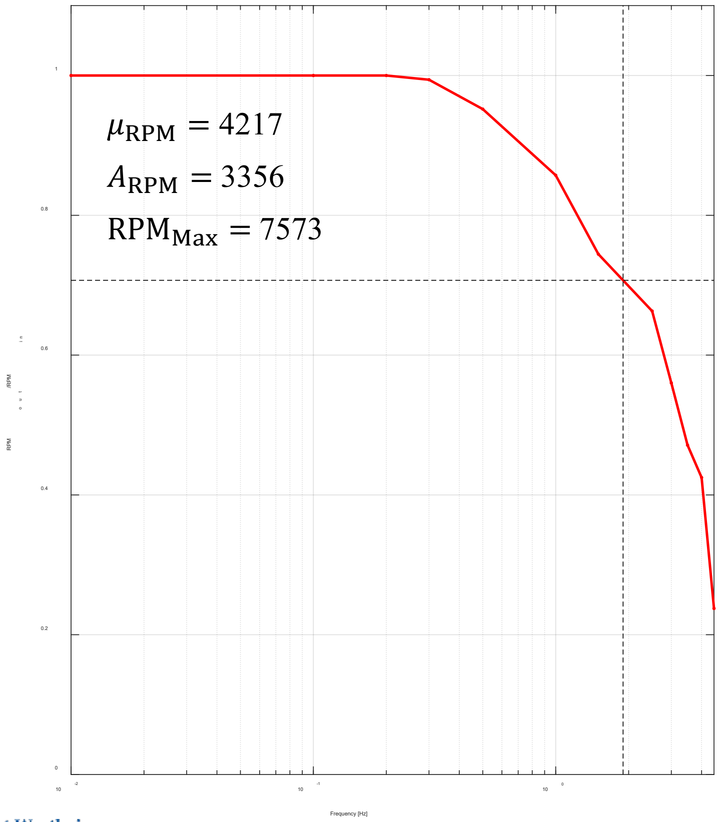


FFM Single Fan Open-Loop Frequency Response

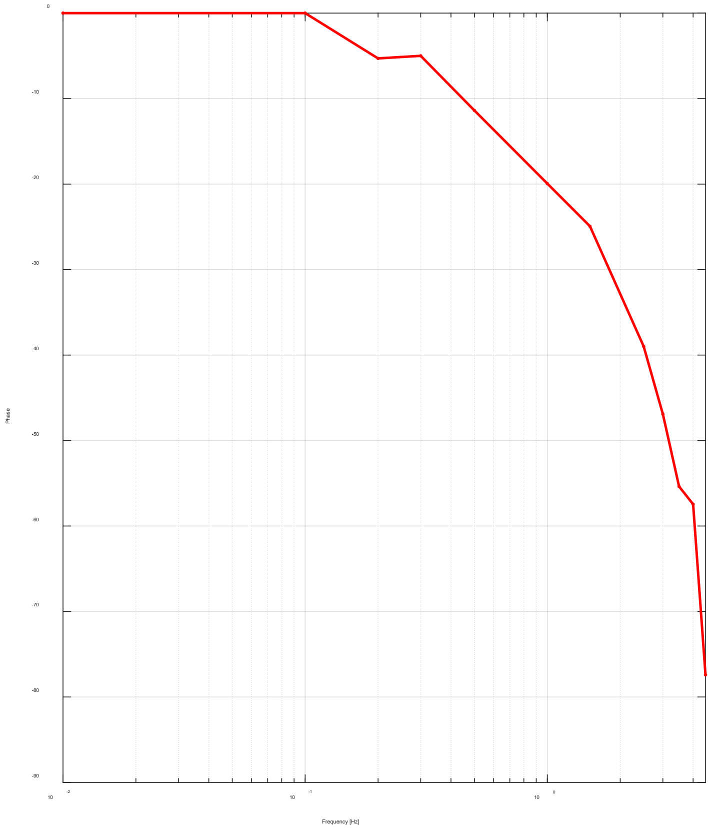


FFM Single Fan Open-Loop Frequency Response

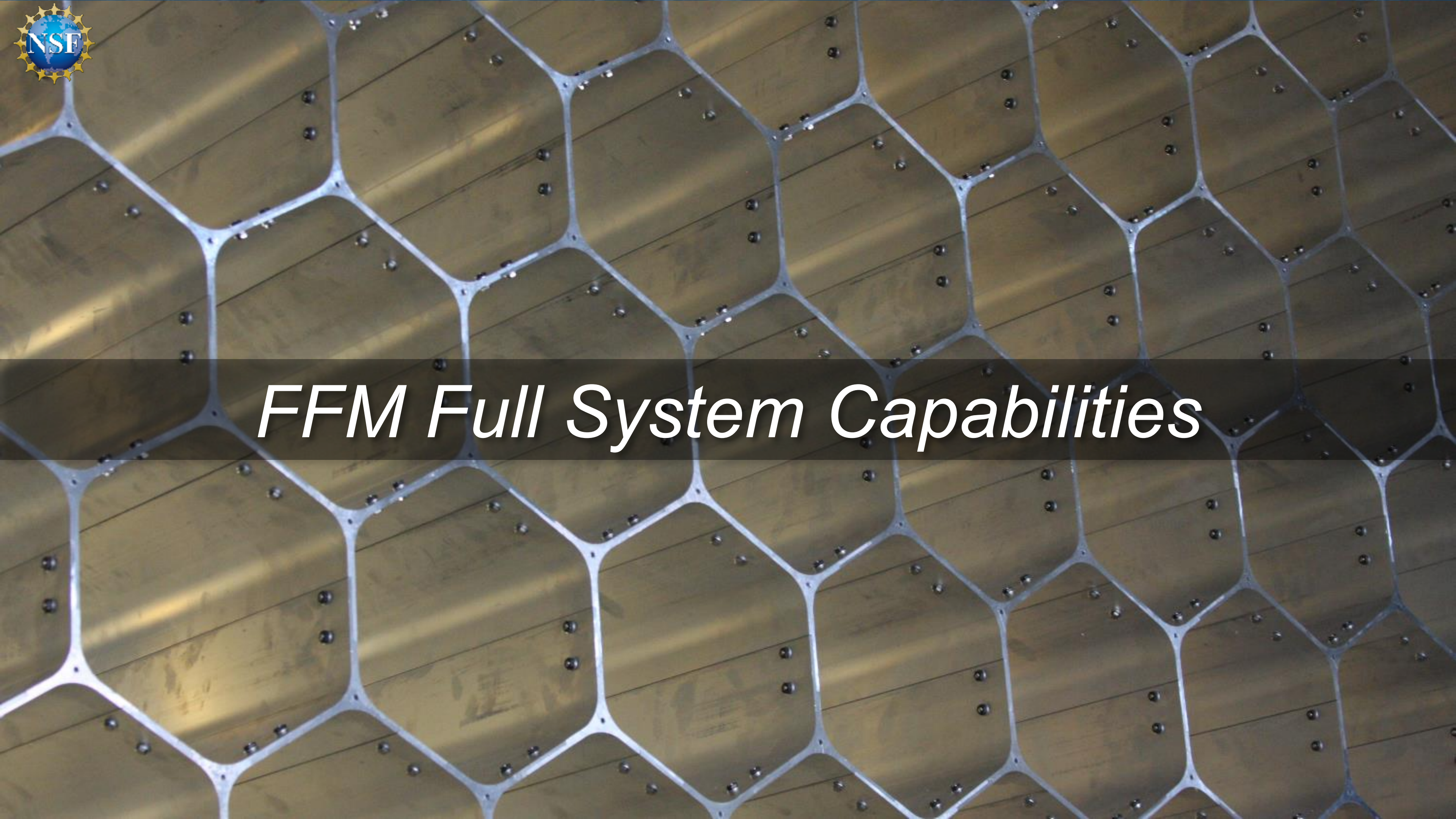
Magnitude



Phase

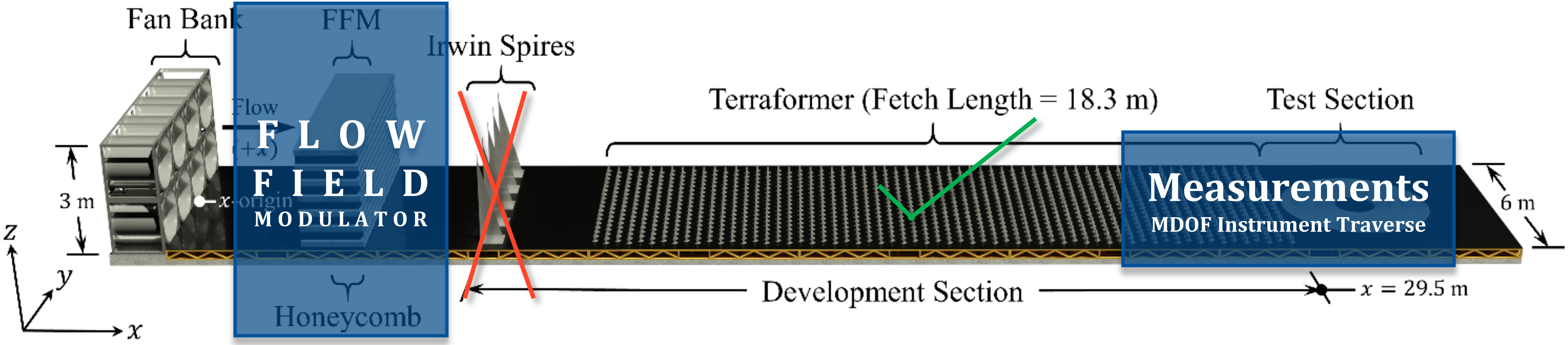


FFM Full System Capabilities



Flow Field Modulator

Mean Velocity and Turbulence Generator



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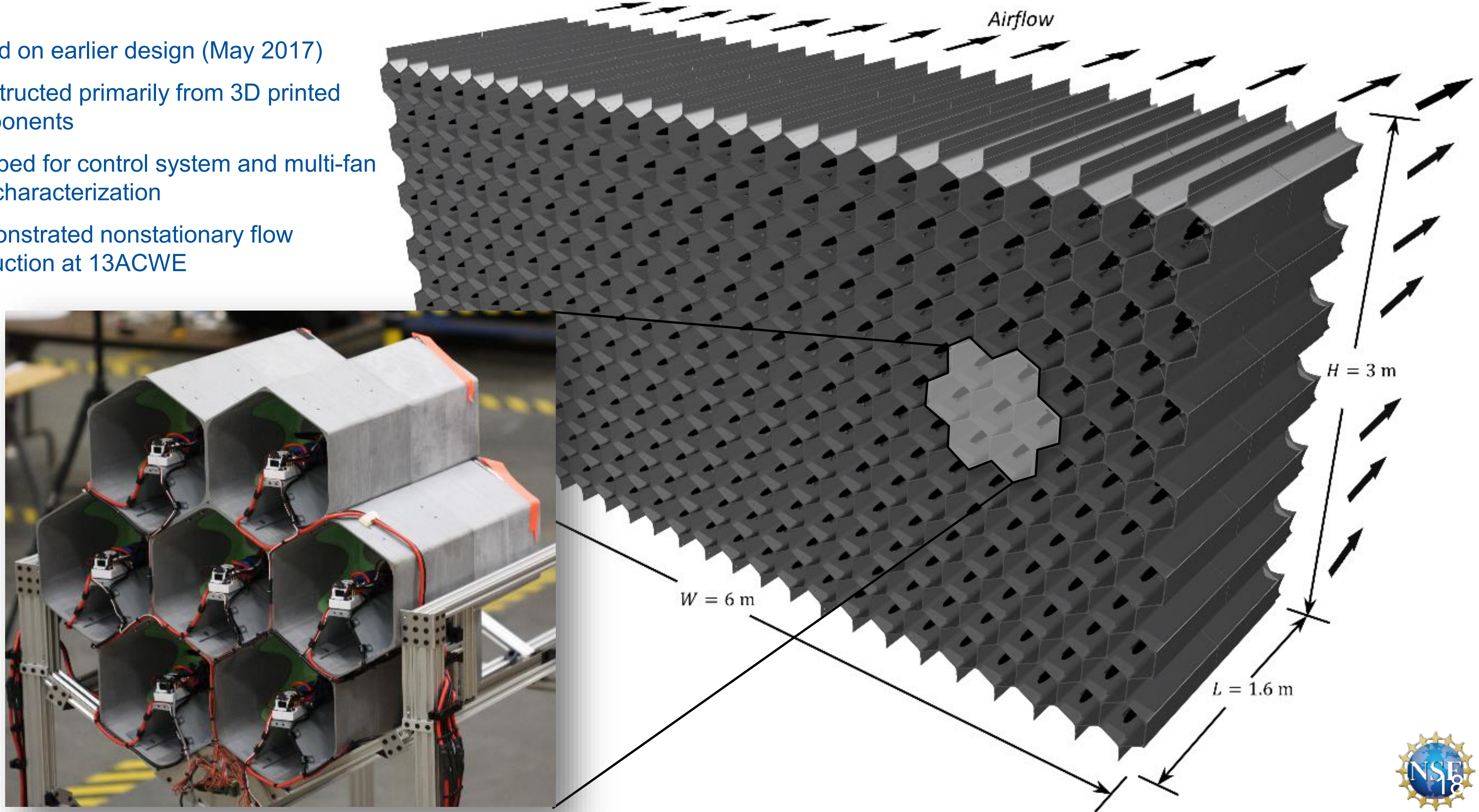
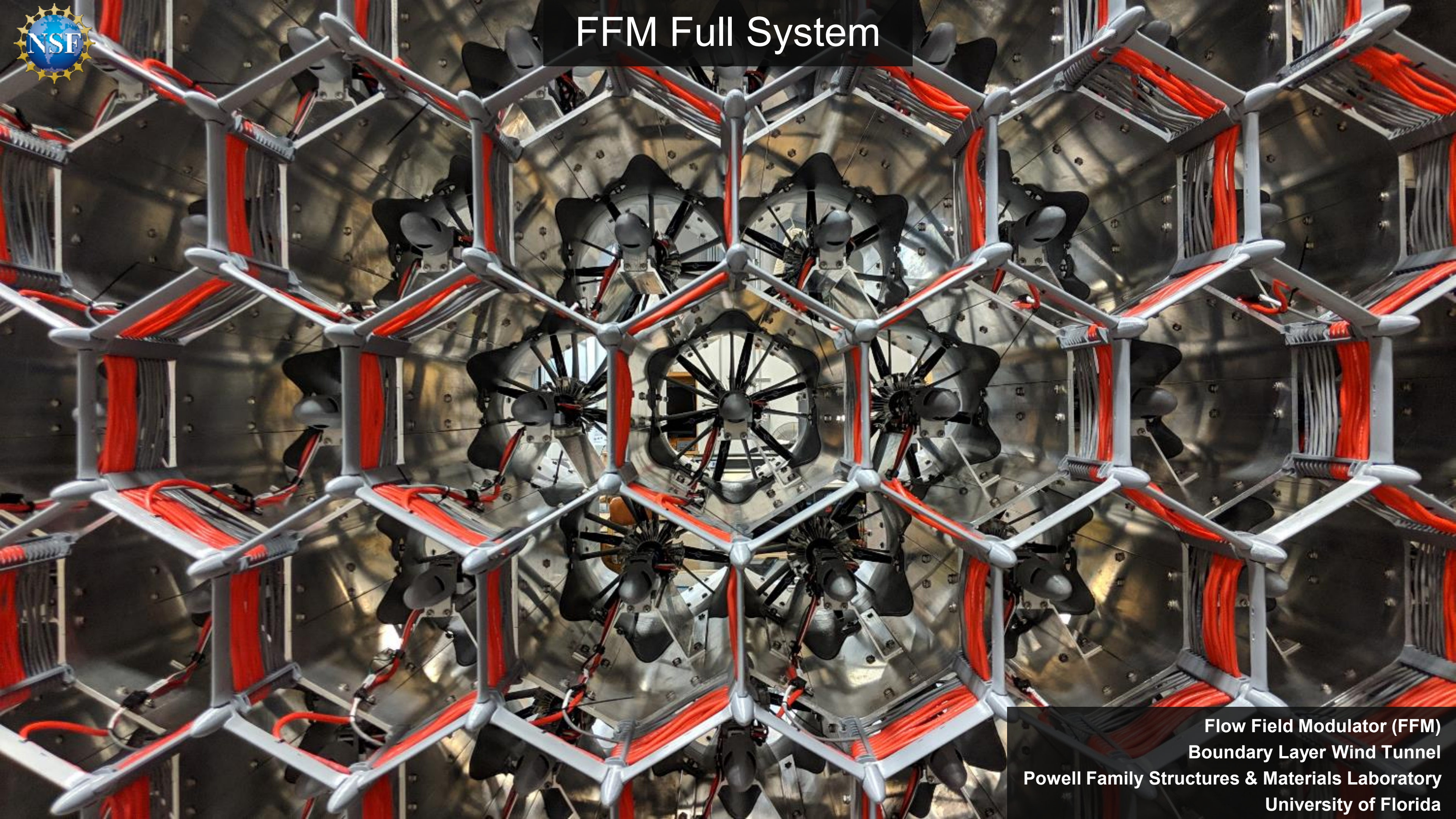
Demonstration of Nonstationary Flow with Scaled Field Data

Previous Nonstationary Hurricane Time History: 7-Cell Prototype

- Based on earlier design (May 2017)
- Constructed primarily from 3D printed components
- Test bed for control system and multi-fan flow characterization
- Demonstrated nonstationary flow production at 13ACWE



FFM Full System



Flow Field Modulator (FFM)
Boundary Layer Wind Tunnel
Powell Family Structures & Materials Laboratory
University of Florida

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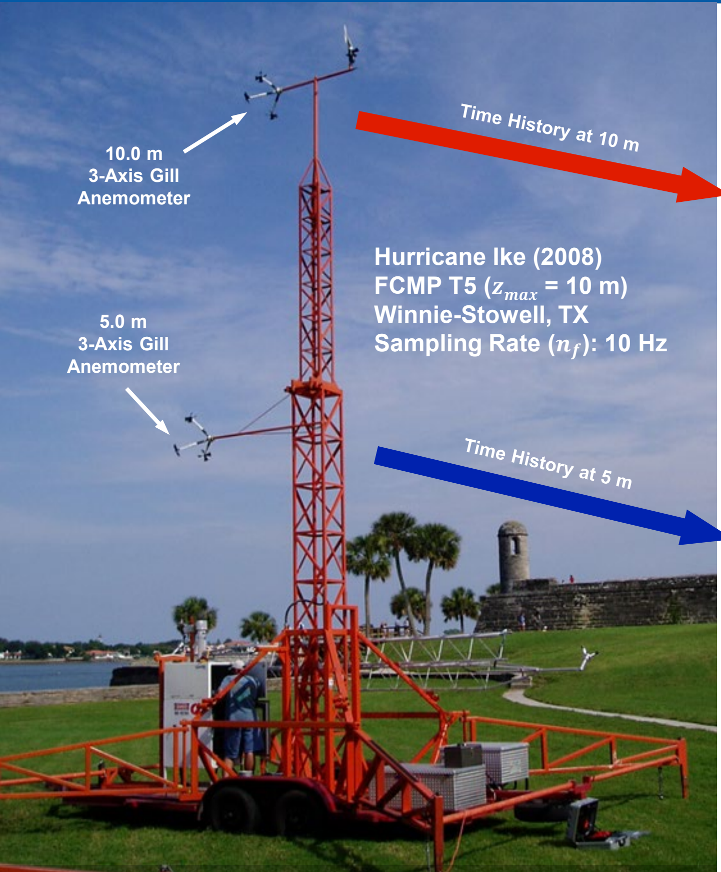
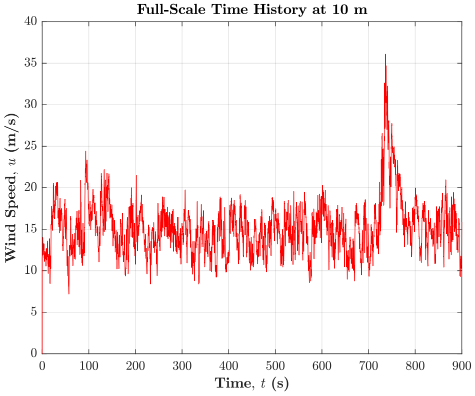
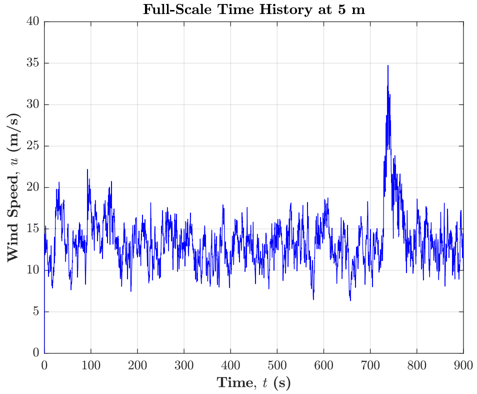
BLWT Nonstationary Hurricane Time History



Hurricane Ike (2008)
FCMP T5 (z_{max} = 10 m)
Winnie-Stowell, TX
Sampling Rate (n_f): 10 Hz

Balderrama, J.A., F.J. Masters, K.R. Gurley, D.O. Prevatt, L.D. Aponte-Bermudez, T.A. Reinhold, J.-P. Pinelli, C.S. Subramanian, S.D. Schiff, and A.G. Chowdhury, 2011: The Florida Coastal Monitoring Program (FCMP): A review. Journal of Wind Engineering and Industrial Aerodynamics, 99, 979-995.





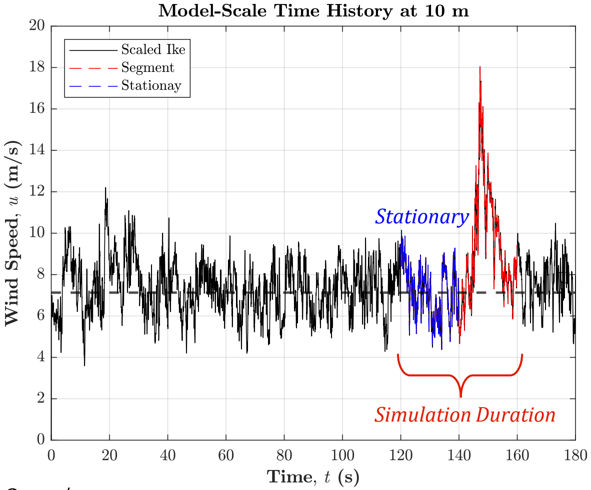
$$U(5) = \frac{u^*}{\kappa}\ln\left(\frac{5}{z_0}\right)$$

$$U(10) = \frac{u^*}{\kappa}\ln\left(\frac{10}{z_0}\right)$$

Reduced Frequency Relationship

$$\boxed{\frac{n_m L_m}{U_m} = \frac{n_f L_f}{U_f}}$$

Velocity Scale (U_m/U_f) = 1:2
Length Scale (L_m/L_f) = 1:10
Time Scale (n_m/n_f)= 5:1



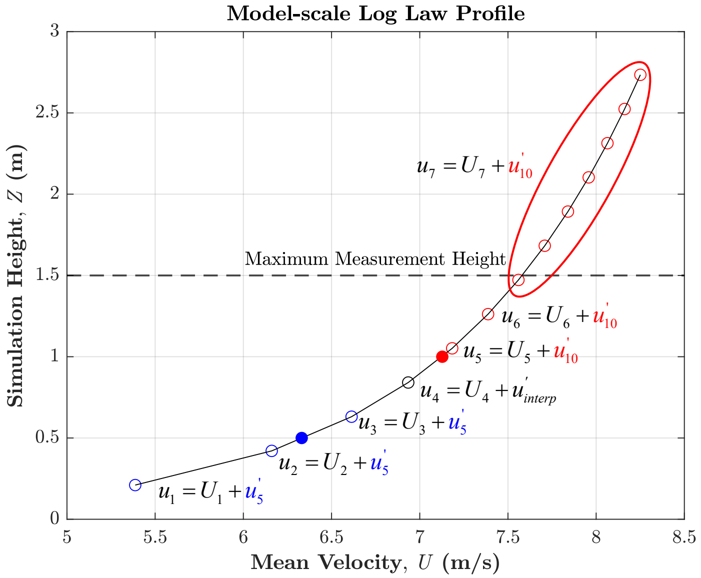
$$u_{*FS} = 0.89 \text{ m/s}$$

$$z_{0FS} = 0.017 \text{ m}$$

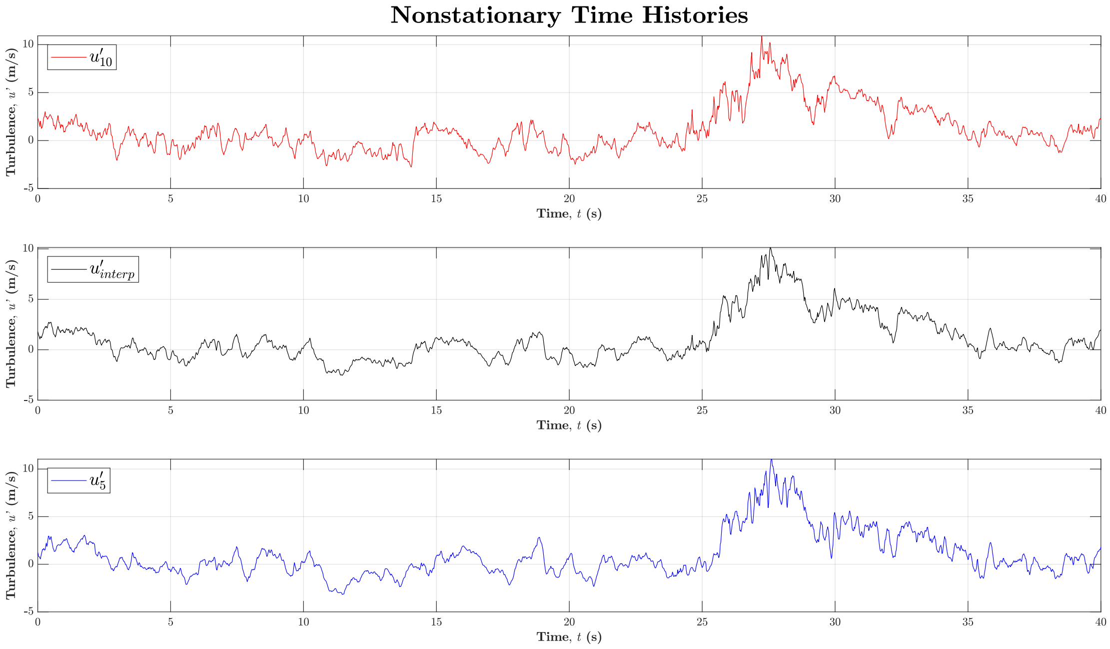
$$\boxed{U(z) = \frac{u^*}{\kappa}\ln\left(\frac{z}{z_0}\right)}$$

Ike Trace Input: $u(z,t) = U(z) + u'(t)$

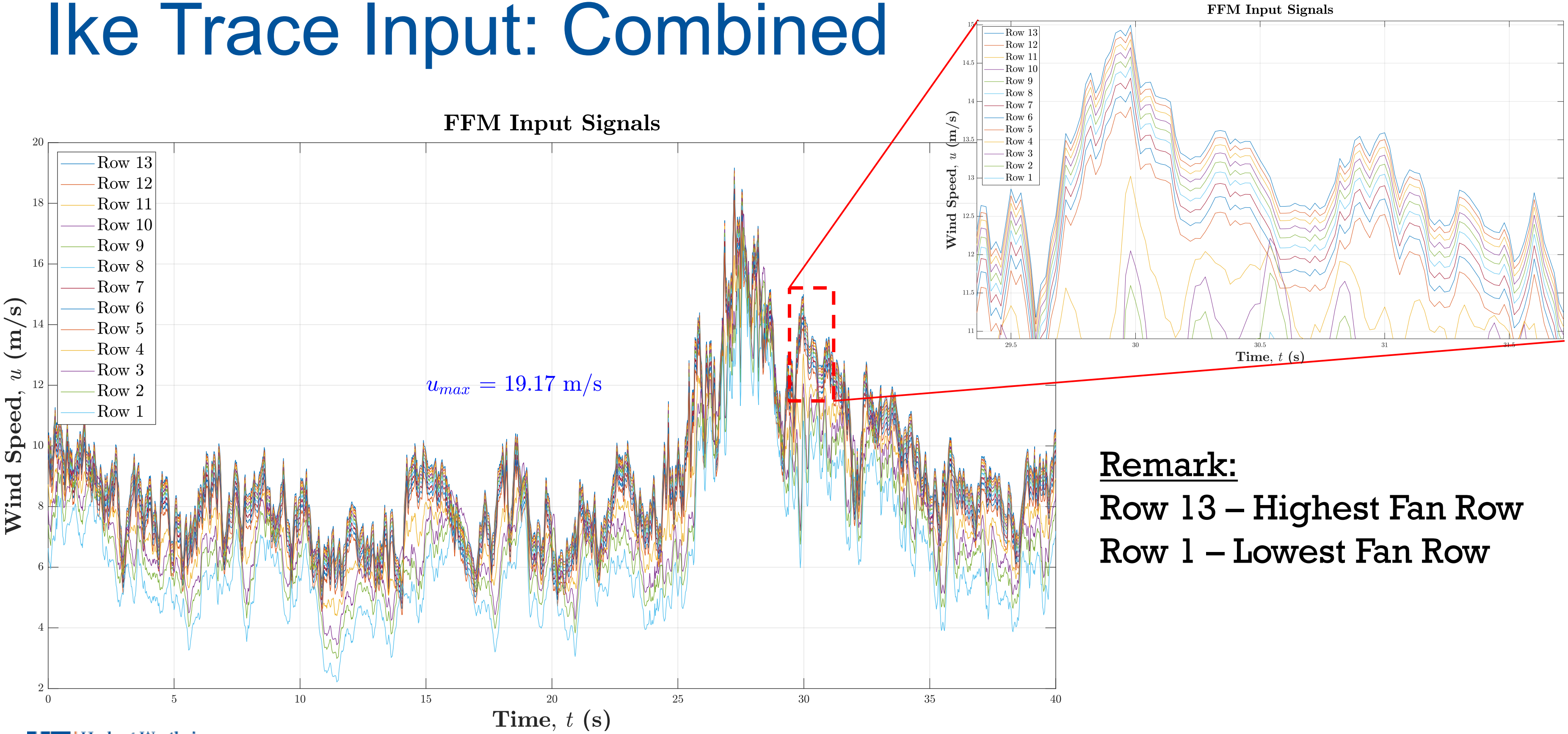
Log Law $U(z)$



Mean Removed Velocity, $u'(t)$



Ike Trace Input: Combined

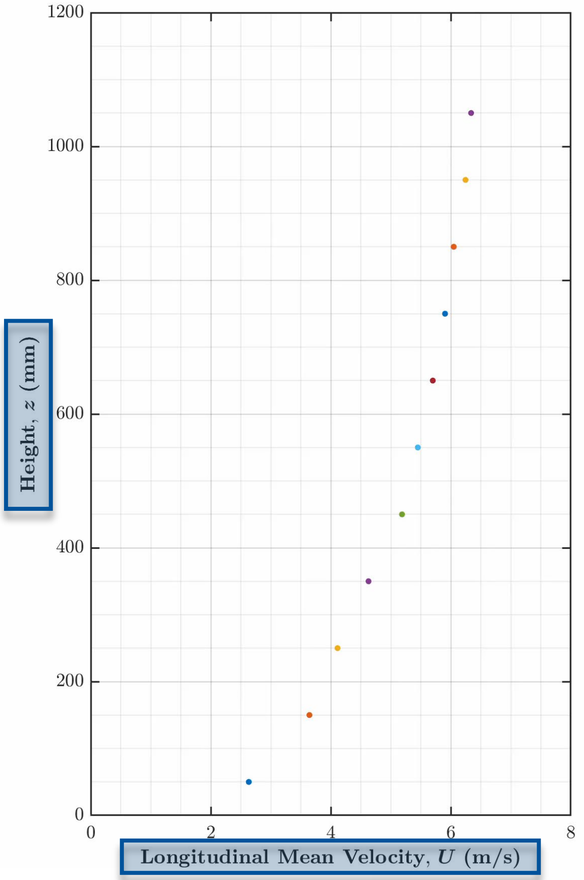


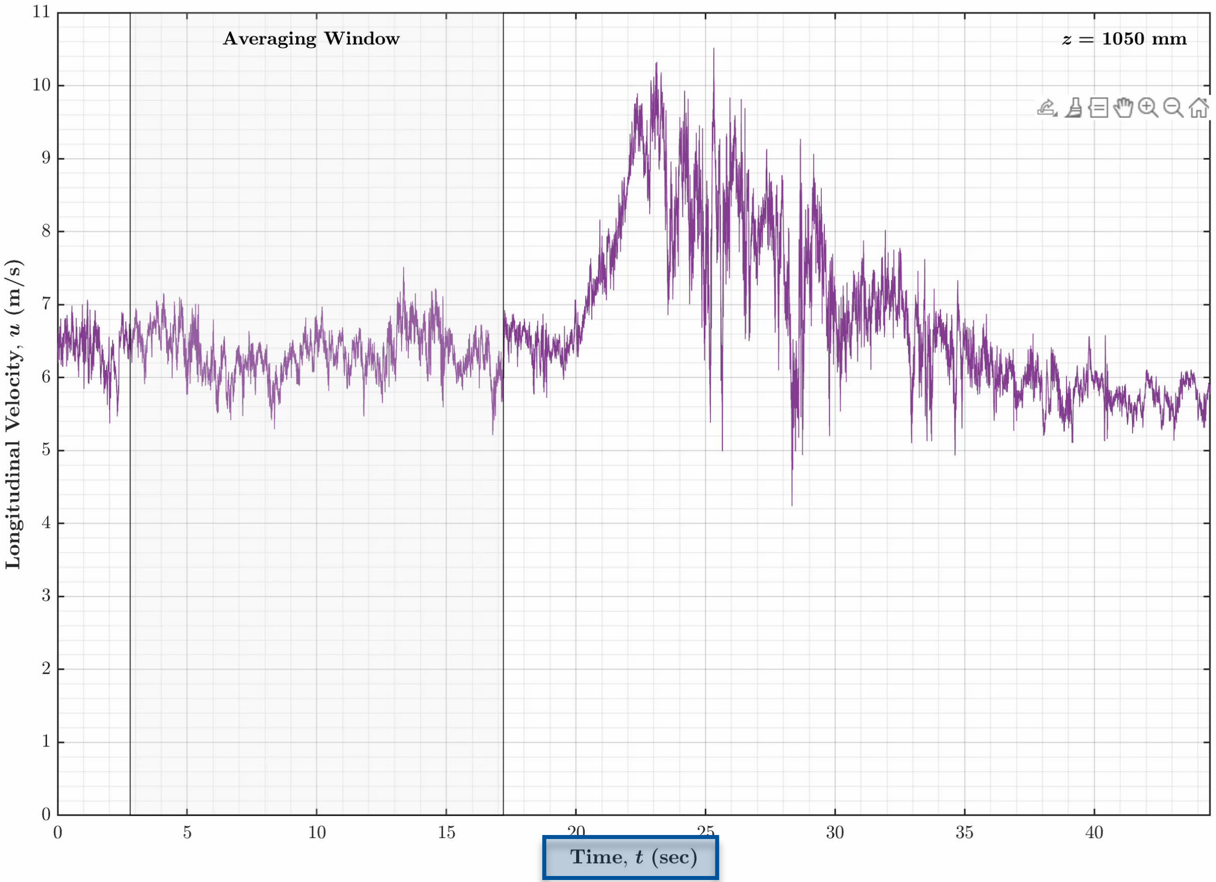
Remark:

Row 13 – Highest Fan Row

Row 1 – Lowest Fan Row

BLWT Nonstationary Hurricane Time History





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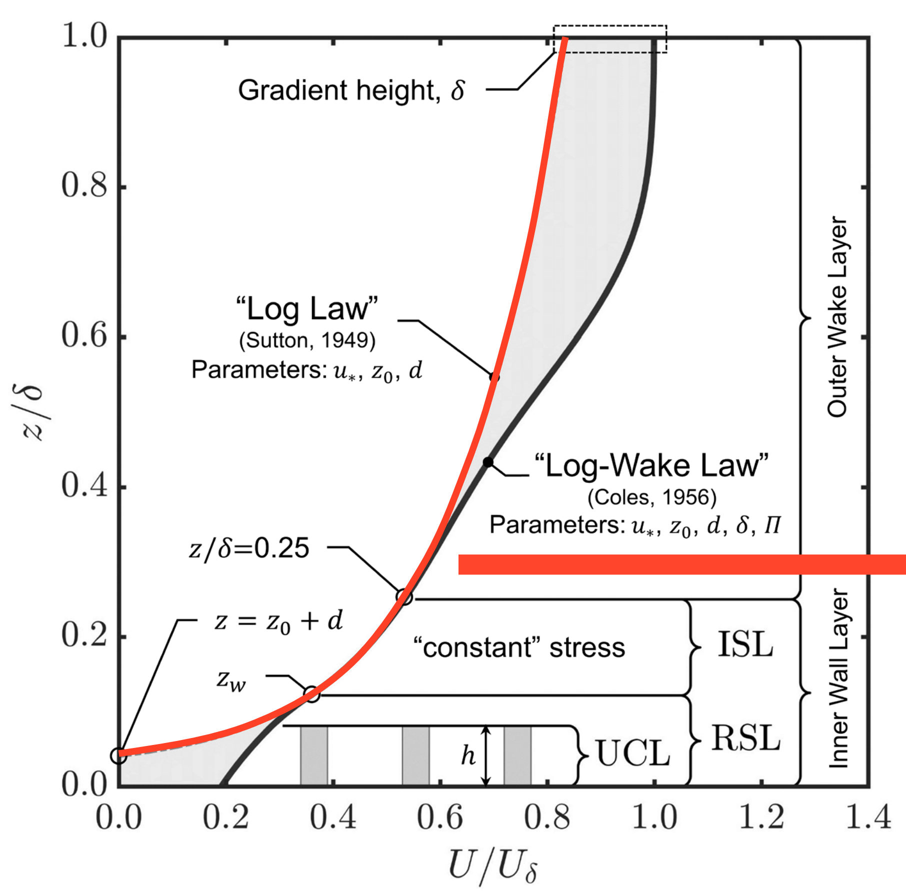
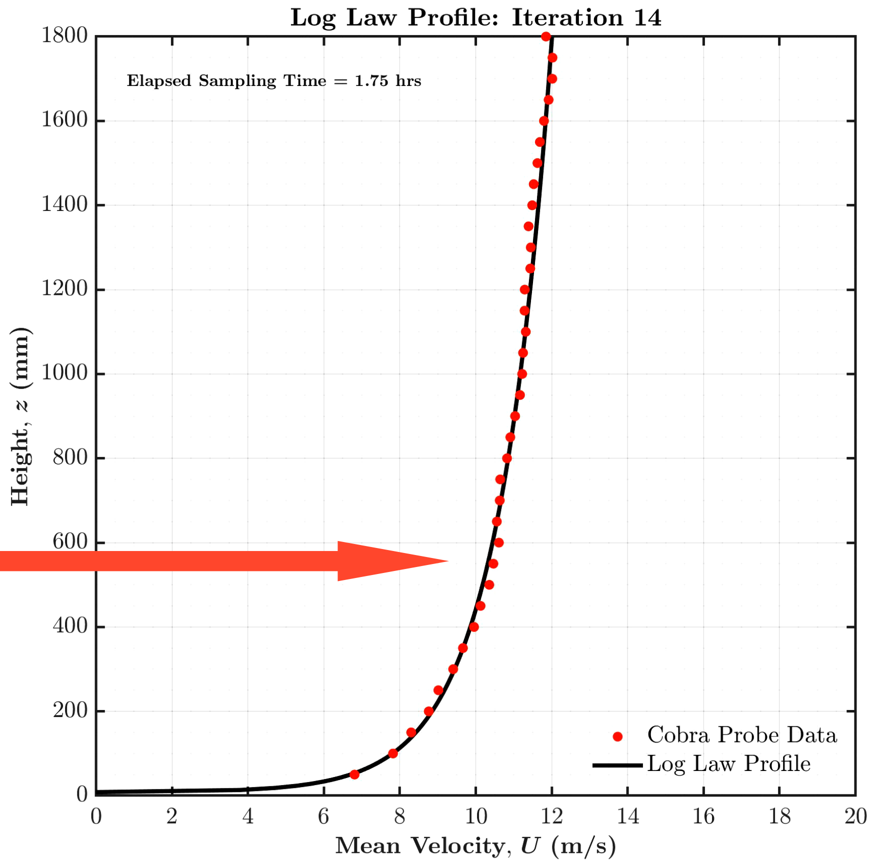
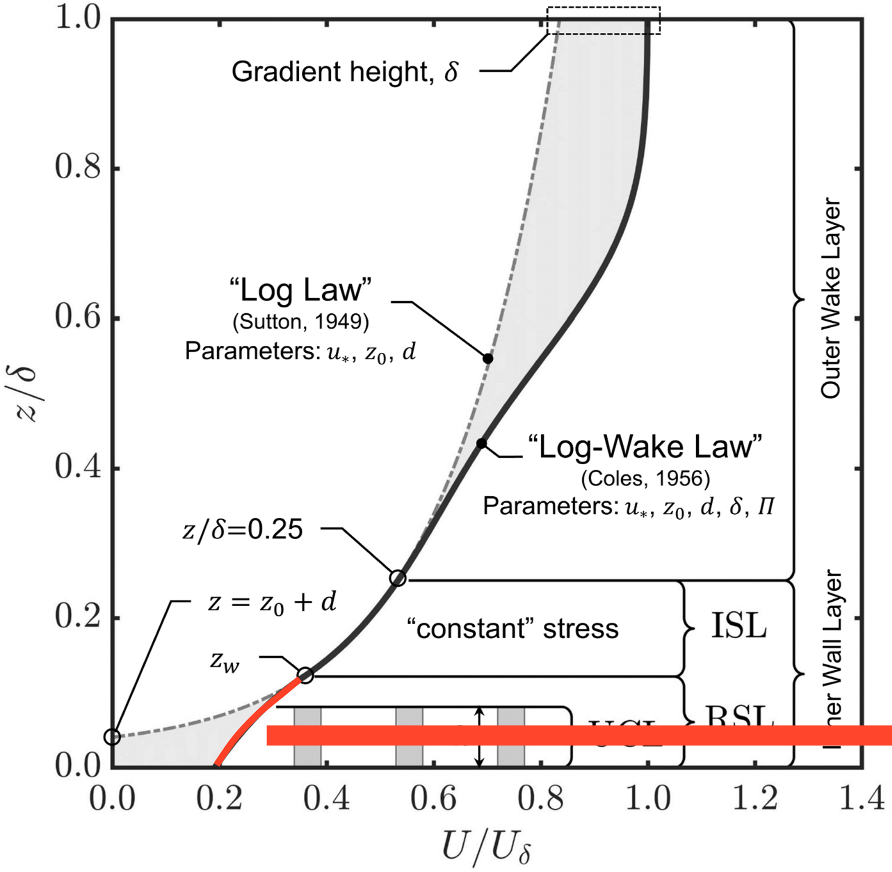
Convergence on User-Specified Stationary Mean Velocity Profiles

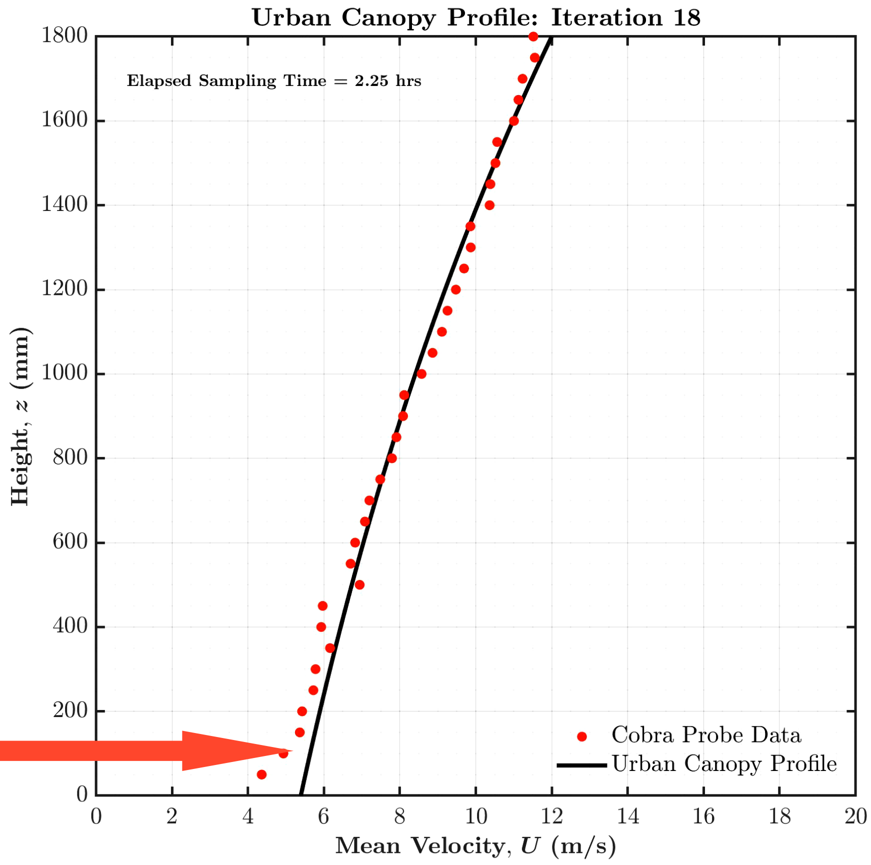
Example Target Profiles – Log Law



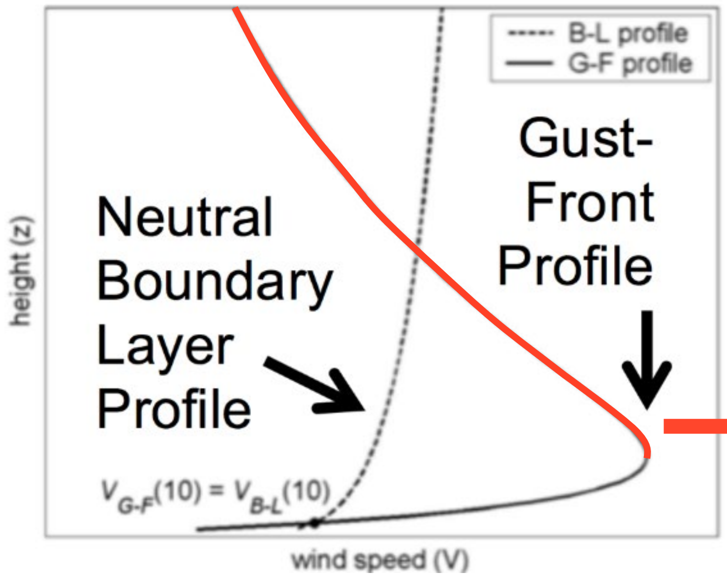


Example Target Profiles – Urban Canopy

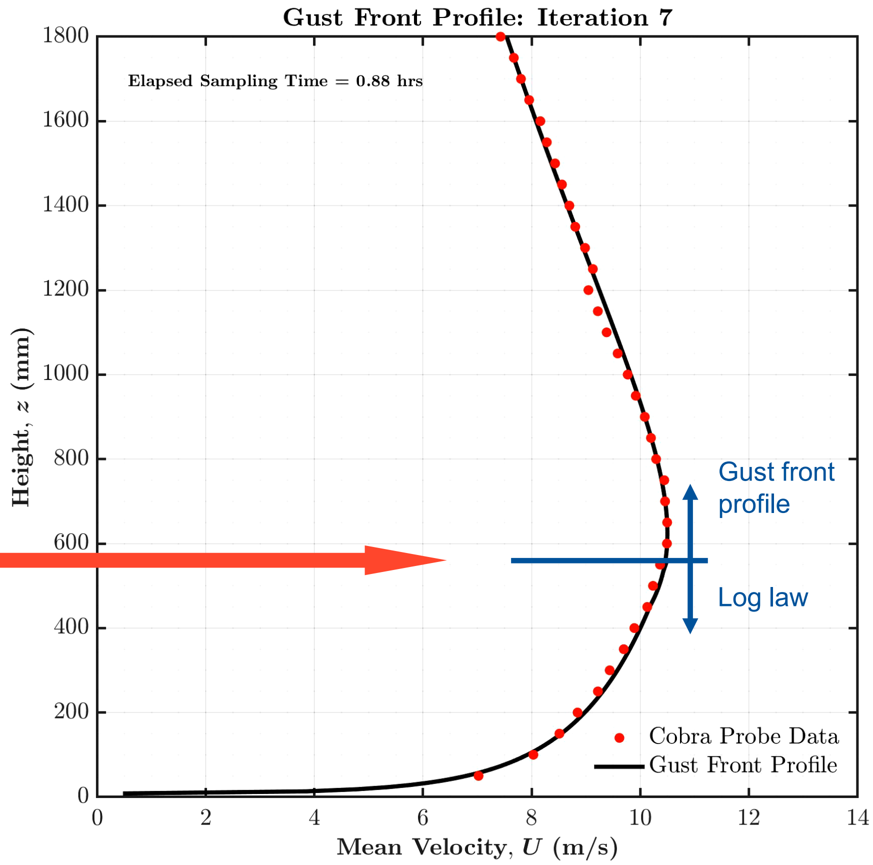




Example Target Profiles – Gust Front-Log Profile



Mean velocity profiles (Kwon and Kareem, 2009)



Kwon, D. K., & Kareem, A. (2009). Gust-front factor: New framework for wind load effects on structures. *Journal of structural engineering*, *135*(6), 717-732.

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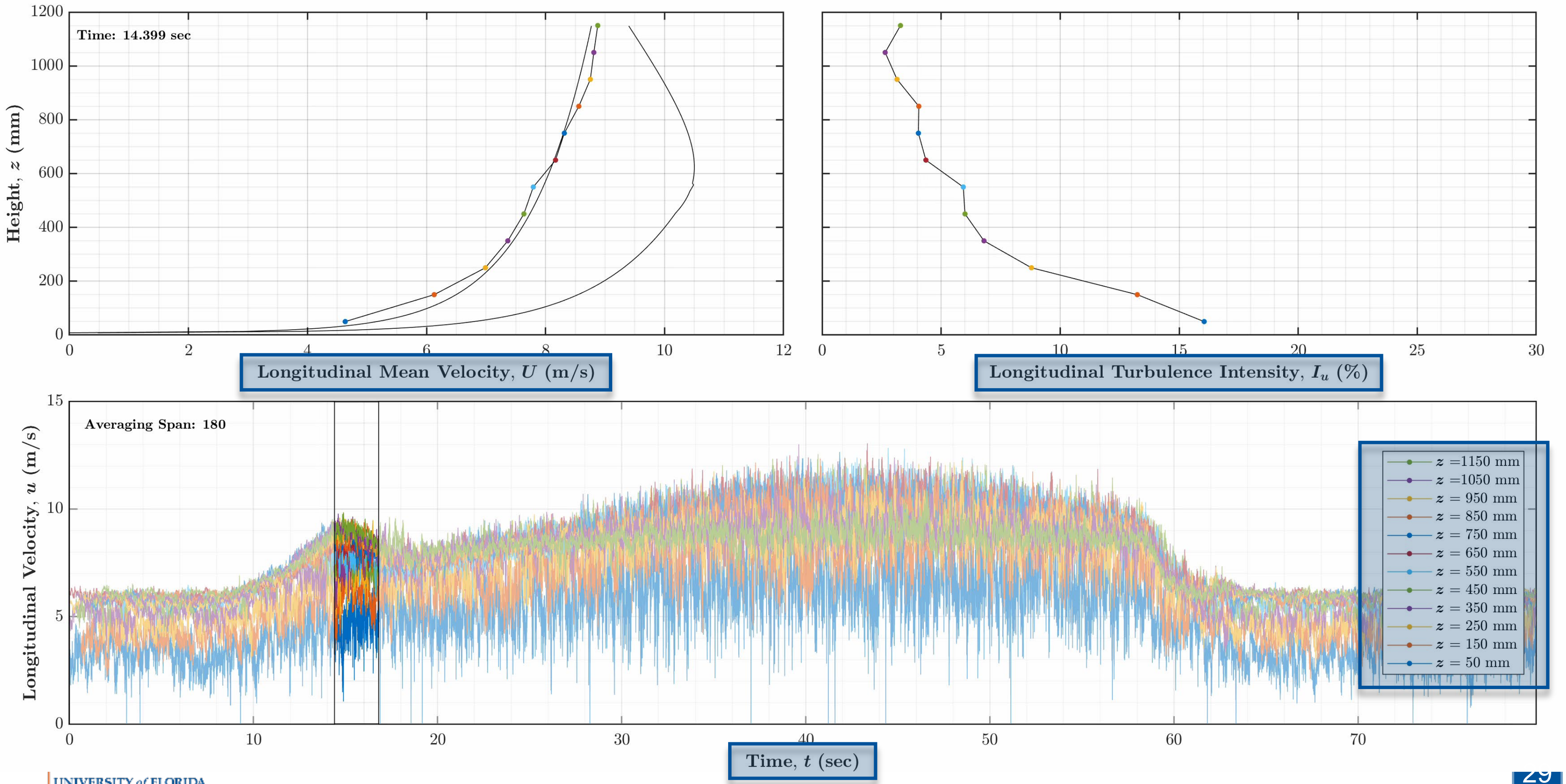
Flow Transition between Two Converged Mean Velocity Profiles

Example Target Flow Transition – Neutral to Gust Front Profile



Turbulence Modulation

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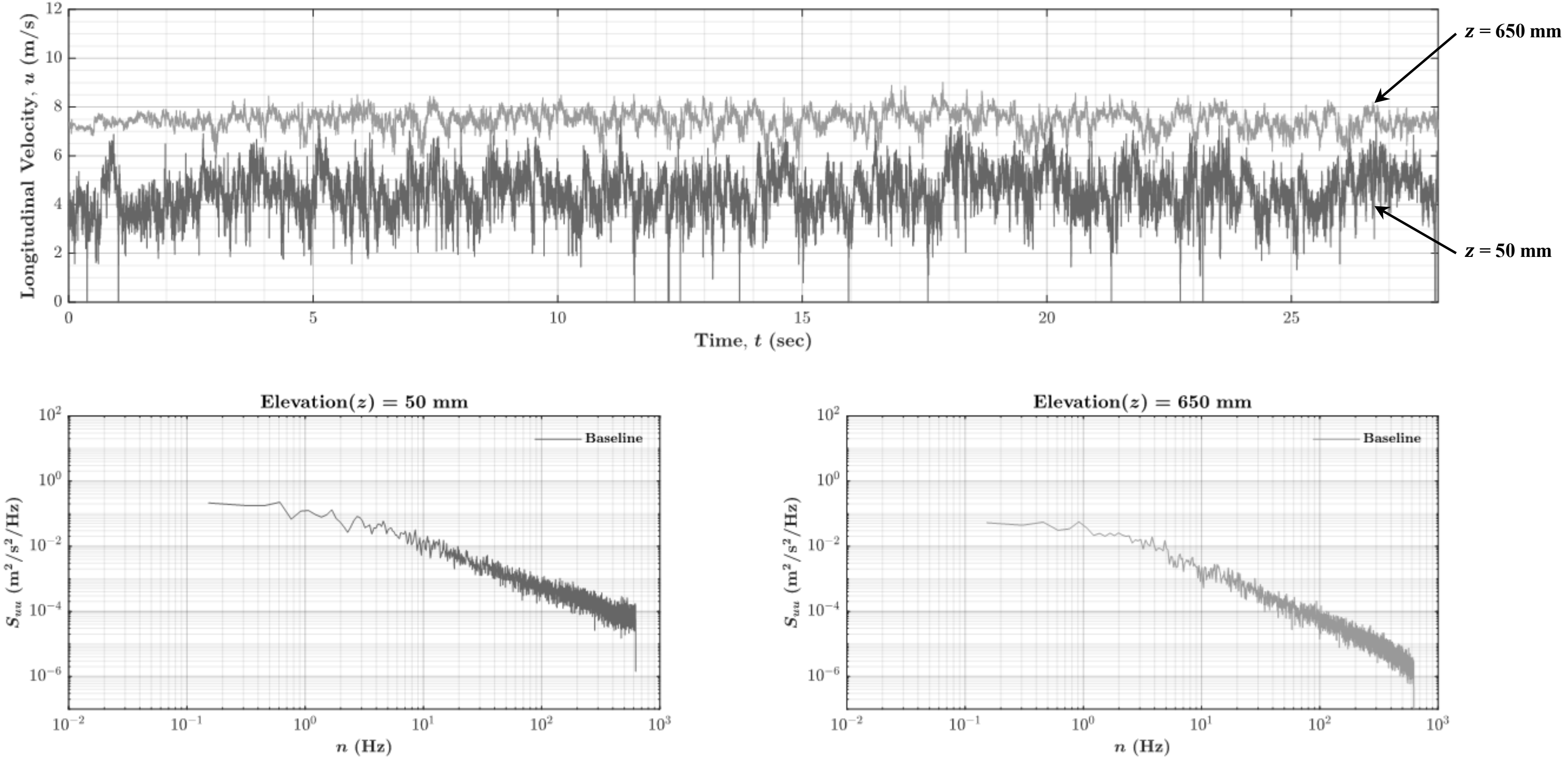
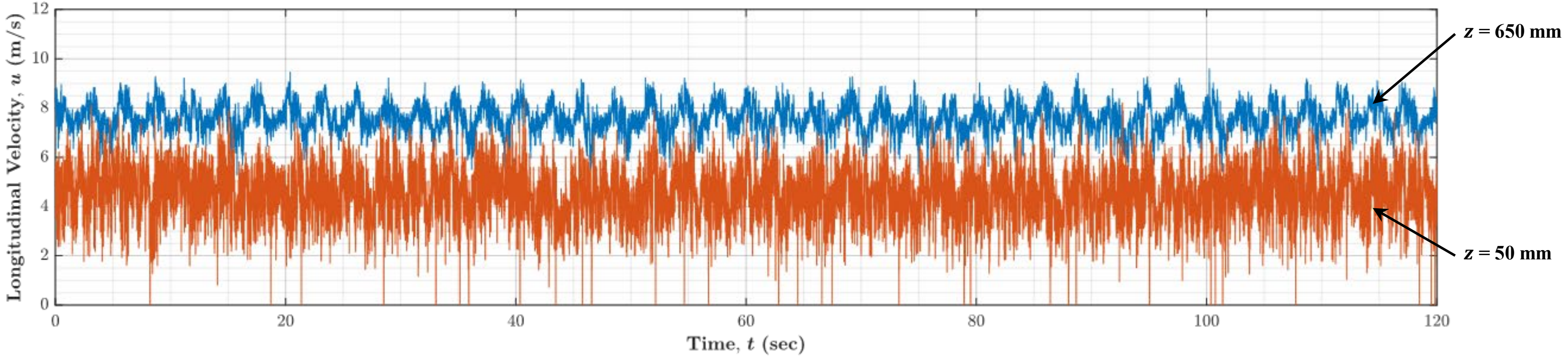
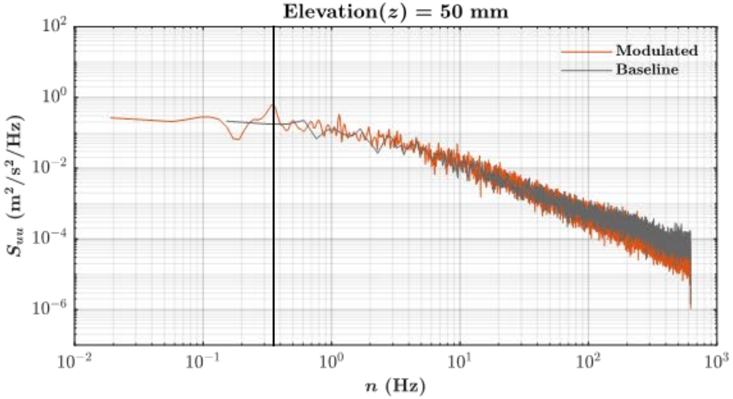
Sine Wave (In-Phase)

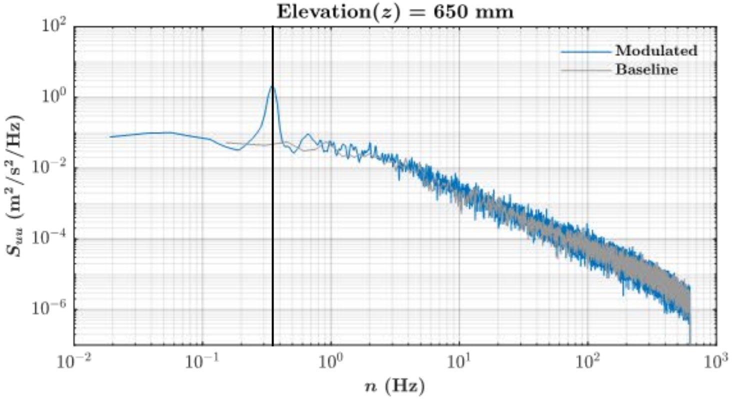
Baseline - Constant FFM Velocity Output



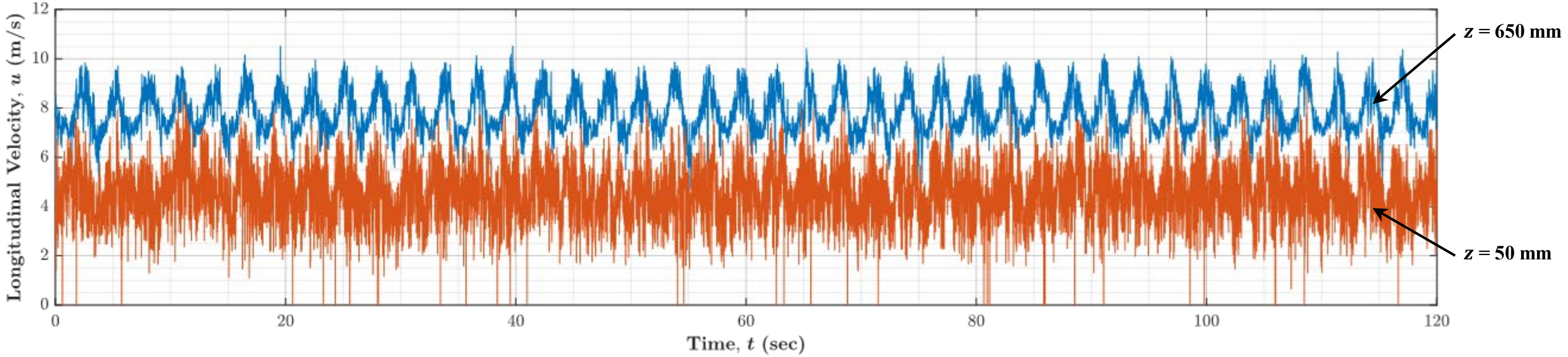
0.5 Hz Sine Wave (In-Phase) – Low Amplitude

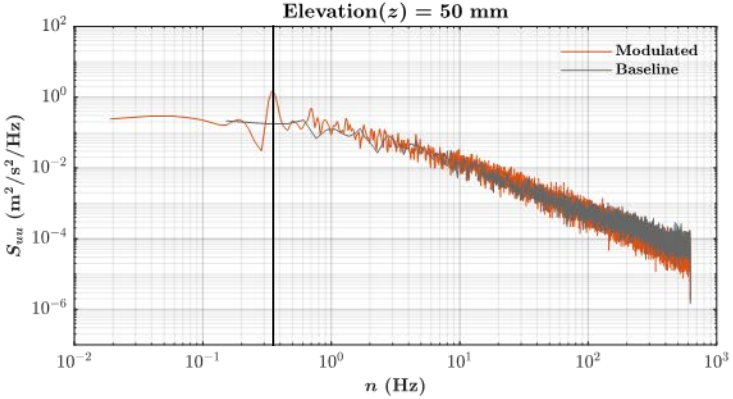


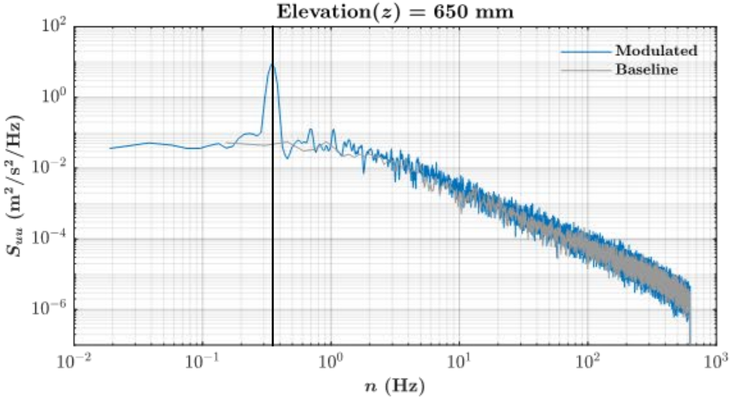




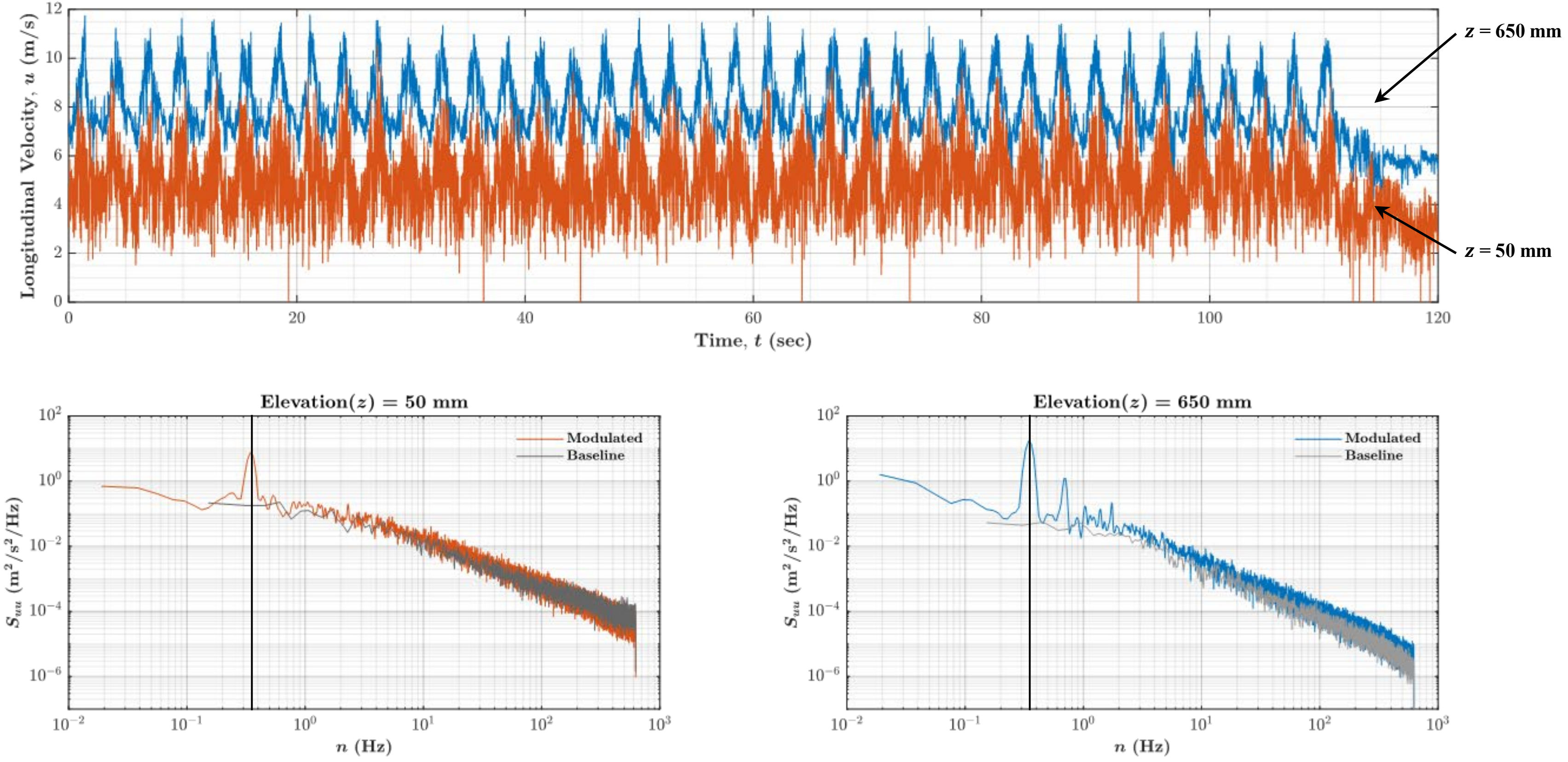
0.5 Hz Sine Wave (In-Phase) – Medium Amplitude



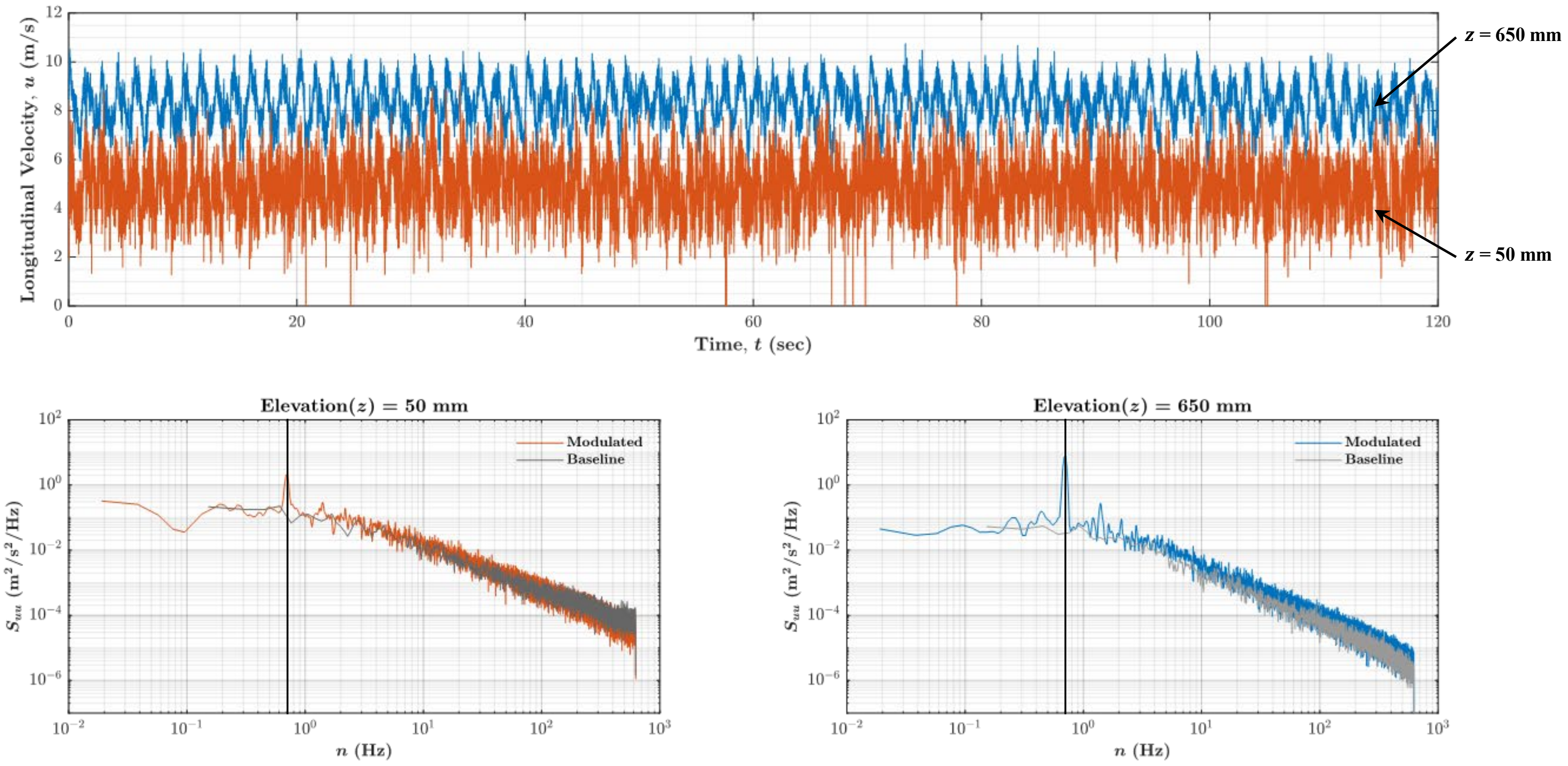




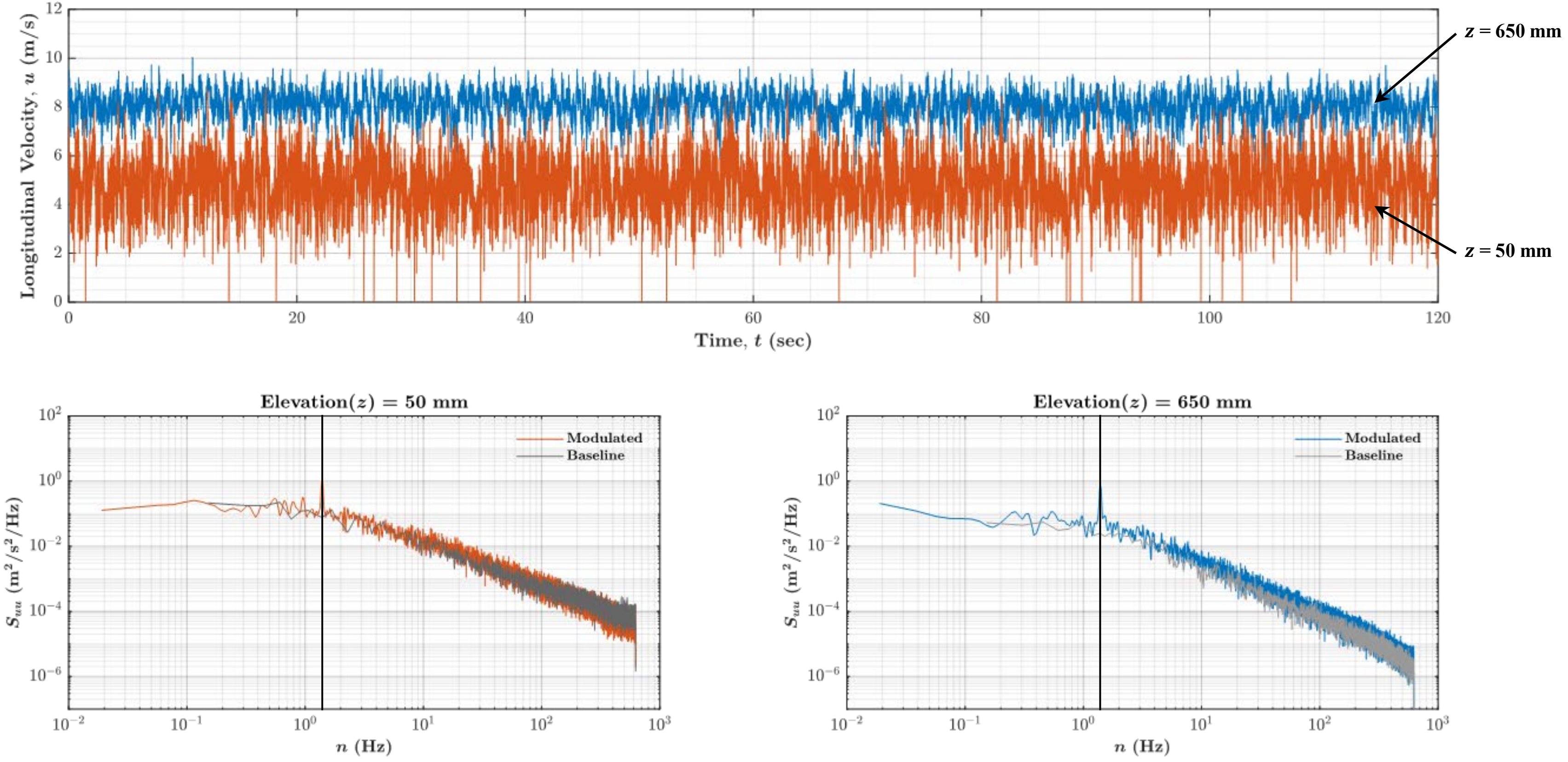
0.5 Hz Sine Wave (In-Phase) – High Amplitude



1.0 Hz Sine Wave (In-Phase) – High Amplitude



2.0 Hz Sine Wave (In-Phase) – High Amplitude



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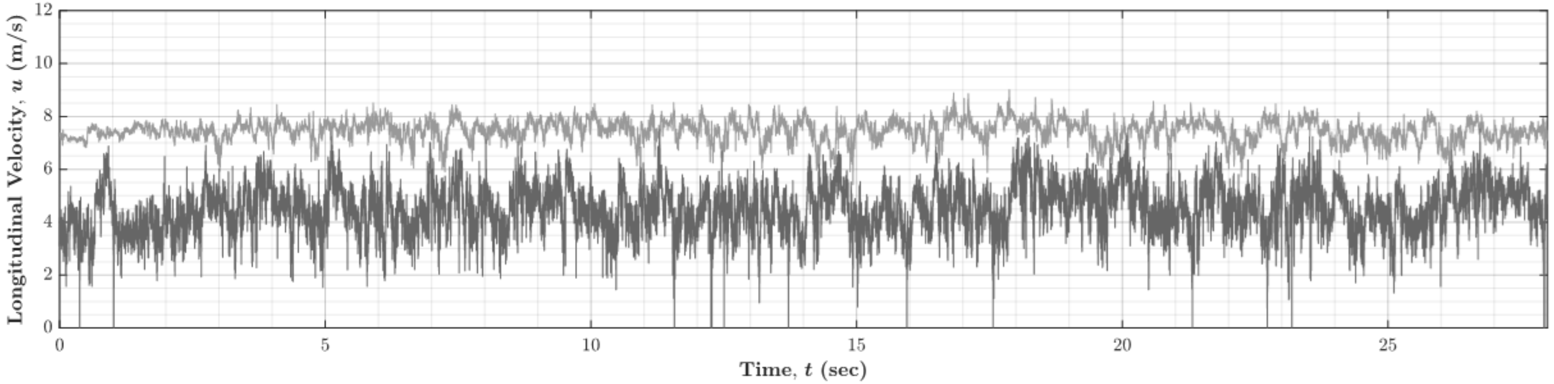
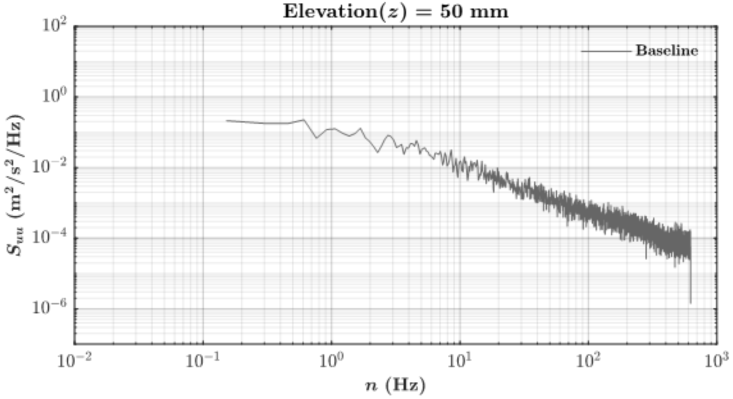
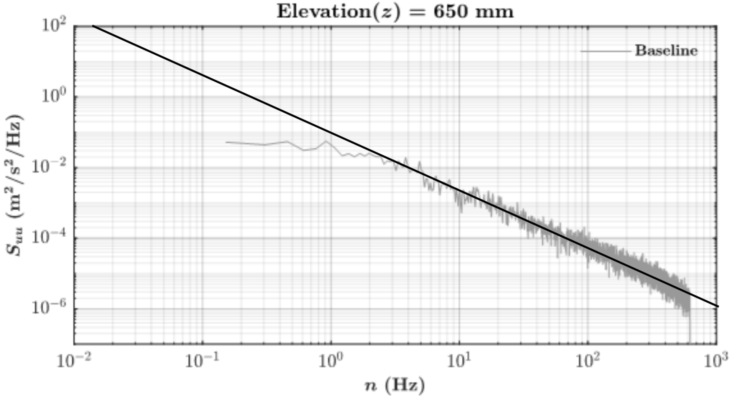
Sine Wave (Random Phase)

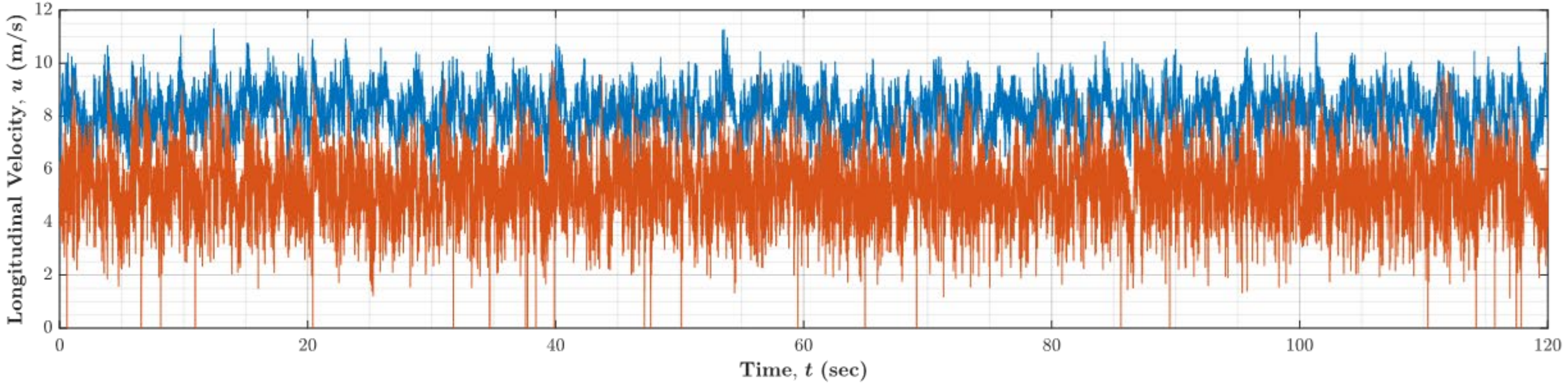
Baseline - Constant FFM Velocity Output

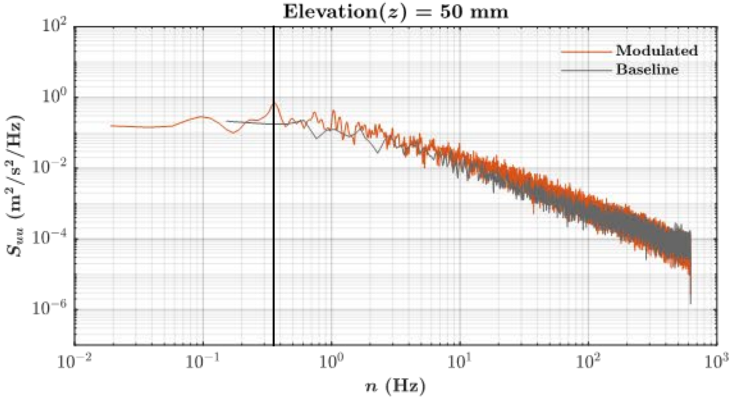


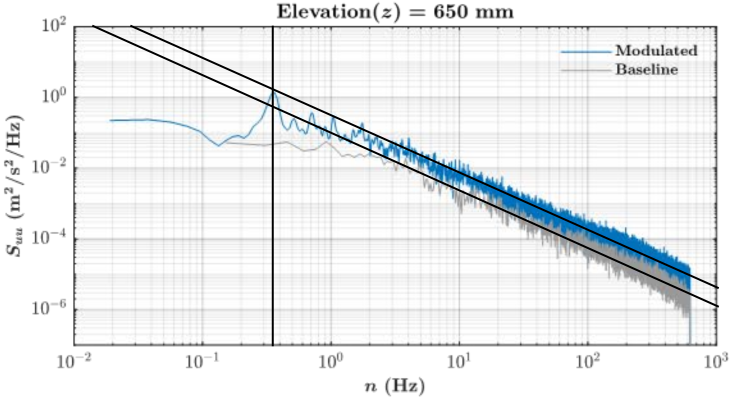




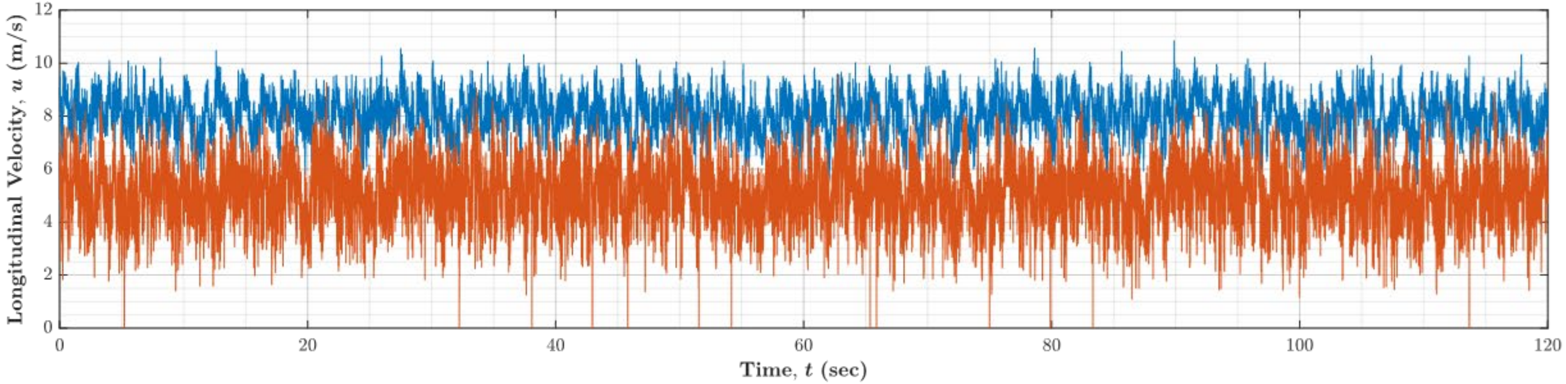
0.5 Hz Sine Wave (Random Phase) – High Amplitude

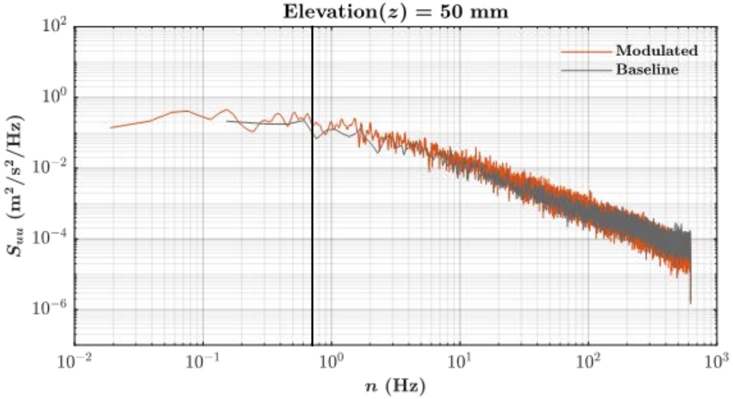


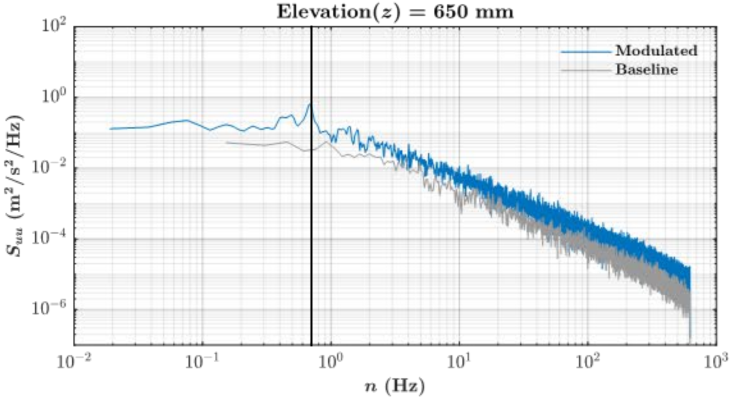




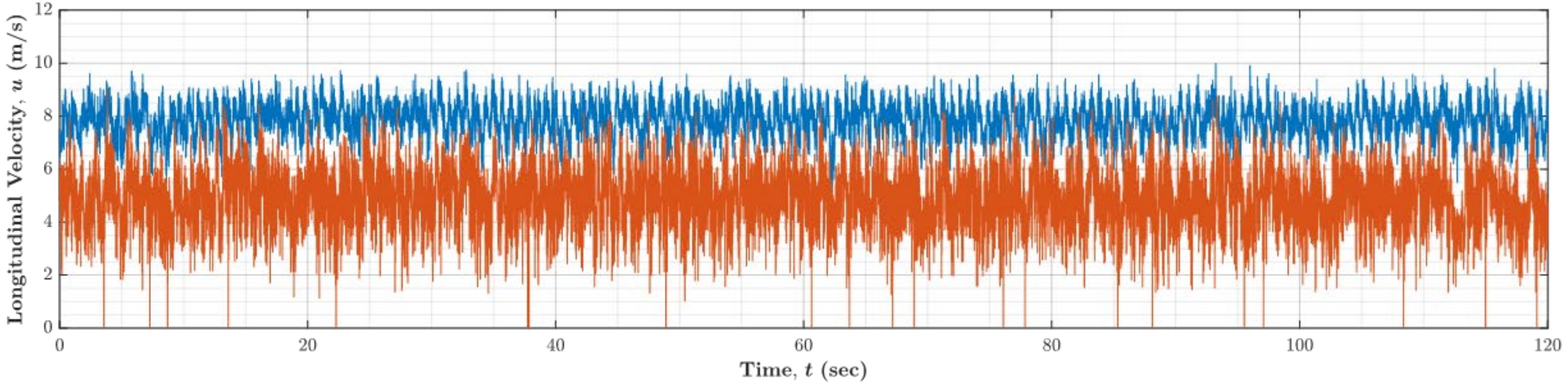
1.0 Hz Sine Wave (Random Phase) – High Amplitude

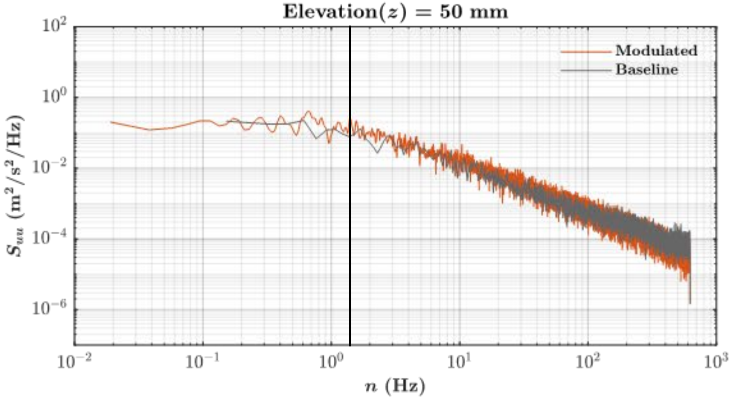


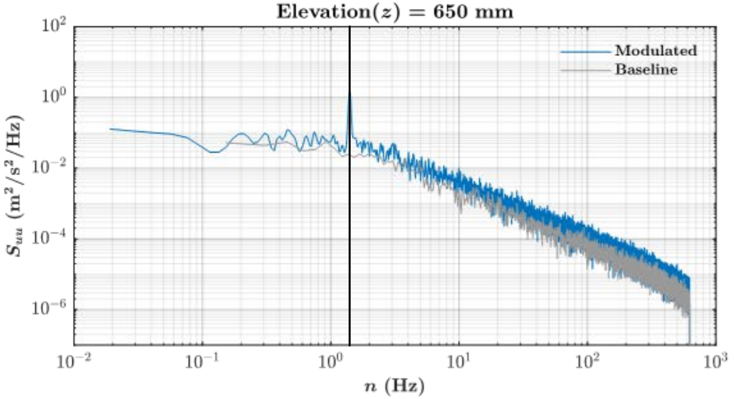




2.0 Hz Sine Wave (Random Phase) – High Amplitude







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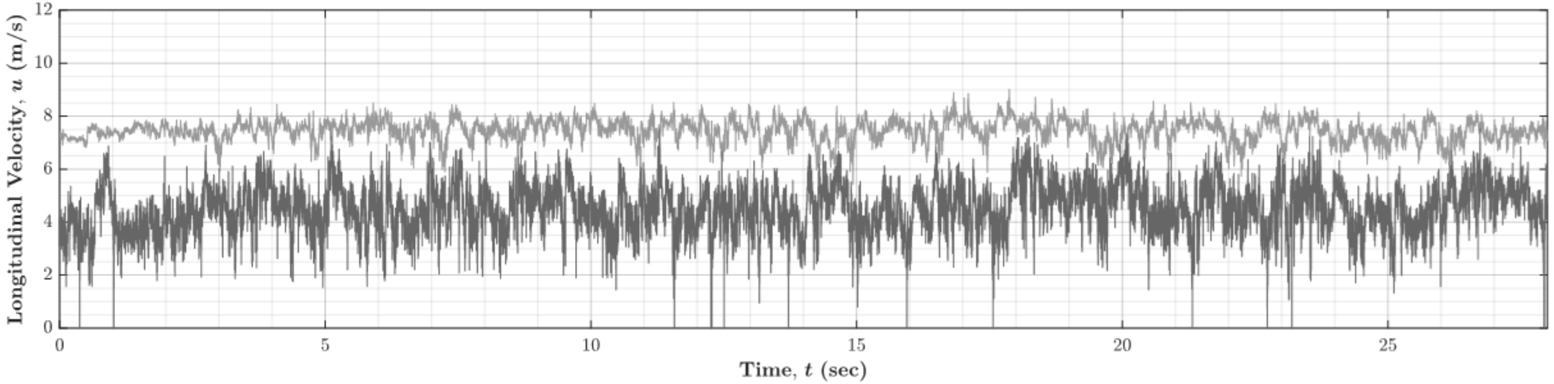
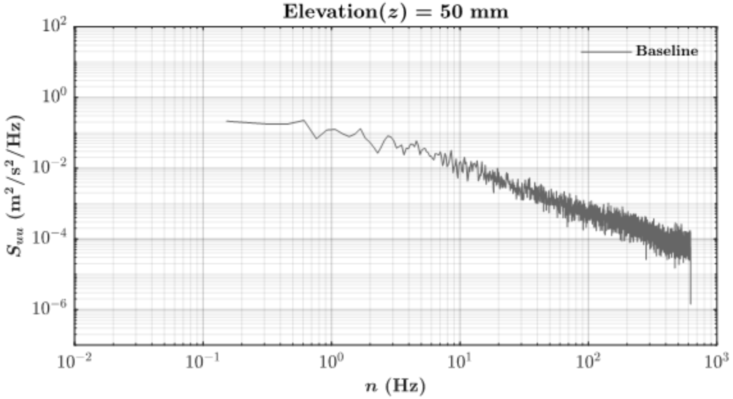
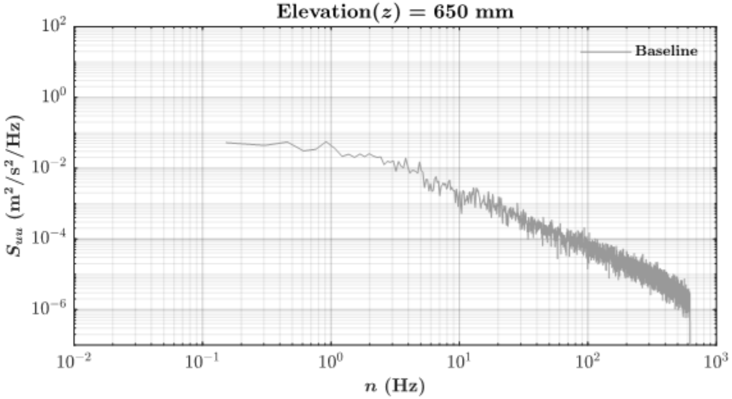
Band-Limited Gaussian White Noise

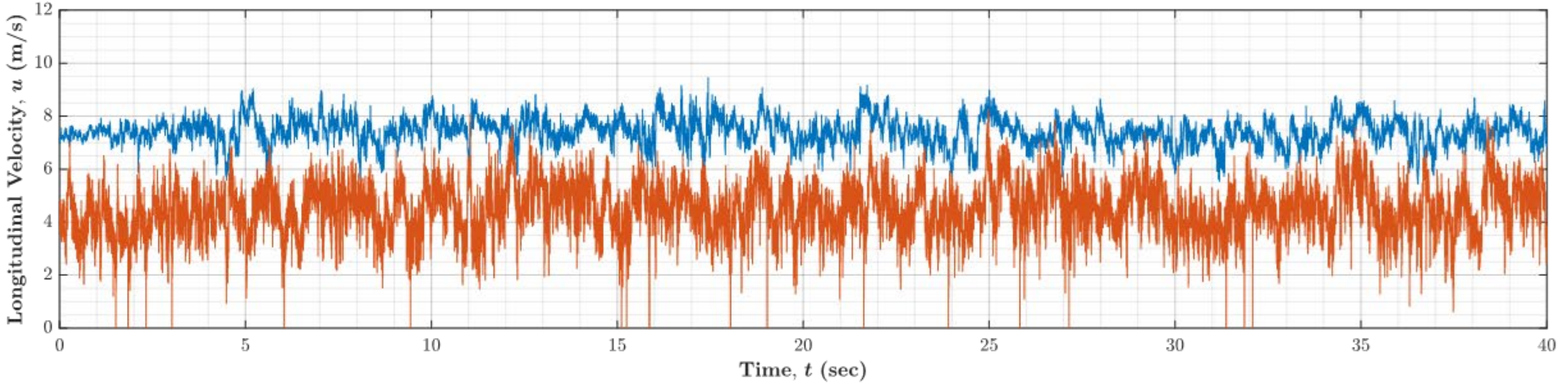
Baseline - Constant FFM Velocity Output

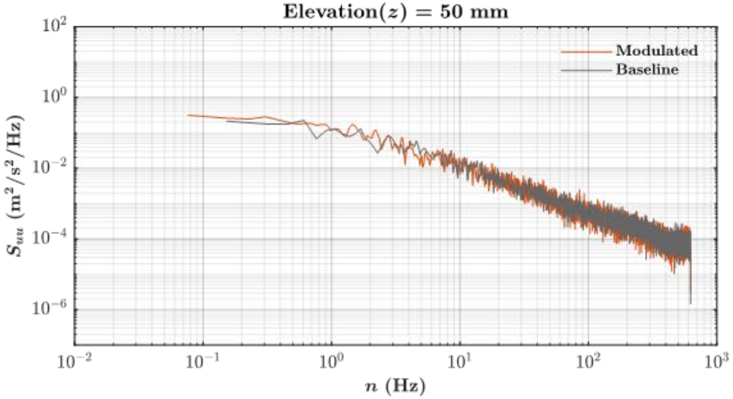


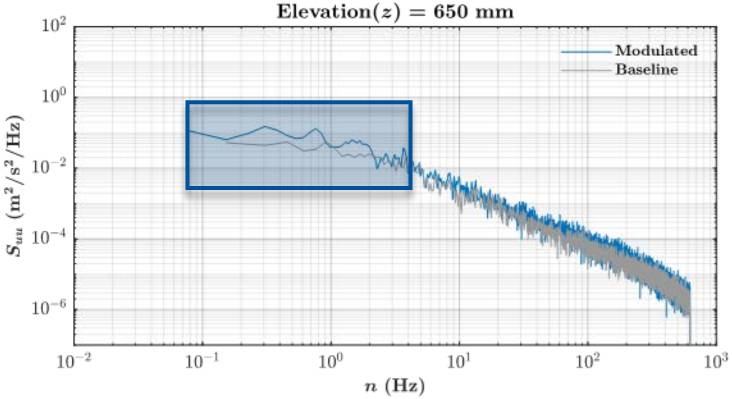




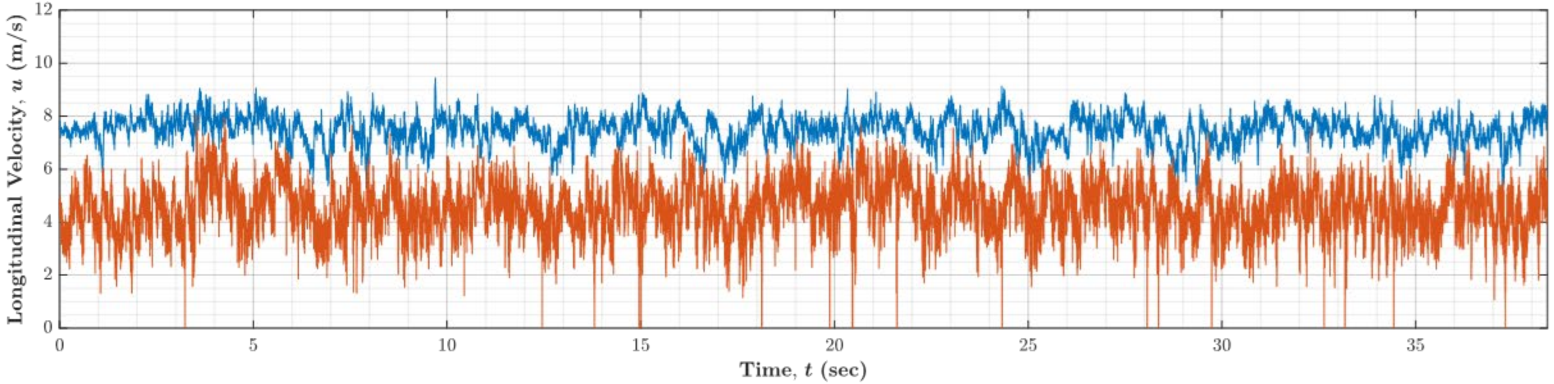
Gaussian White Noise – 1 Hz Cutoff

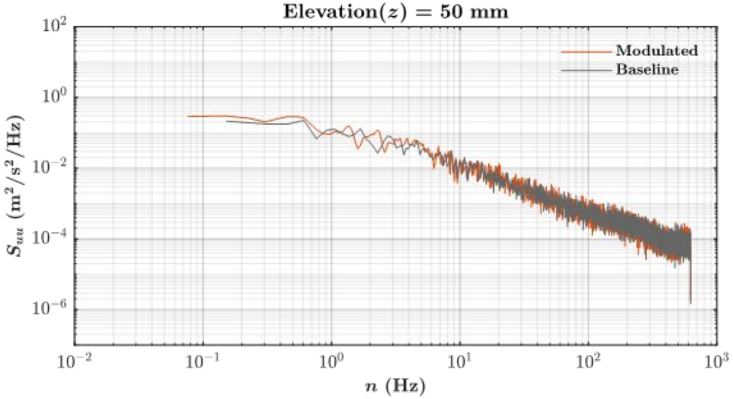


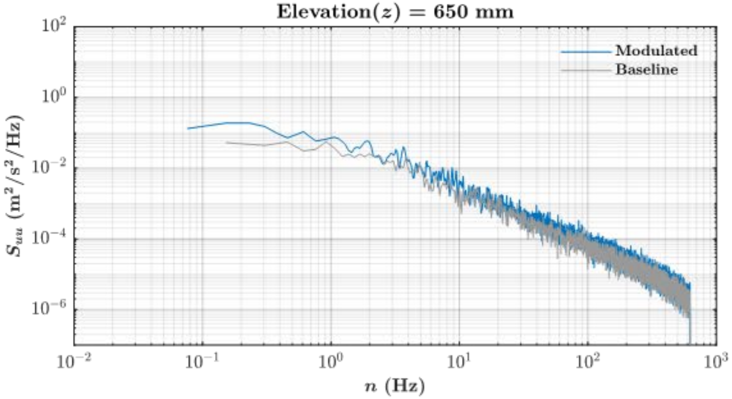




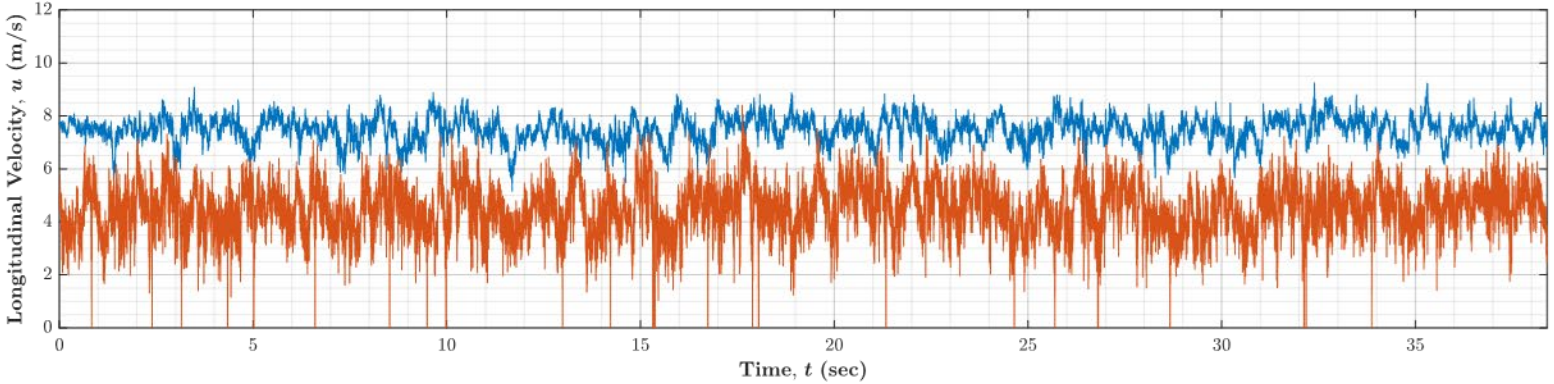
Gaussian White Noise – 2 Hz Cutoff

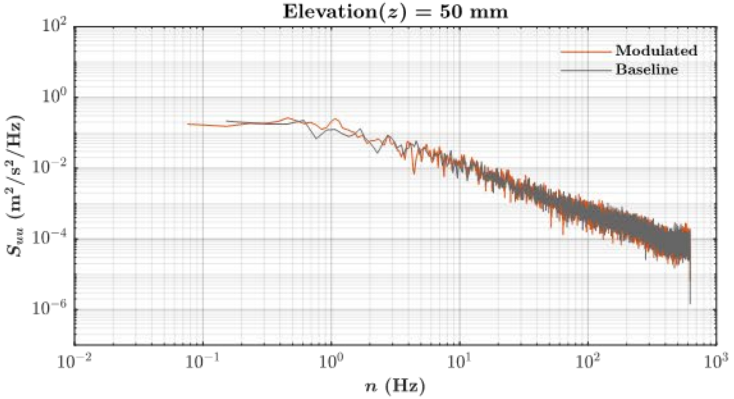


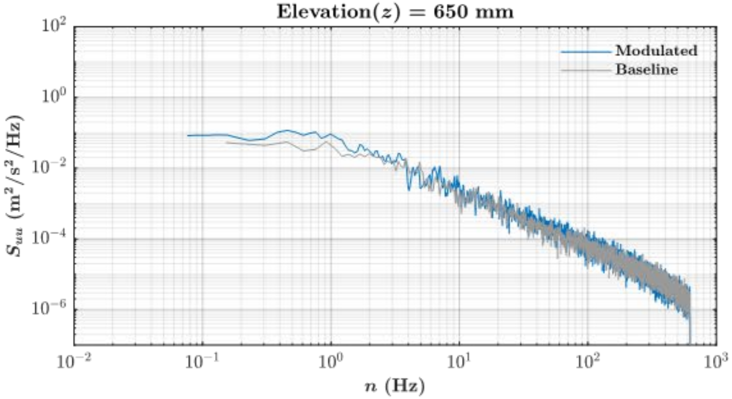




Gaussian White Noise – 3 Hz Cutoff







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Next Step: Combine Flow Transition with Turbulence Modulation

FFM Status Updates

- Open-loop control system is complete and operational
- Closed-loop control work ongoing (completion expected 3-4 months)
- Increasing available power (from 4 to 6 power modules)
- Initiating list of available data sets for potential target profiles
- Conducting feasibility of implementing an upwind test section (1-5 m downwind of FFM)
- Investigating 12 velocity probe rake for time-correlated full-depth profiles

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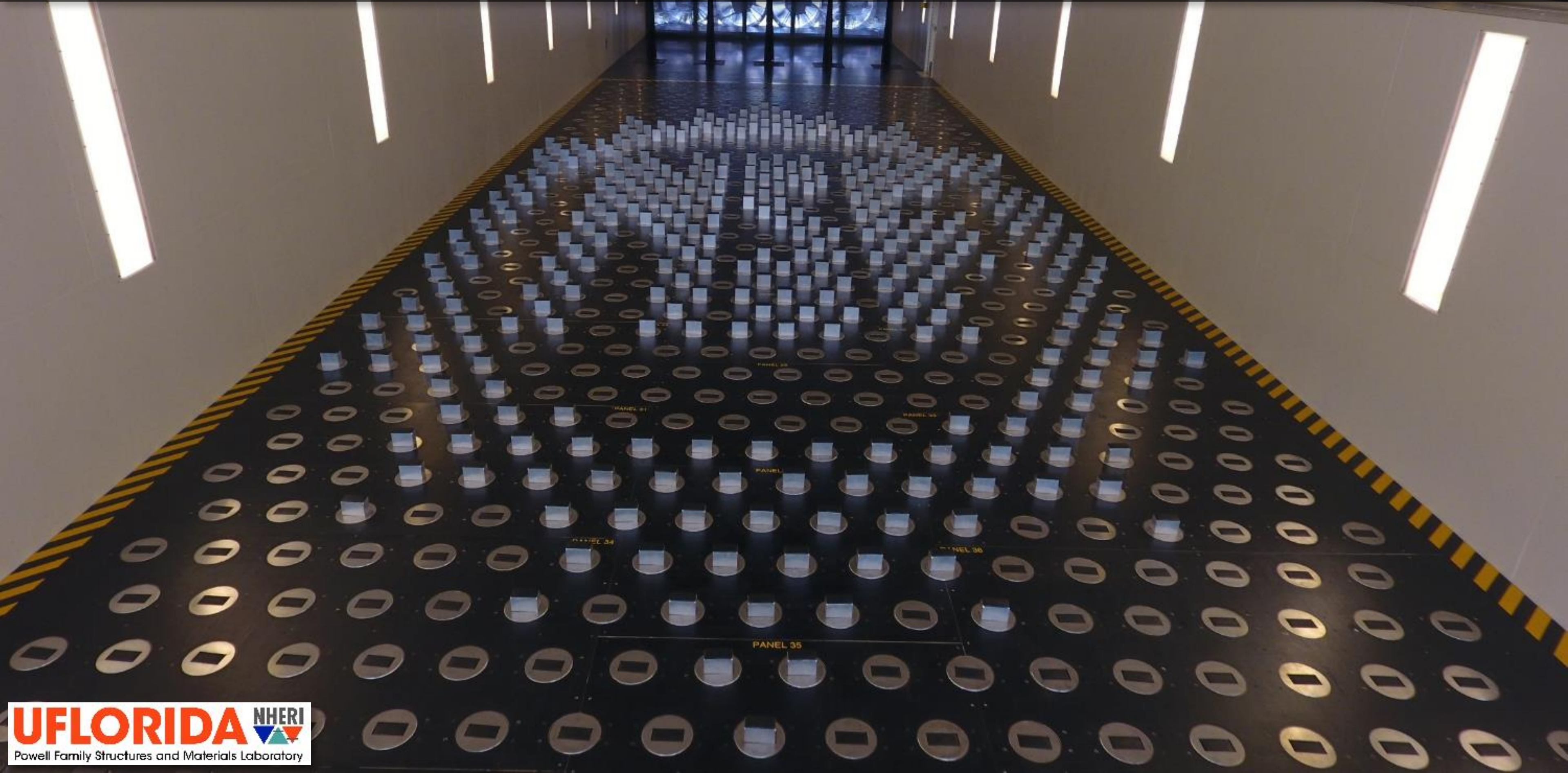
Takeaways

- We presented the current state of what we know we can accomplish
- We are working on better defining the capabilities/limits of the system
- We've made significant progress toward developing a unique capability for the wind engineering community
- There is a huge space in transient and non-synoptic simulation research that is waiting for users to step into our lab
- A series of domain experts will elaborate this afternoon
- Let us help you facilitate your ideas

Discussion



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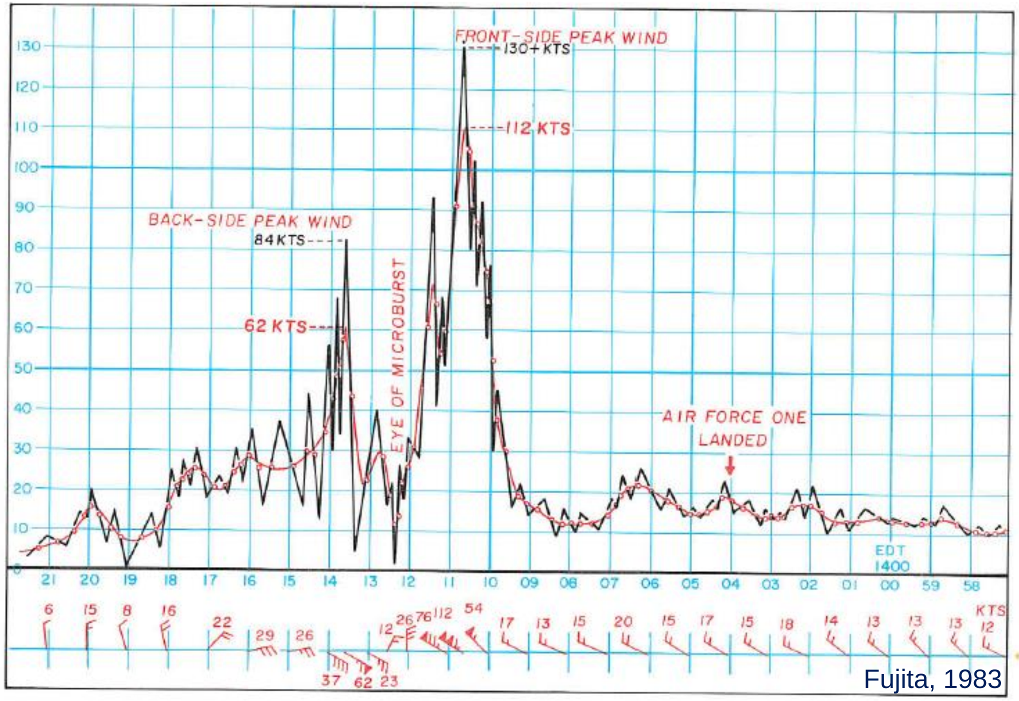
The Need for New and Revised Targets for Transient Winds



Franklin T. Lombardo
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

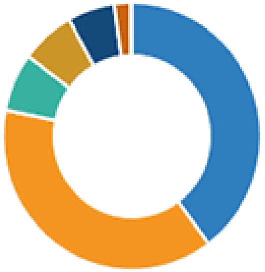
UF BLWT Transient and Non-Synoptic Workshop
May 19, 2021

WIND ENGINEERING RESEARCH LABORATORY
University of Illinois at Urbana - Champaign

INTRODUCTION

- A significant proportion of windstorm damage is driven by **transient** and/or **non-synoptic** events

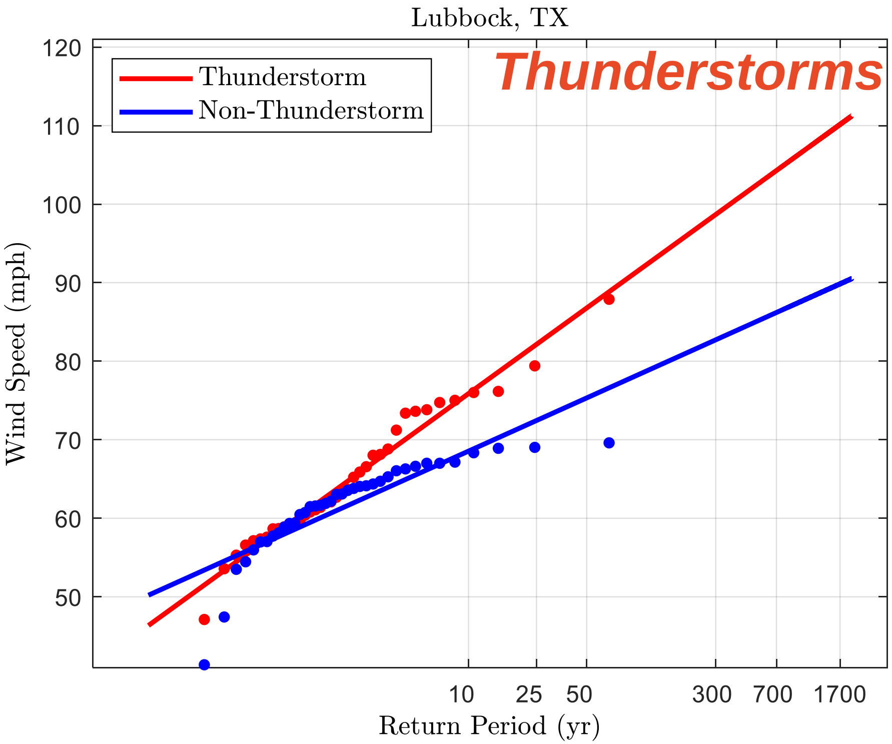
Inflation-Adjusted U.S. Insured Catastrophe Losses By Cause Of Loss, 1997-2016
(2016 $ billions)



Events including tornadoes (2)	$168.1	39.9%
Hurricanes and tropical storms	161.1	38.2
Other wind/hail/flood	29.7	7.1
Winter storms	28.2	6.7
Terrorism	25.0	5.9
Fires (3)	8.4	2.0
Other (4)	0.8	0.2
Total	**$421.2**	**100.0%**

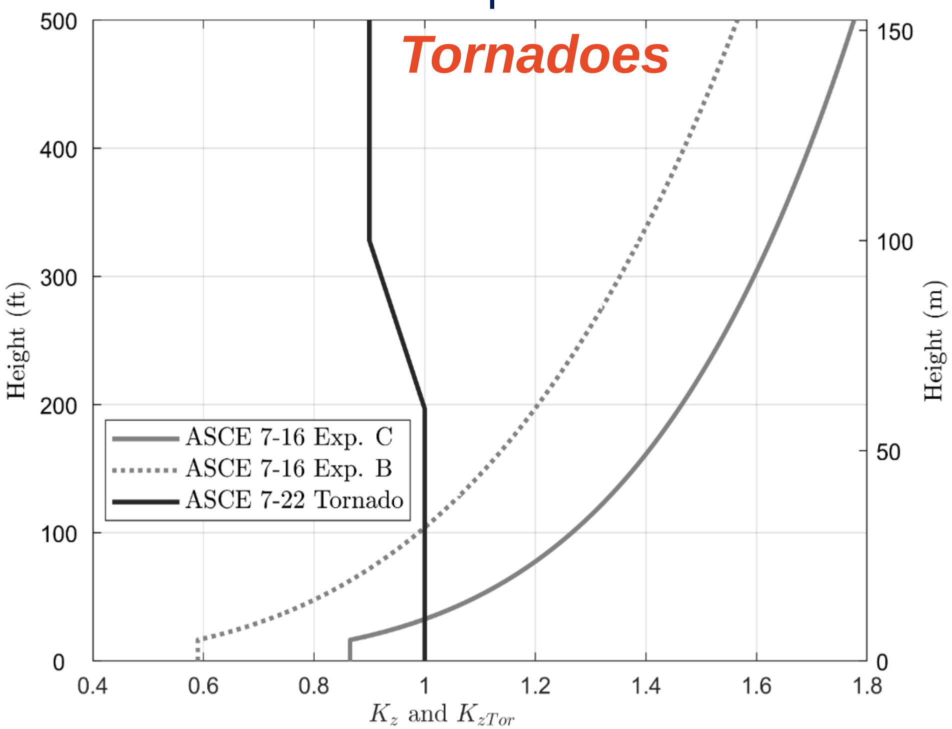
Source: The Property Claim Services® (PCS®) unit of ISO®, a Verisk Analytics® company.

ENGINEERING IMPORTANCE



- Event of interest at low probability of occurrence for many U.S. locations
- What does 700-yr. event look like (105-110 mph)?

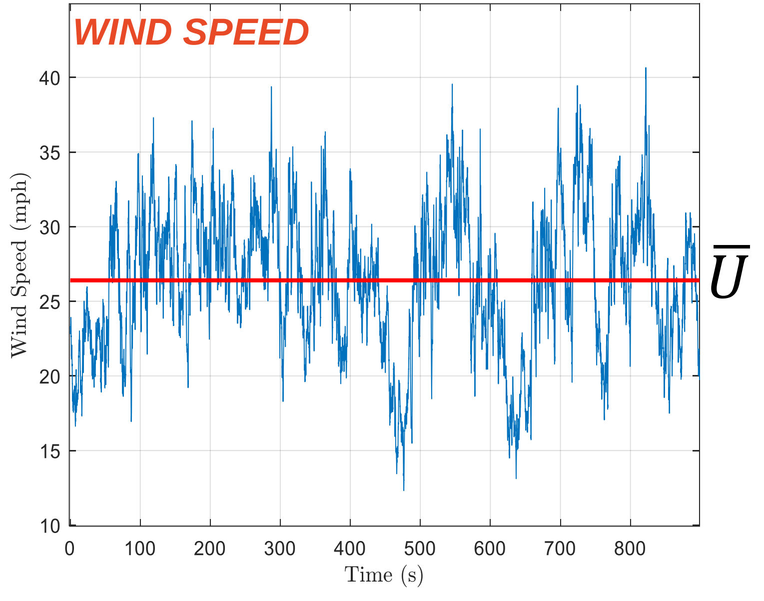
- ASCE 7-22 will incorporate tornado design
- Characteristics clearly different

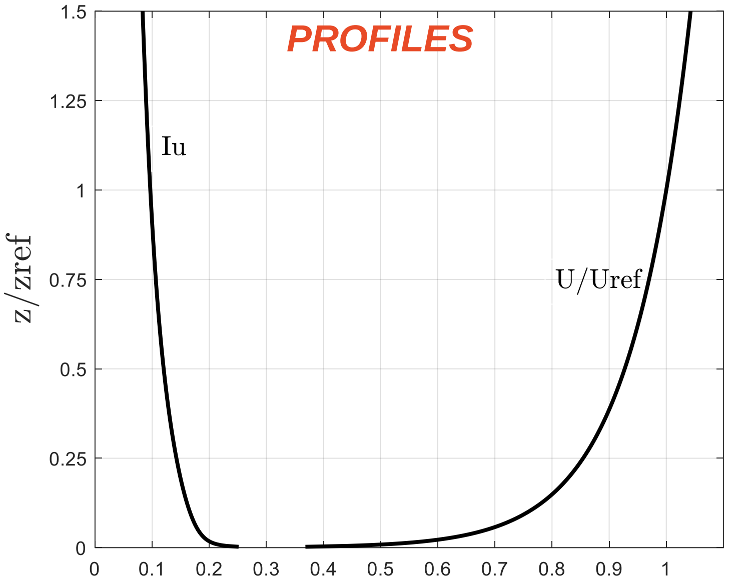


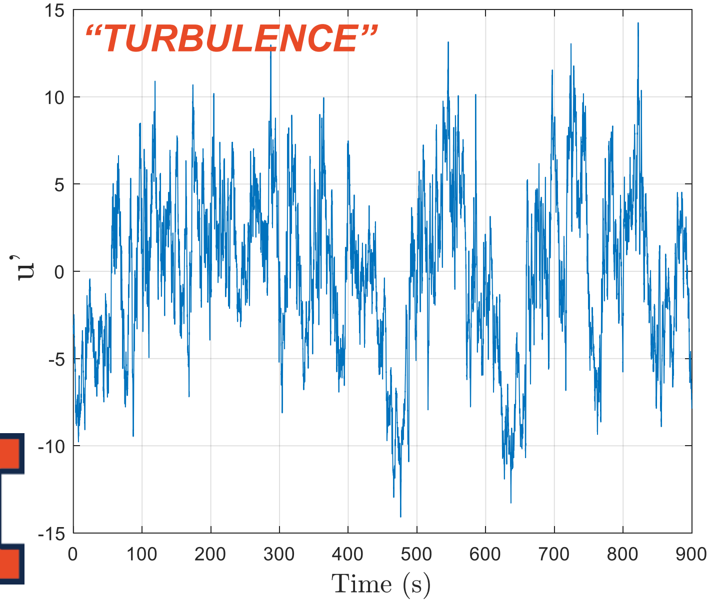
NEED TO SIMULATE CHARACTERISTICS

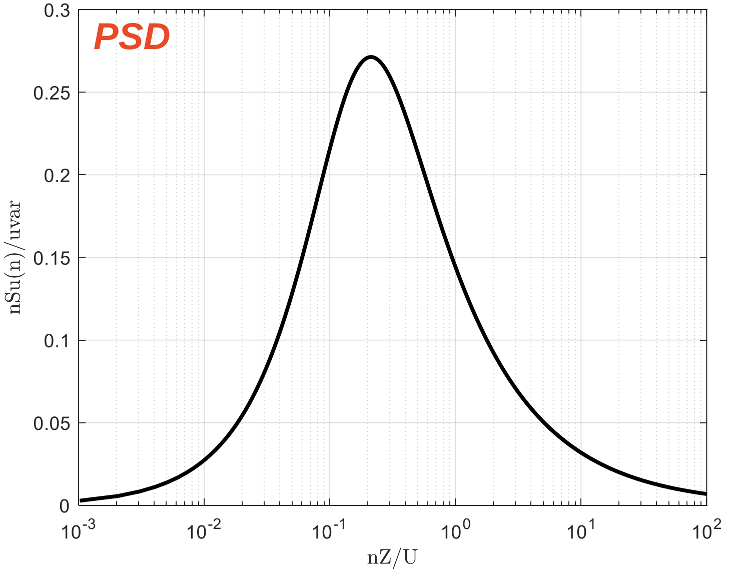
“TARGETS” – ABL

- Atmospheric boundary layer (ABL)



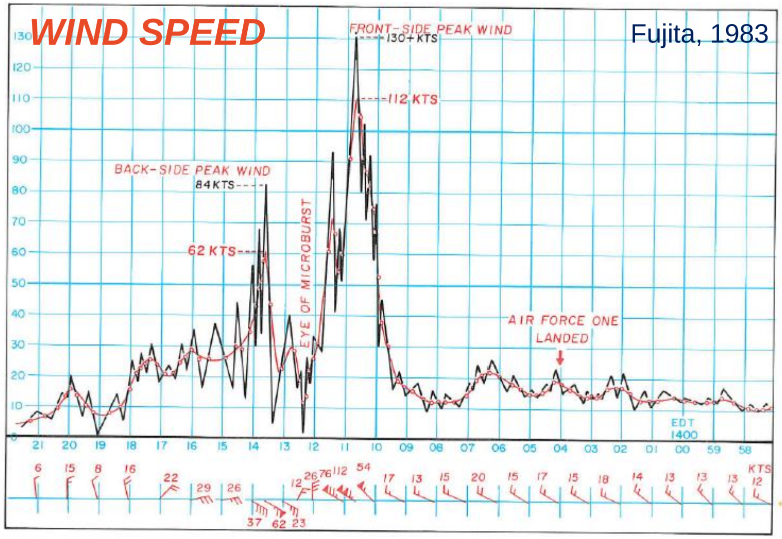






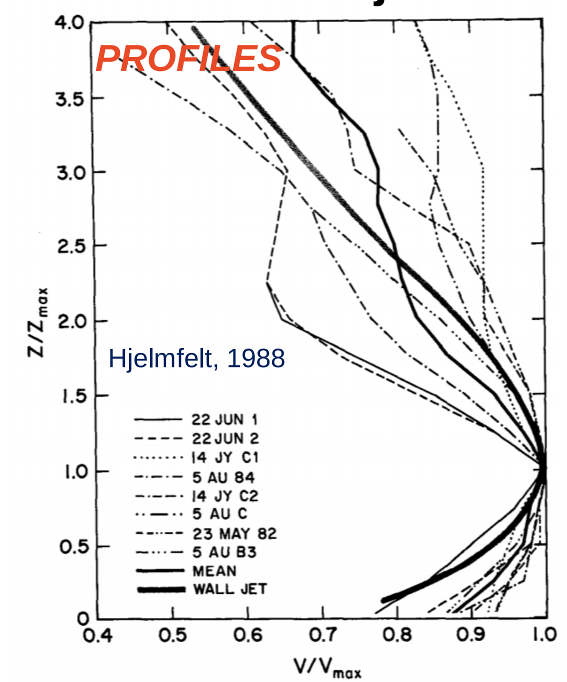
“TARGETS” – TRANSIENT

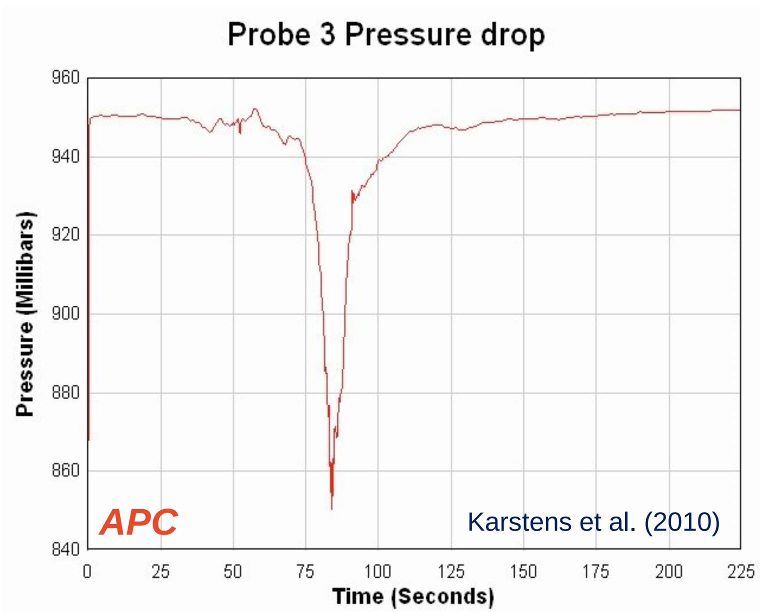
- No ‘standard’ targets – couple prevalent targets used widely



AAFB Event

JAWS Project

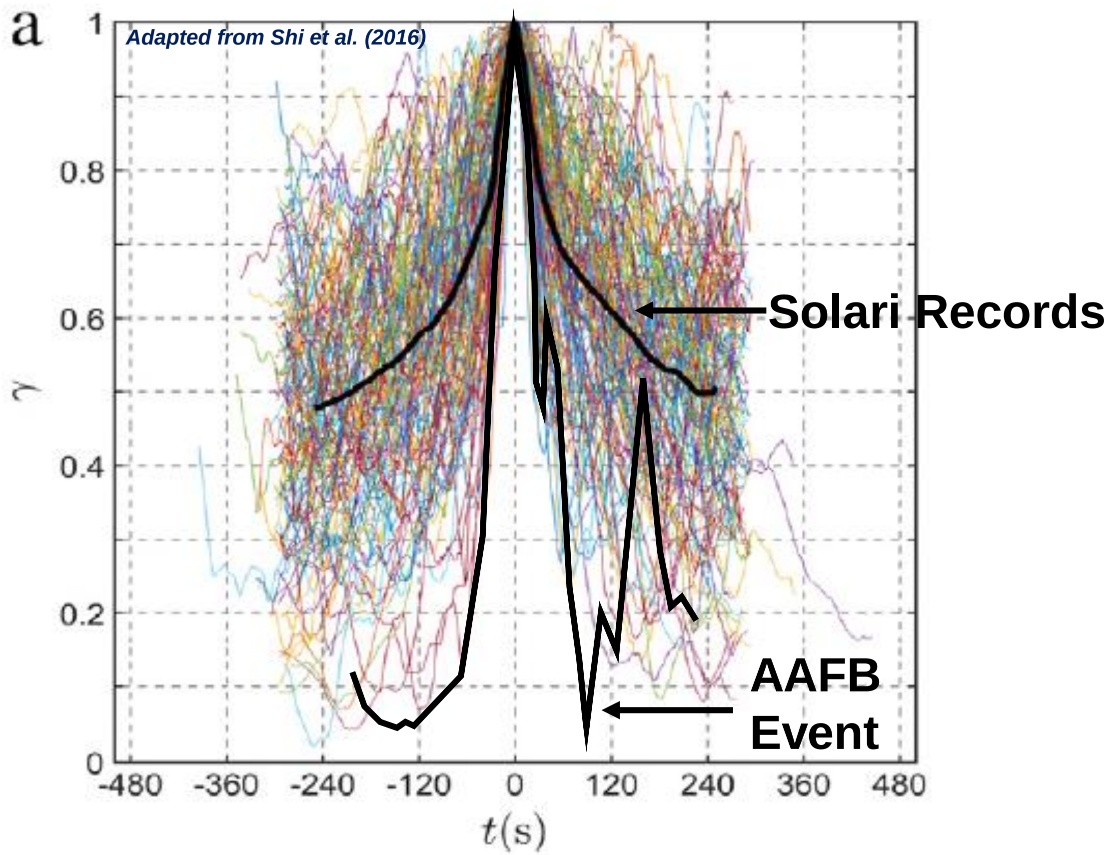




Manchester, SD Tornado

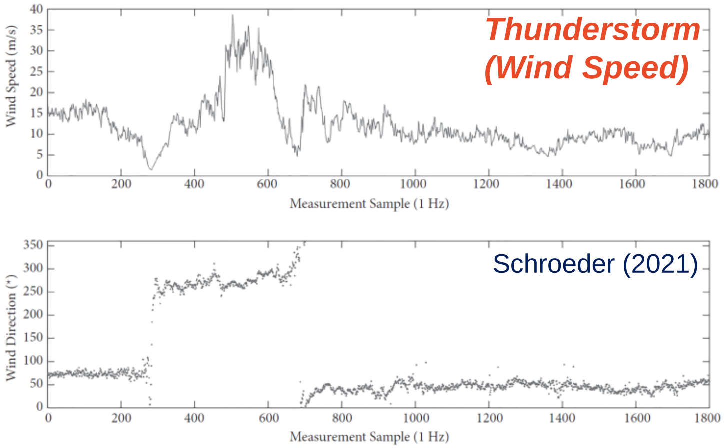
AAFB EVENT

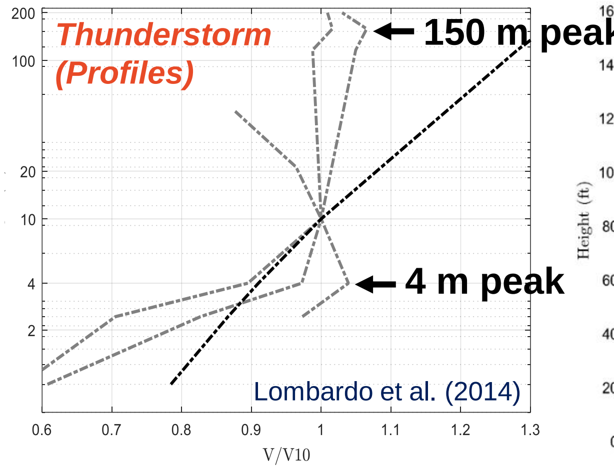
- The record is notable in the following ways:
  - “149+ mph” peak wind speed – nothing even close to that in records
  - Character of time history (see figure below)
  - Engineering models based on a digitized record of a single (cup) anemometer record (separated from atmospheric pressure)

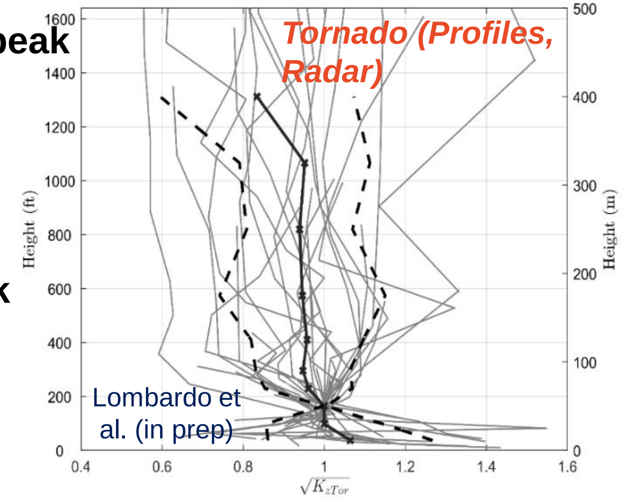


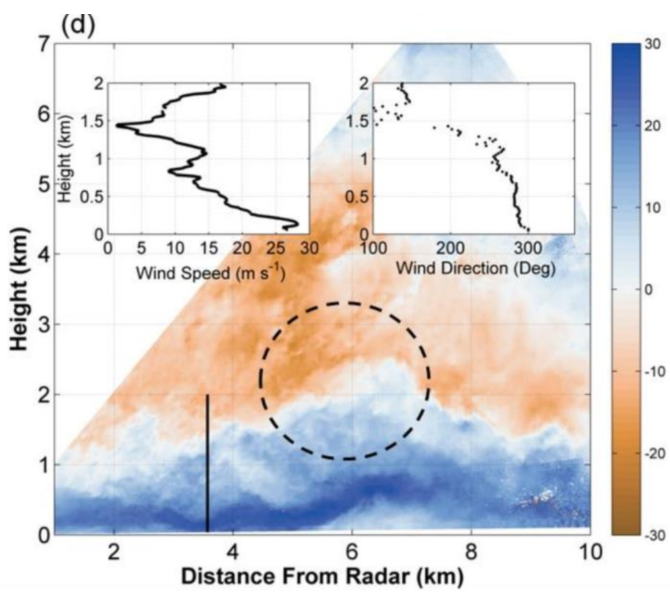
ENGINEERING-CENTRIC RESEARCH/ANALYSIS

- Has shed considerable insight – however variability is large









Gunter and Schroeder (2015)

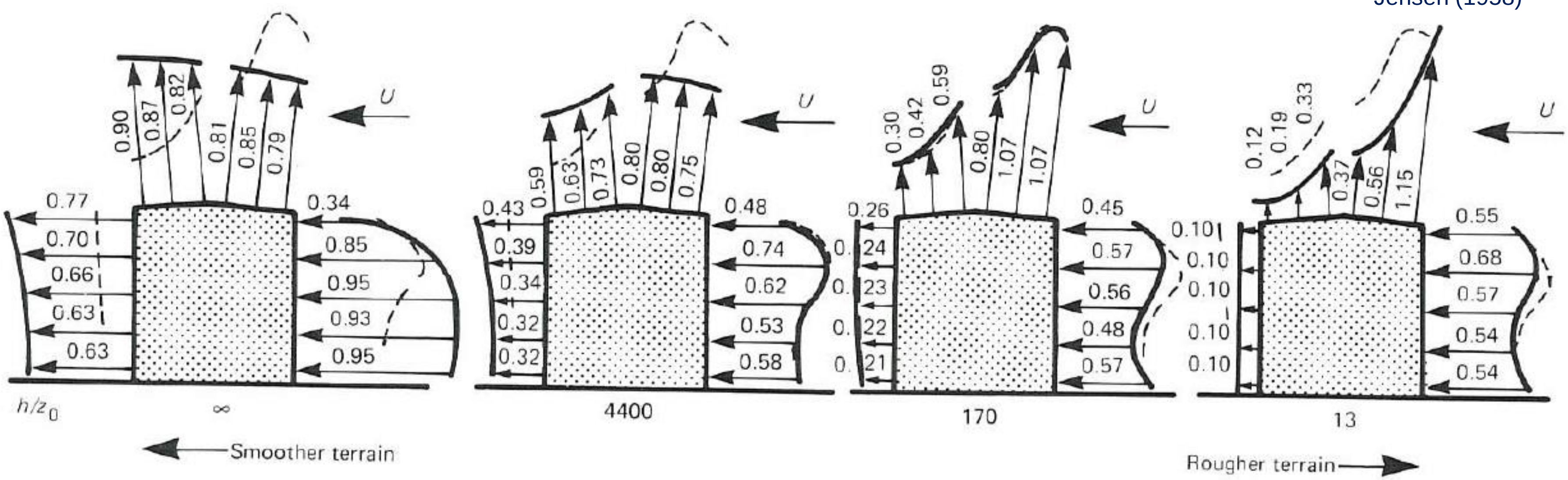
- We do not have an ABL analog (we need targets) – see Haan presentation
- Have a path forward (we need more data)

IMPORTANT PARAMETERS TO CONSIDER

- Transient ‘gusts’ or other phenomena lead to transient aerodynamics and peak loading (e.g., Kareem and Wu, 2013)
- What parameters contribute to peak loading and are *endemic* to transient events and what are their relative contributions?
- We can learn some from ABL (which has transients)
- Parameters can be implemented into frameworks (e.g., Kareem/Kwon – GFF)

PROFILES

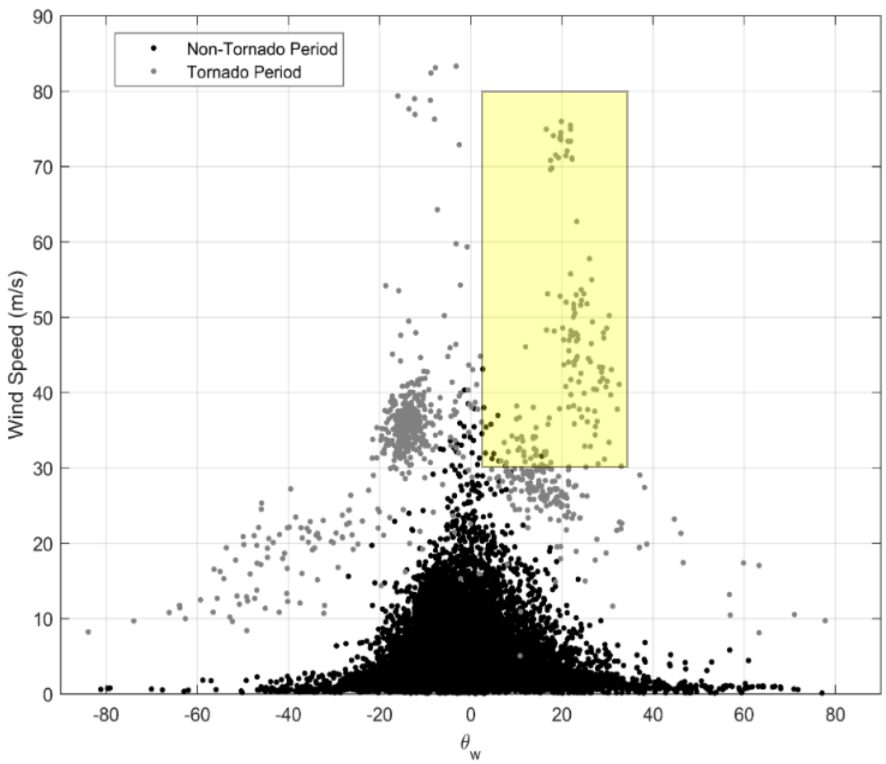
Jensen (1958)

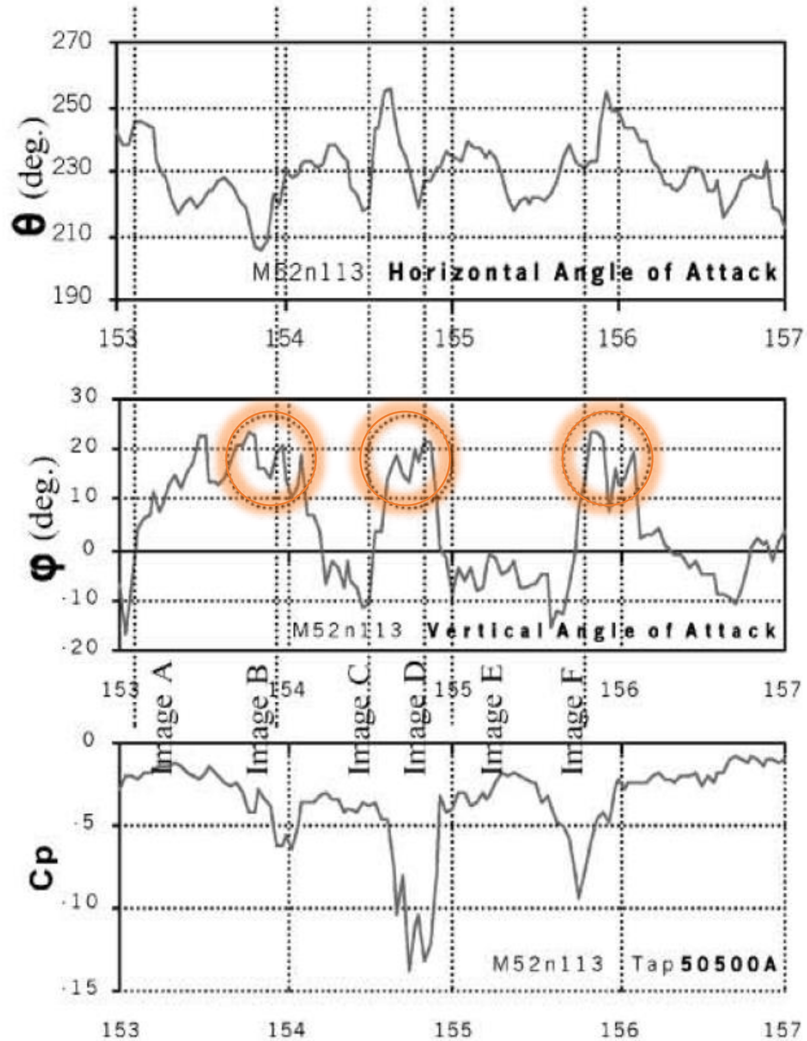


Uniform Profile ***Sheared Profile***

IMPORTANT PARAMETERS TO CONSIDER

VERTICAL WIND COMPONENT (ANGLE OF ATTACK)

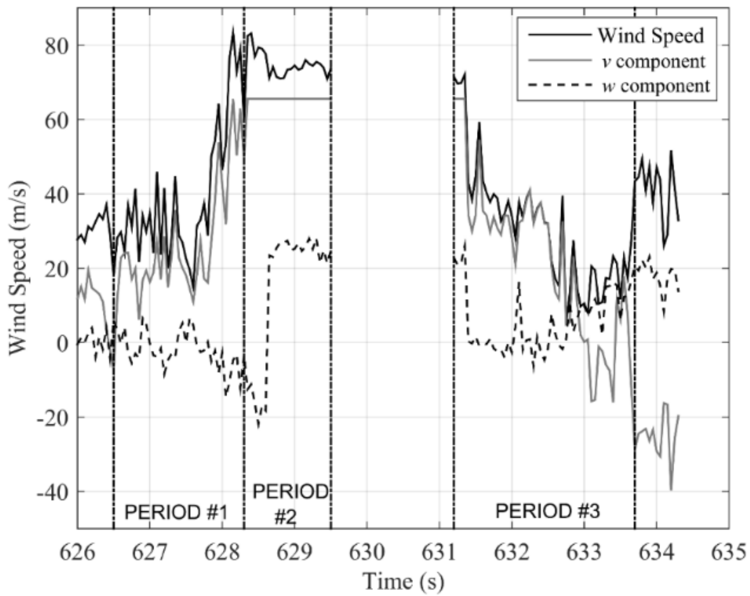




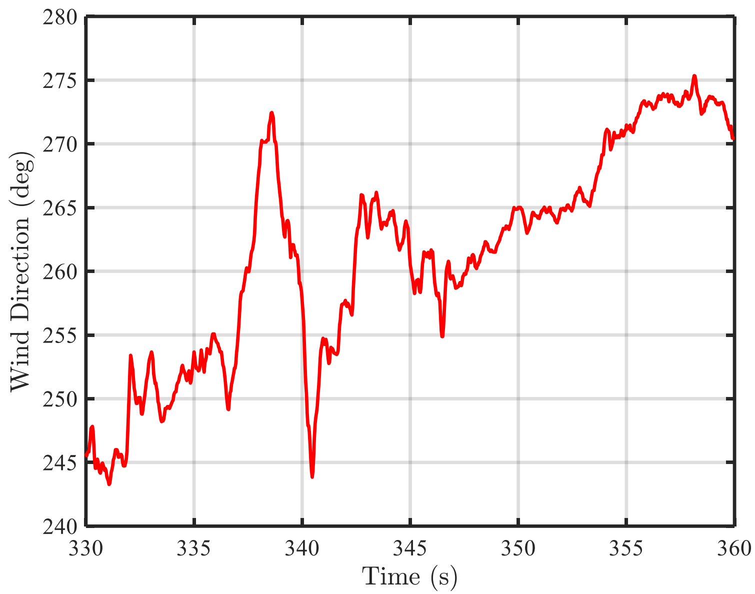
Wu (2001)

IMPORTANT PARAMETERS TO CONSIDER

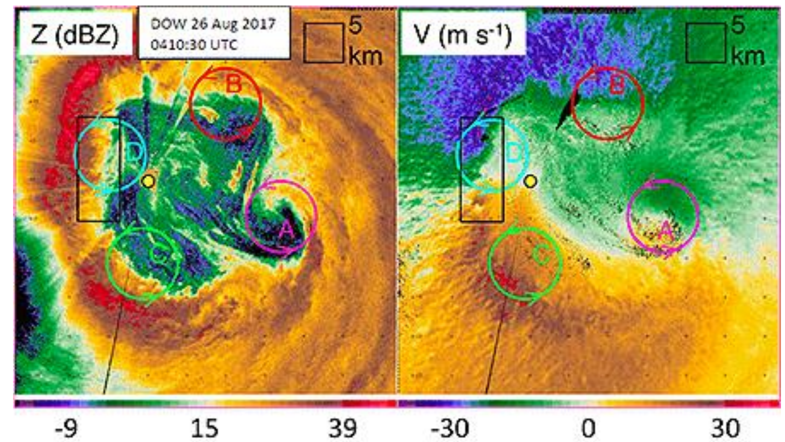
FLOW ACCELERATIONS



DIRECTIONAL CHANGES



MESOVORTICES



Physical Phenomena (Examples)
Tornadoes
Wake Flows
Mesovortices
Ring Vortices (e.g., downburst)
Parameters (Examples)
Flow accelerations
Sweeps/ejections
Thermal stratification/convective effects
Non-log profiles
Vertical components
Internal/Atmospheric pressures
Directional changes
Terrain/topography
Shielding/interference

GOING FORWARD

Consensus that there is a **lack of information/data** on thunderstorms – we need:

- A more 'realistic' experimental setup (e.g., interaction with the suburban environment) – reimagining of older experiments (e.g., JAWS, NIMROD) with an **engineering focus**
- 4-d characteristics incl. turbulence with high resolution in space and time, thermodynamics, stability, spectral content, longitudinal/lateral variability and coherence
- Building loading data in close proximity to wind data

GOING FORWARD

To acquire valuable data we need **collaboration**:

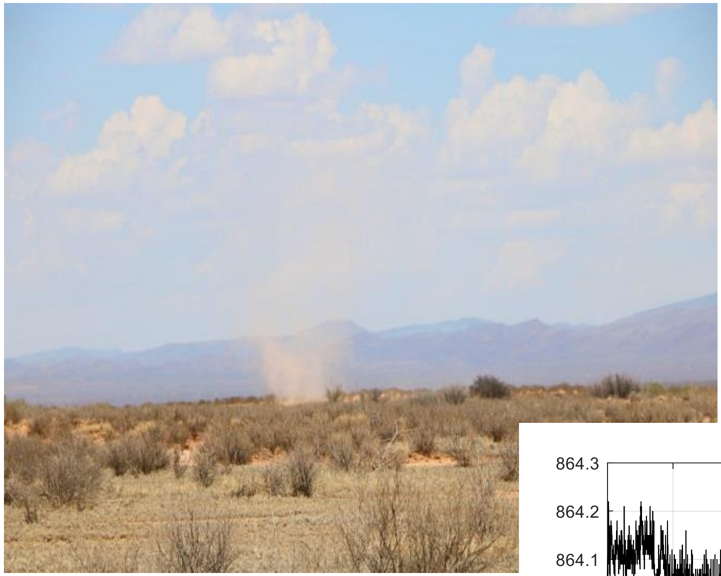
- Coordinated deployment strategies
- Potential Issues to work through:

  1) Different interests/objectives among groups

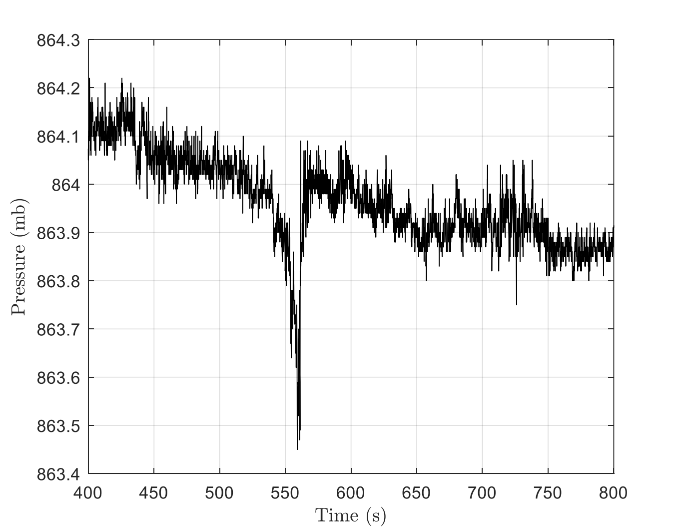
  2) Scale mismatches (temporal and spatial)
- **All information collected is essential** but there must be coordination to link upper-level measurements to surface characteristics, for example, a combination of LiDAR, radar, and surface measurements. (see Schroeder)
- Also link with the following :
  - 1) modeling efforts in WRF, LES – and perhaps using models to inform deployment locations
  - 2) post-storm event analysis (e.g., tree-fall, structural damage)

GOING FORWARD

- Isolate and identify transients in the flow



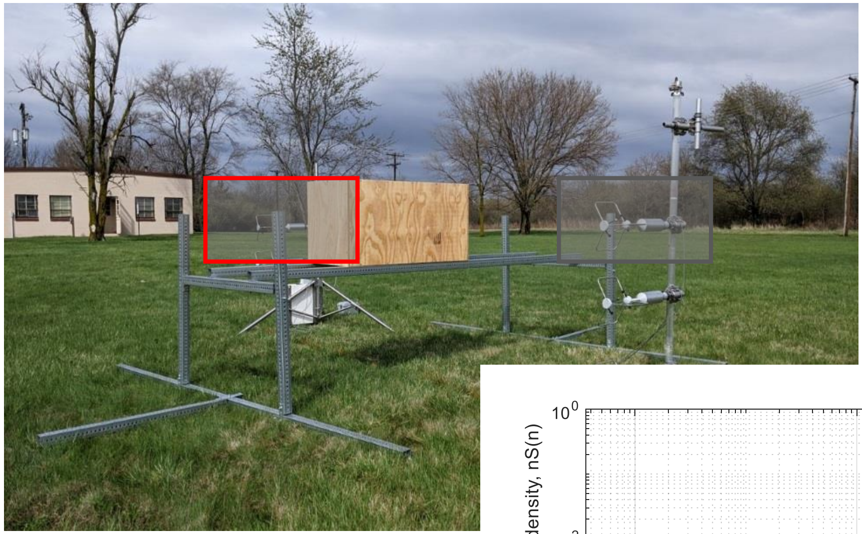
- Scouting trip (May 6-7) – La Jornada Experimental Range, NM
- Visually observed ~100 dustdevils
- One directly impacted small line of BP sensors



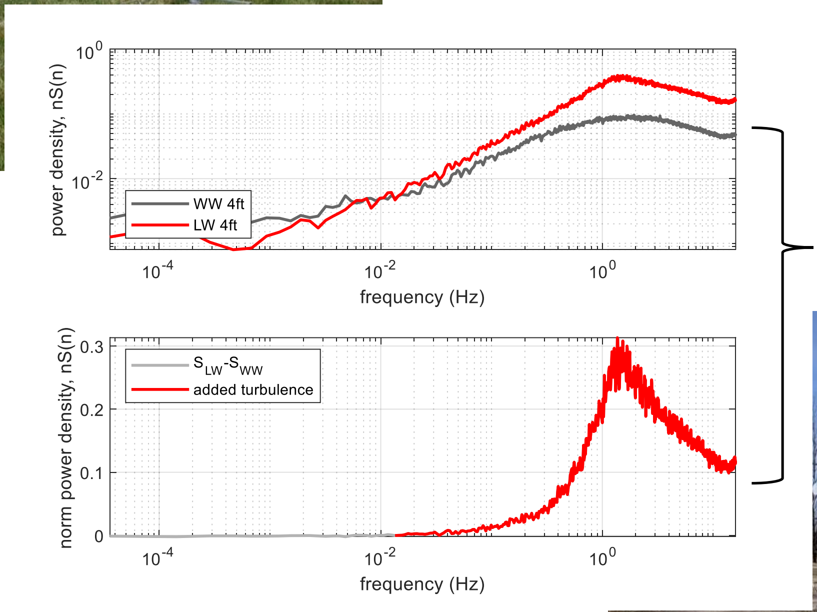
Zaldivar de Alba et al. (2021)

GOING FORWARD

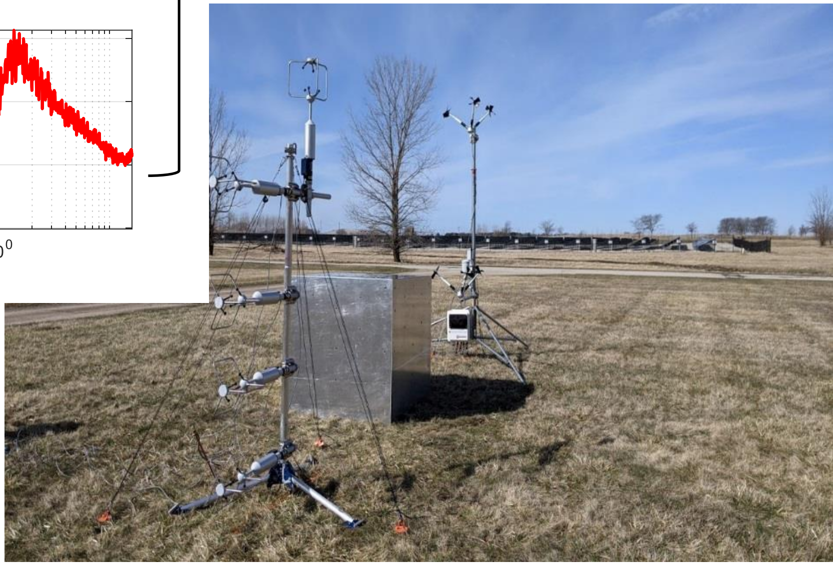
- Isolate and identify transients in the flow



- Turbulence generator
- Modify intensity, scale and frequency of freestream turbulence



Vertical Turbulence (4 ft)



THANK YOU!

QUESTIONS?

National Wind Institute

Measuring Engineering-Relevant Characteristics of Non-Stationary Wind (NSW) Events

Boundary Layer Wind Tunnel Simulation of Transient and Non-synoptic Wind Events Workshop

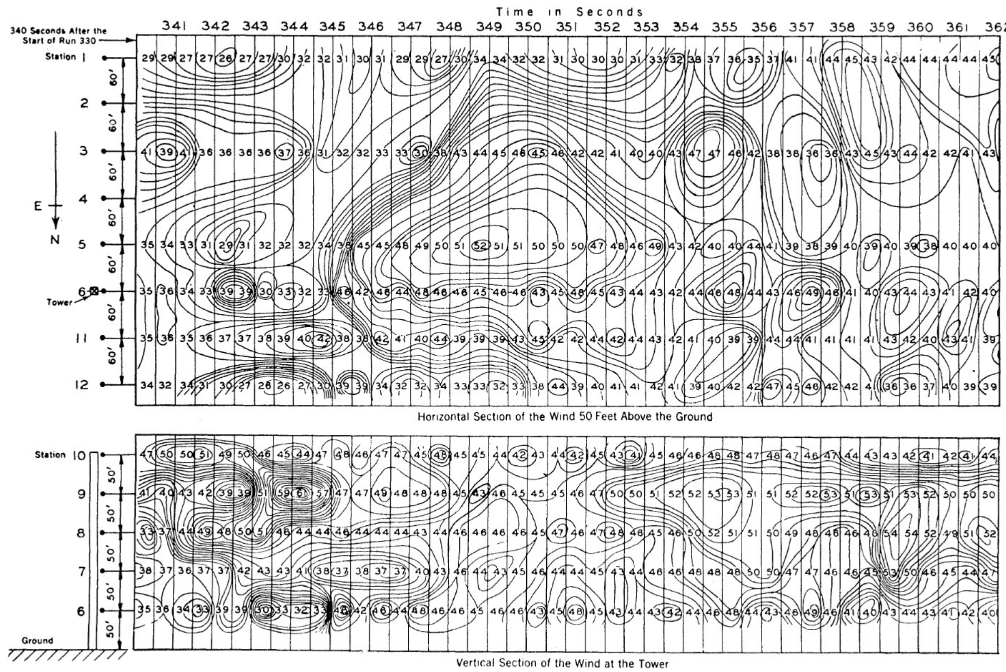
Dr. John Schroeder
Senior Director, National Wind Institute
Professor of Atmospheric Science

National Wind Institute

The NSW Challenge

- **GOAL: Obtain relevant four-dimensional NSW events at sufficient spatial and temporal scales to assist engineers**
  - Spatial resolutions of tens of meters
  - Temporal resolutions on the order of a few seconds

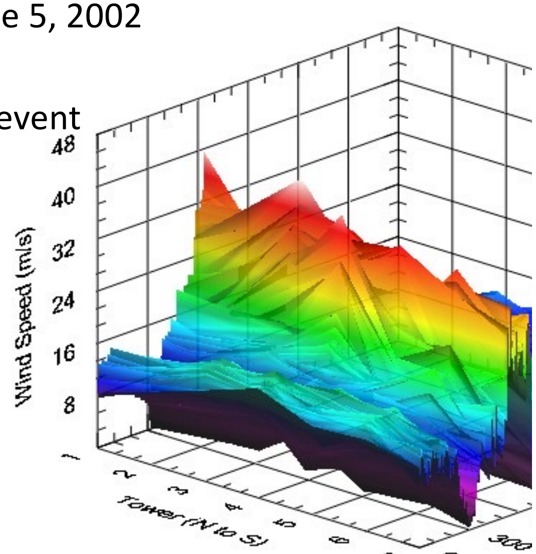
- **NSW events are:**
  - Quick-hitting
  - Spatially localized
  - Often embedded in larger-scale wind systems that include other hazards (hail, flooding, lightning, broader scale wind)
  - Highly variable

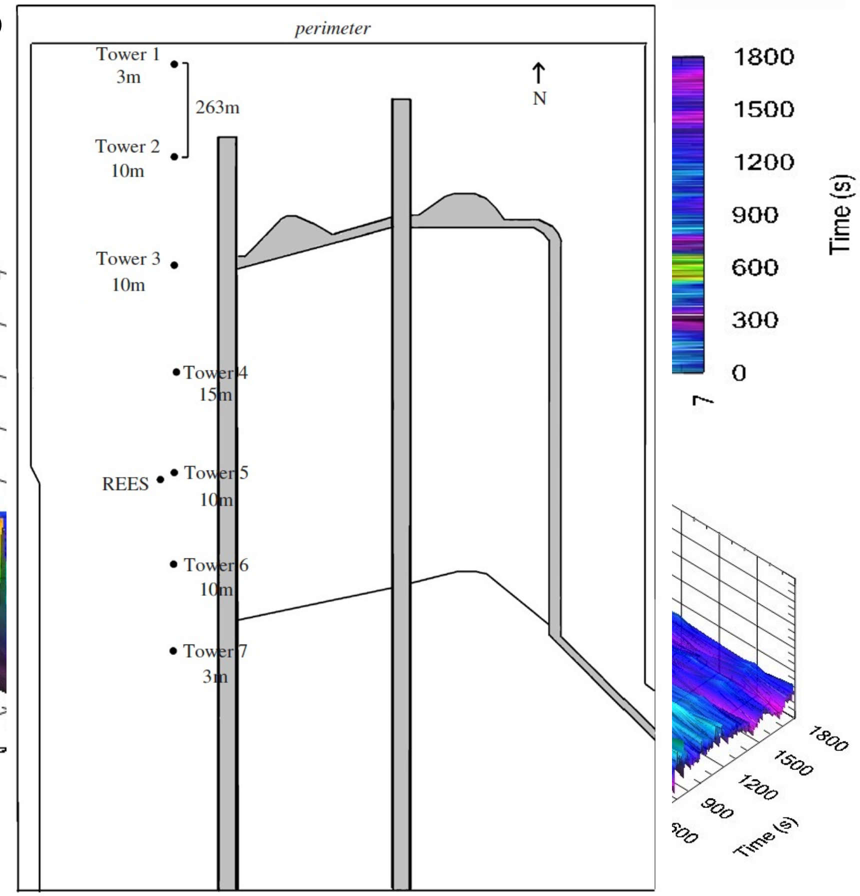


(Sherlock and Stout, 1937)

Tower-Based Measurements

- **NSW Target:**
  - Lubbock supercell rear flank downdraft (RFD) at Reese Technology Center; June 5, 2002
- **Record/Event Duration:**
  - 30-minute record / 5-minute event
- **Tower Array:**
  - 7 - 10m+ towers
  - 263 m spacing
  - 1 Hz sampling
- **Classic time histories**
- **Near design-level event**
- **Event served as an example for multiple numerical and laboratory experiments**



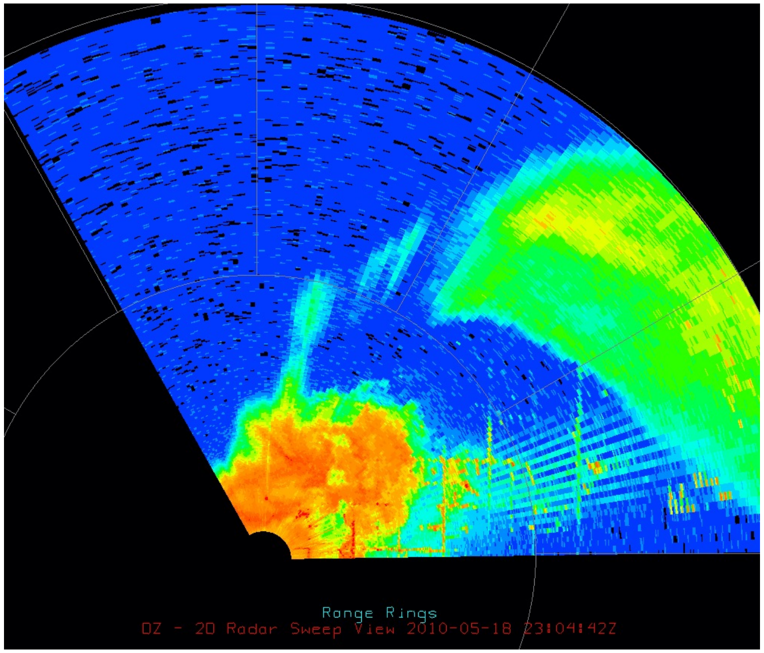


(Orwig and Schroeder, 2007)

Dual-Doppler PPI-Based Studies

National Wind Institute

- **NSW Target:**
  - Dumas, Texas supercell RFD during VORTEX2; May 18, 2010
- **Record Duration:**
  - 6-minutes
- **Radars:**
  - TTUKa radars with 0.49° beamwidth
  - Baseline of 3.3 km
- **"Snap shots" of the low level wind field every minute**
- **Near design-level event**
- **Localized nature of the embedded pulses**



(Skinner et al., 2014)

Dual-Doppler PPI-Based Studies

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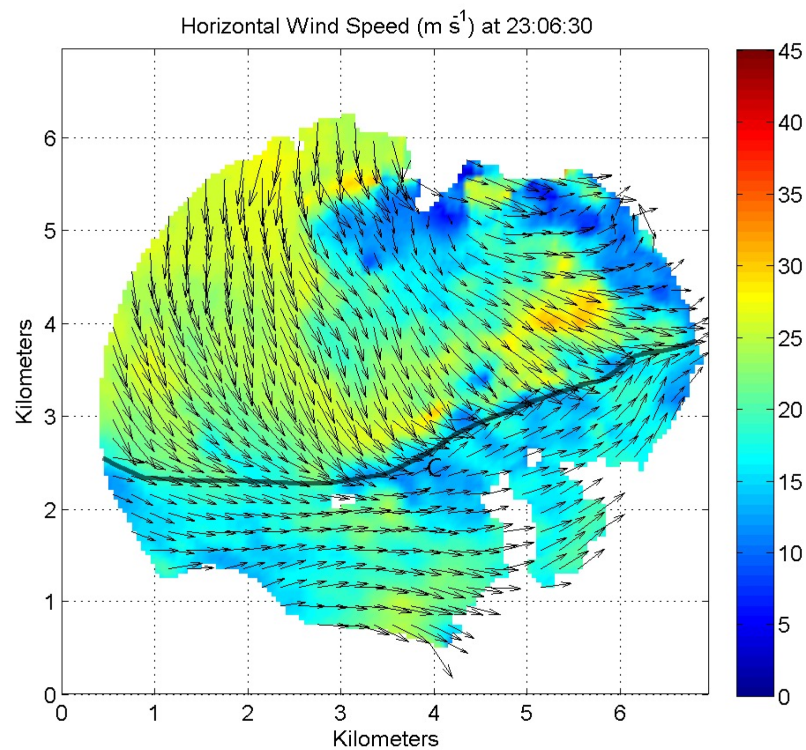
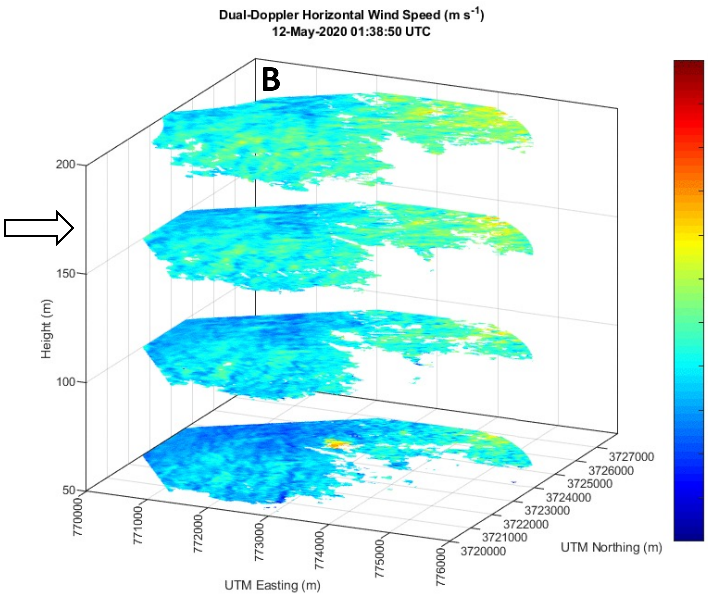


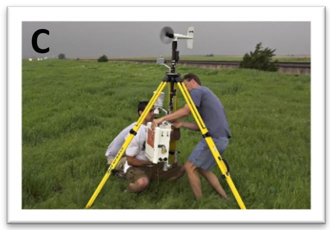
(Skinner et al., 2014)

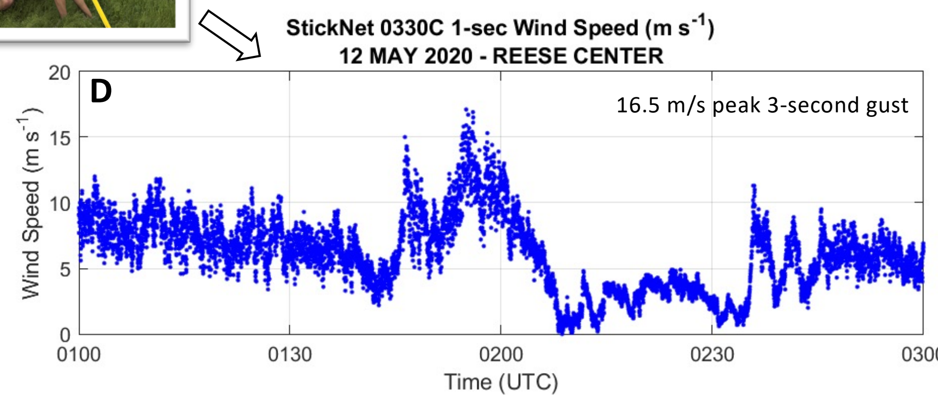
National Wind Institute

Measurement Paradigms

- **Differing Perspectives**
  - Tower based measurements
    - High resolution temporal information
    - Typically from a single location; sometimes deployed in an array
  - Scanning remote sensing based measurements
    - Scanning based technologies (e.g. lidar or radar) offer radial velocity scans
    - Range and resolution varies by instrument
    - Dual-doppler synthesis can yield an estimate of the wind field
- **Bridging these different measurement paradigms offers a path forward**

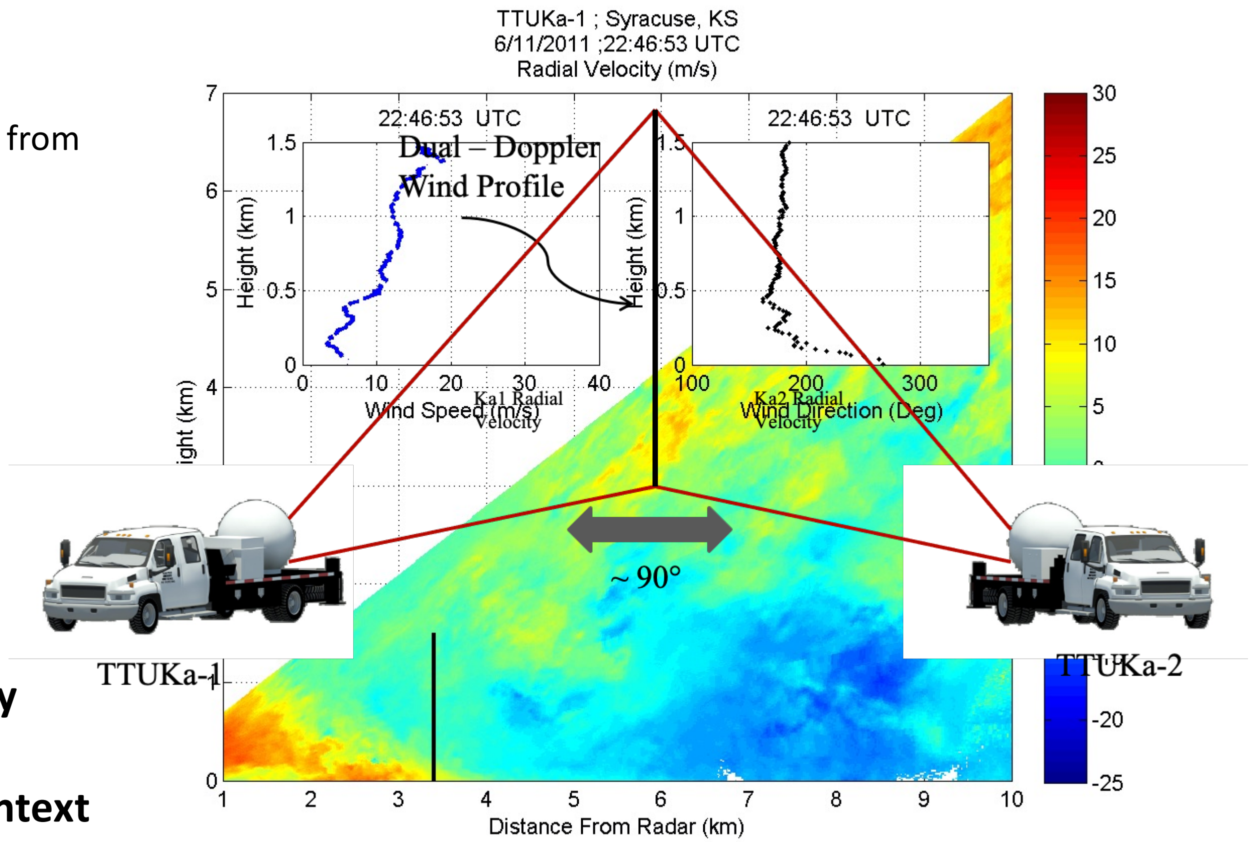






Dual-Doppler RHI-Based Studies

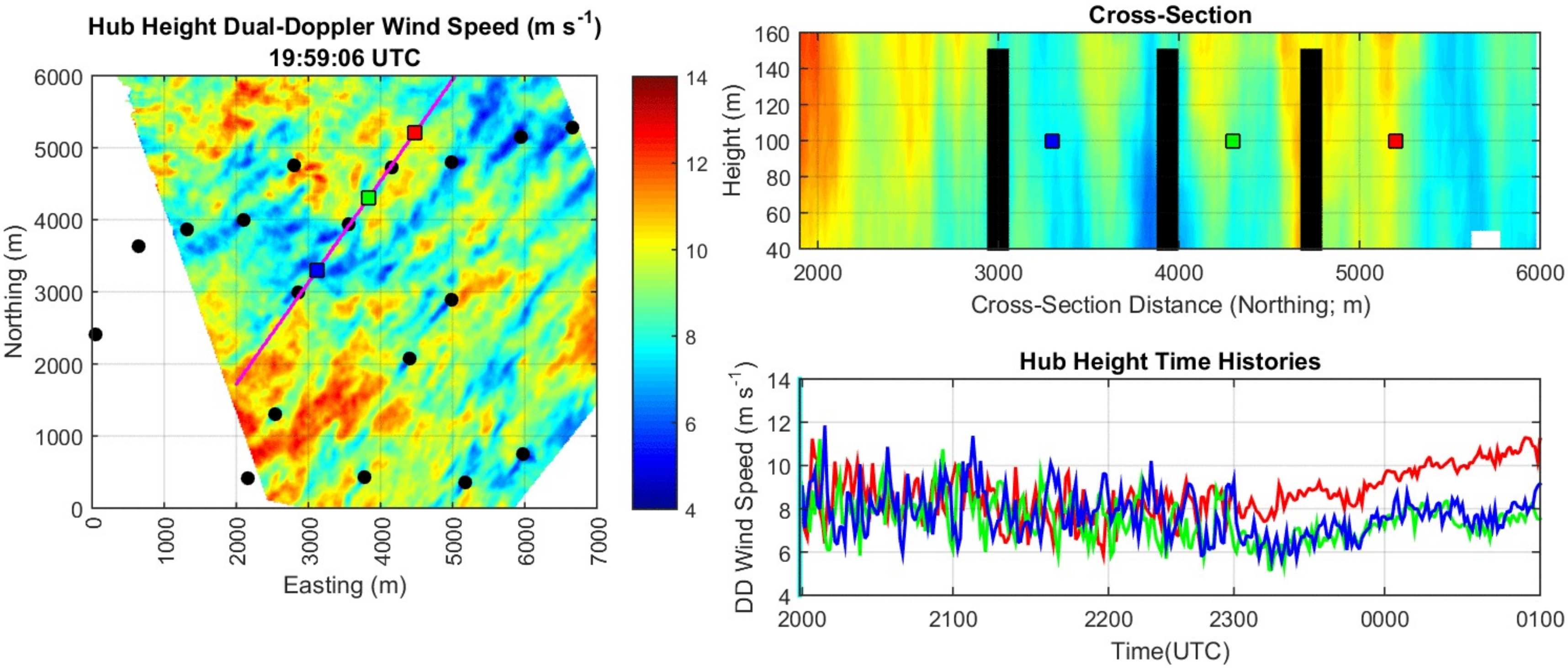
- **NSW Target:**
  - Syracuse, Kansas TSTM outflow event from MCS in Project SCOUT; June 11, 2011
- **Record Duration:**
  - 13-minutes
- **Radars:**
  - TTUKa radars with 0.49° beamwidth
- **Deployment:**
  - 3.6 km to intersection point
  - 109° crossing angle
- **Wind speed profiles updated every few seconds**
- **Interlaced with PPIs to provide context**



(Gunter and Schroeder, 2015)

National Wind Institute

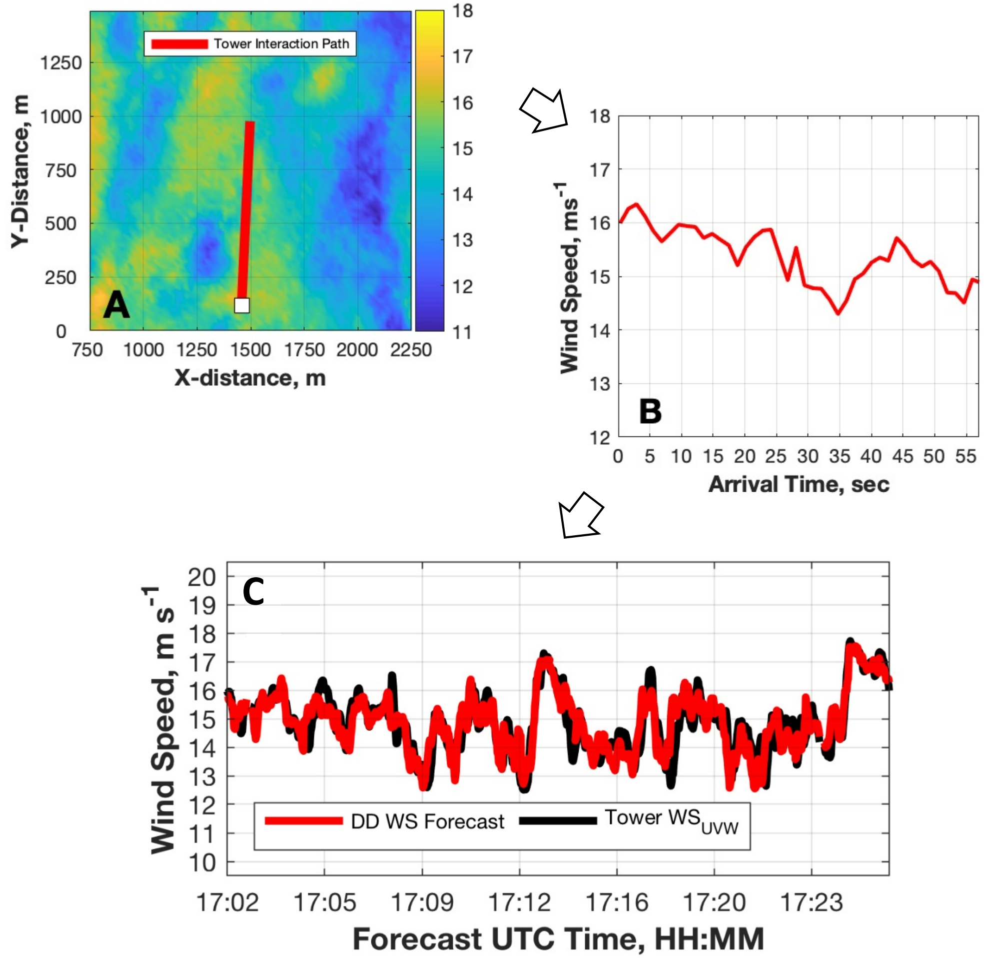
Inspiration from Wind Energy Research



Extracting Engineering-Relevant Wind Structure

National Wind Institute

- Employs 2-D correlation methodologies of dual-Doppler synthesized data to extract sub-volume information
- Results in a high-resolution time history at an identified point, which can then be validated

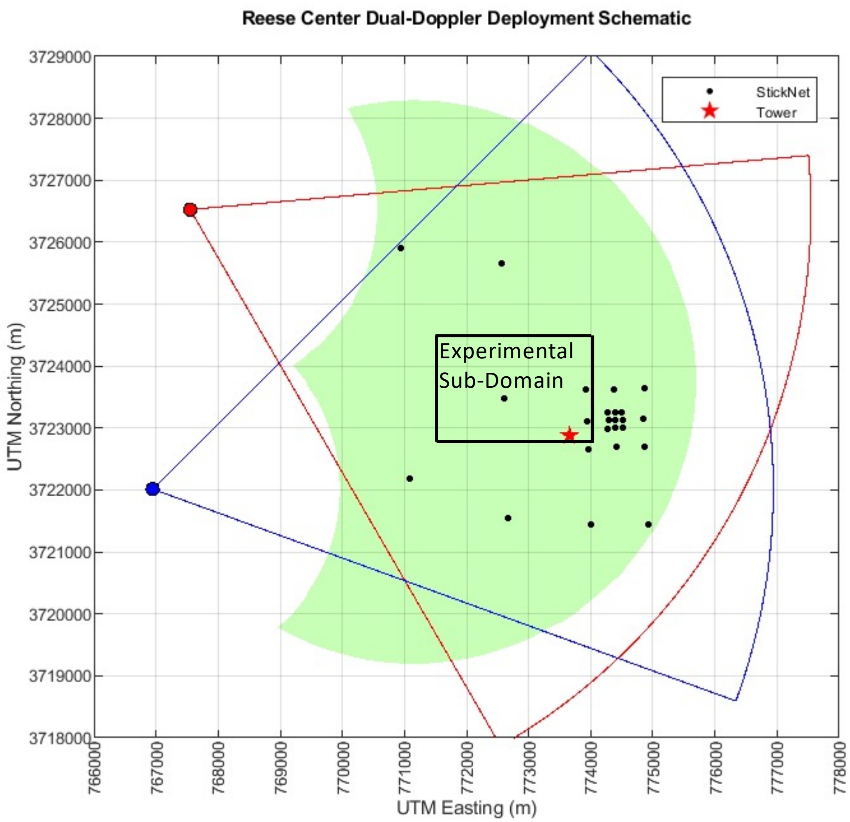


(Duncan Jr. et al., 2019)

Extracting Engineering-Relevant Wind Structure

- **Event Target:**
  - Reese Technology Center (RTC) Test Case
  - Clear air / moderate wind; 7 May 2019
  - Consistent wind direction ~155-160°
- **Record Duration:**
  - 19:10:45 – 21:39:47 UTC (149-minutes)

- **Radars:**
  - TTUKa radars with 0.33° beamwidth
  - Radar volumes every ~64 seconds
  - Baseline of 4.5 km

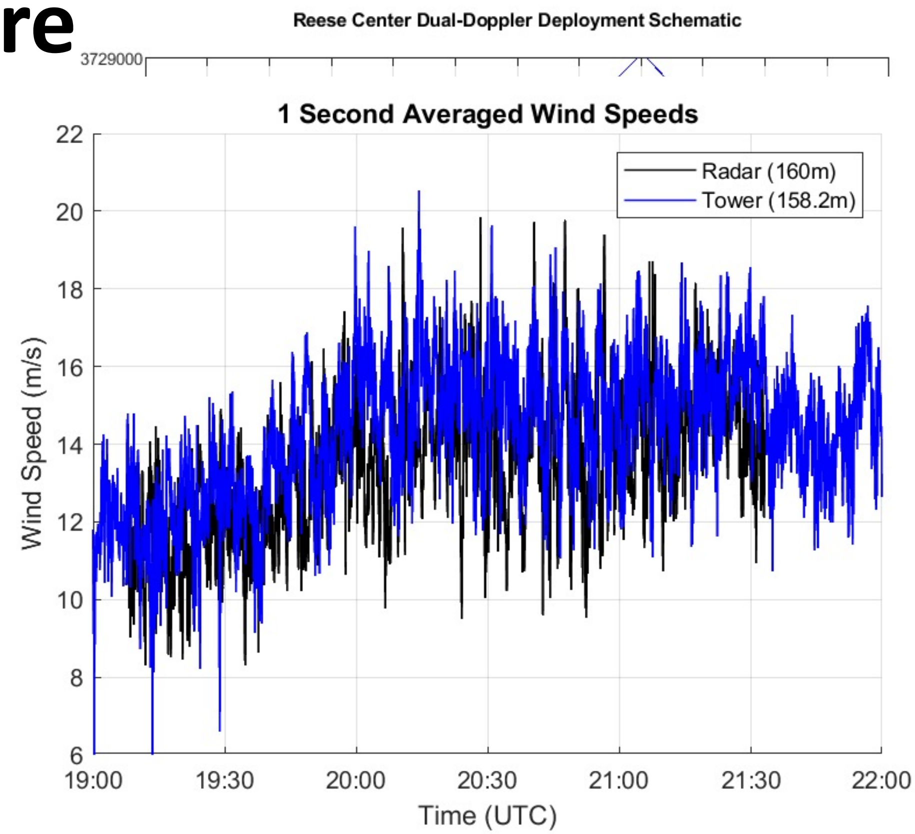


Extracting Engineering-Relevant Wind Structure

- **Comparison to the 200 m tower:**
  - Separation of measurement locations
  - Tower wake influence

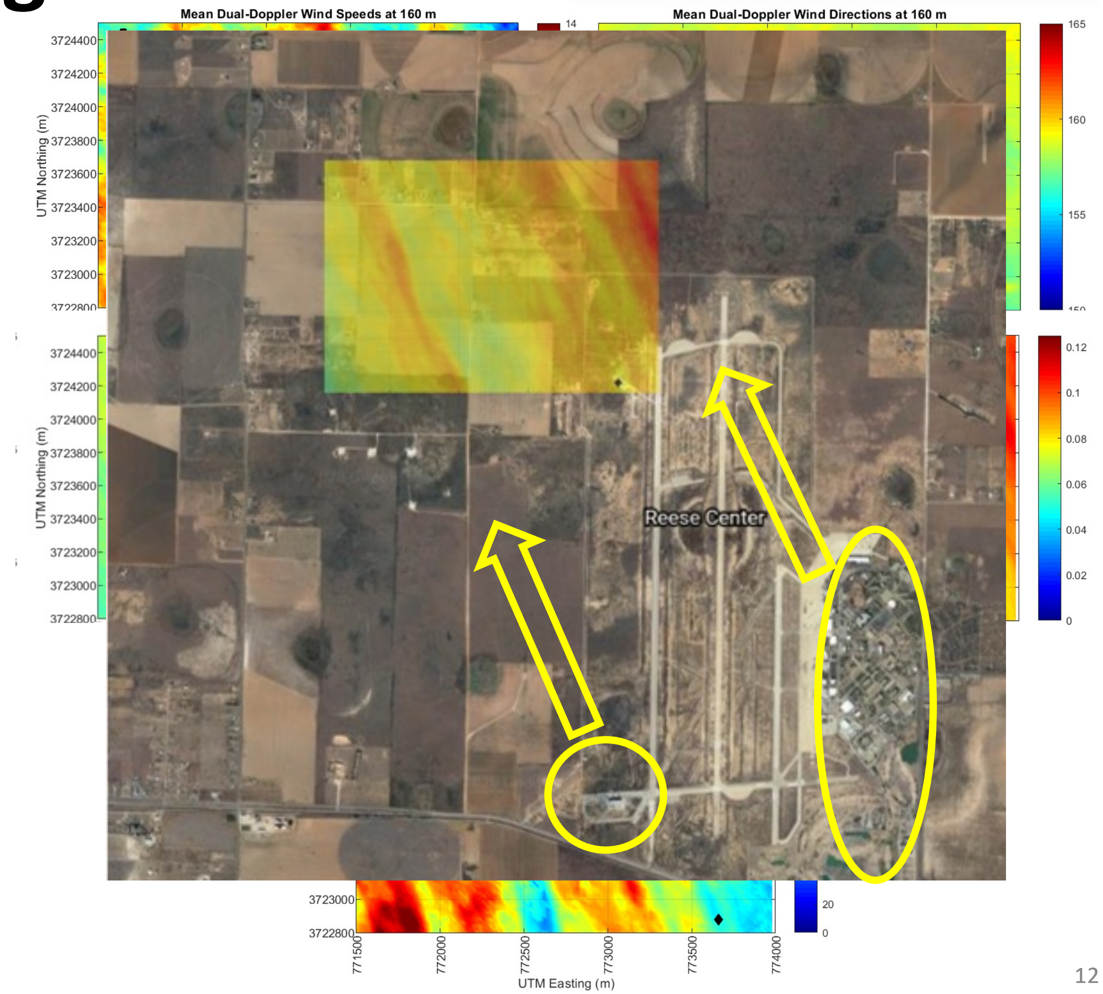
- **Results:**
  - Wind speed averages compare well at 1-minute and longer time scales
  - Bulk turbulence parameters compare well
  - Spectra down to frequencies of ~0.25 Hz also compare well

- **Expand the Method:**
  - Apply at every grid point across the experimental subdomain; creating time histories at each point



Extracting Engineering-Relevant Wind Structure

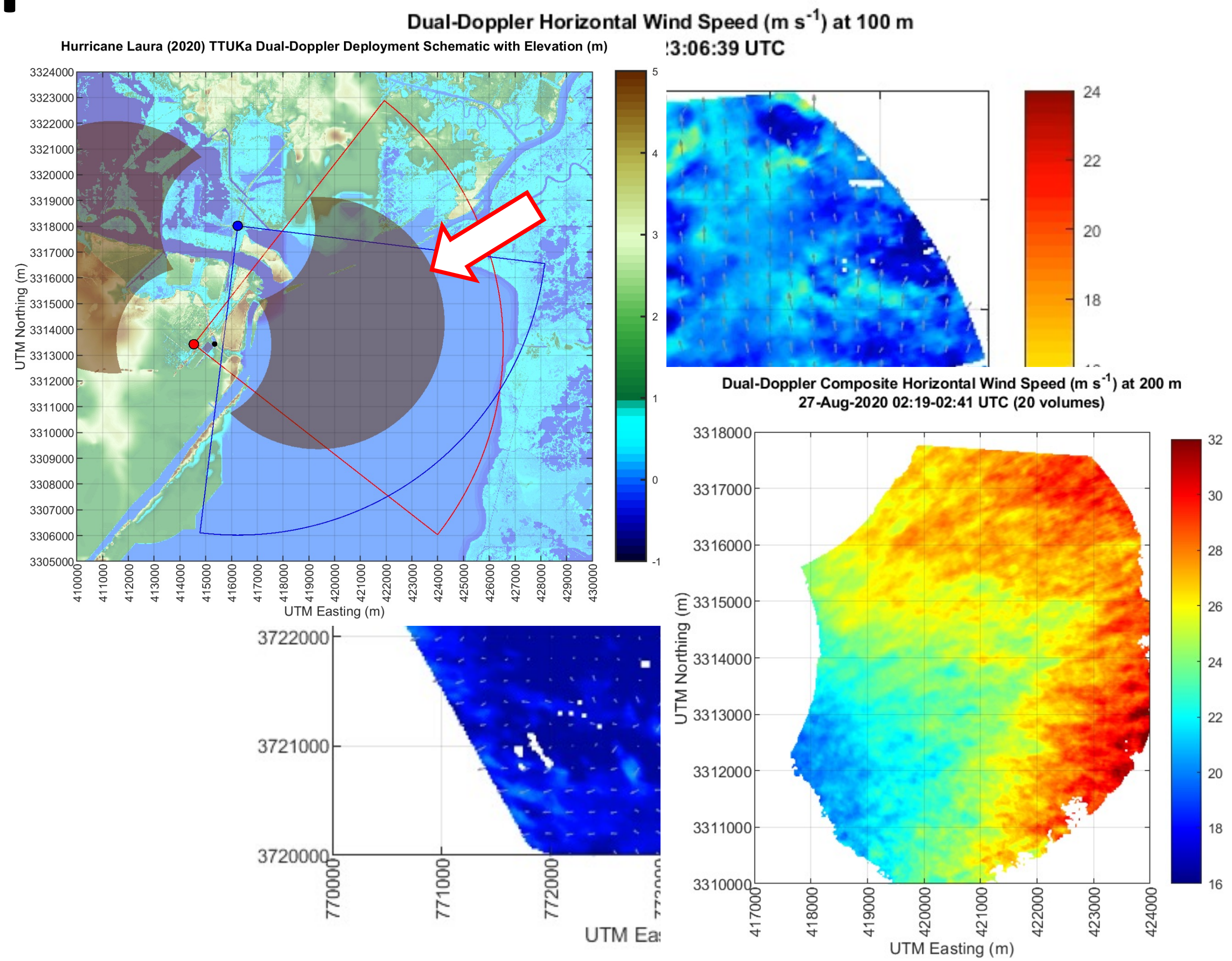
- Use the resultant time histories to:
  - Estimate relevant characteristics of turbulence across the 3-D grid
  - Provide statistical representations and spatial mappings of parameters
  - Available from ~50-200 m



Extending Techniques to NSW Events

- **Complications:**
  - Higher momentum events result in more evolution over shorter periods
  - Localized changes in wind direction (e.g. along boundaries) are difficult to unravel
  - Wind speed gradients create challenges (e.g. coastal gradients)

- **GOAL: Generate relevant four-dimensional wind fields from *some* NSW events at sufficient spatial and temporal scales to assist engineers**



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Funding Acknowledgements

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- NIST Award #: 70NANB19H055

National Wind Institute

Scaling concerns for experimental simulations of tornado-induced wind loading

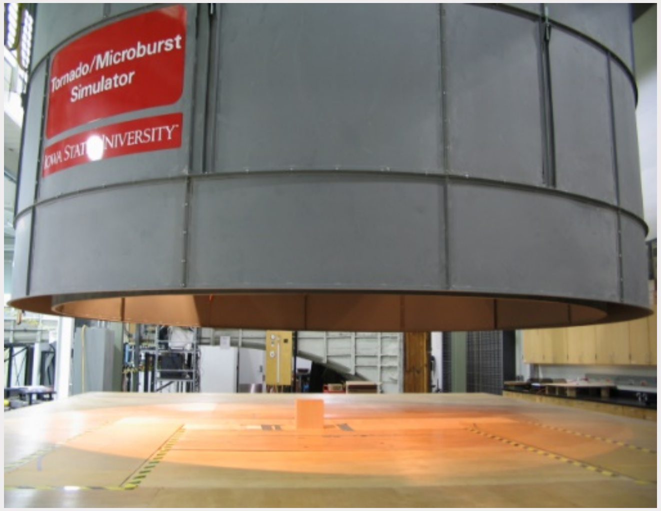
Fred L. Haan, Jr.

Boundary-Layer Wind Tunnel Simulation of Transient and Non-synoptic Wind Events Workshop

May 19, 2021

Main Scaling Question:

What are the best experimental tools for acquiring the various components of tornado-induced loading?



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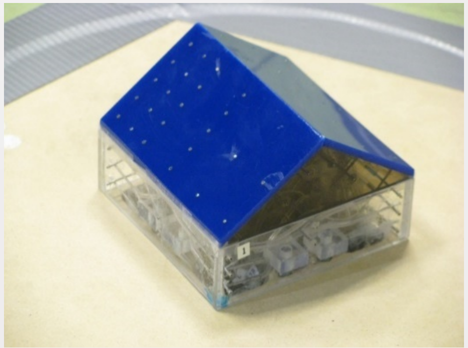
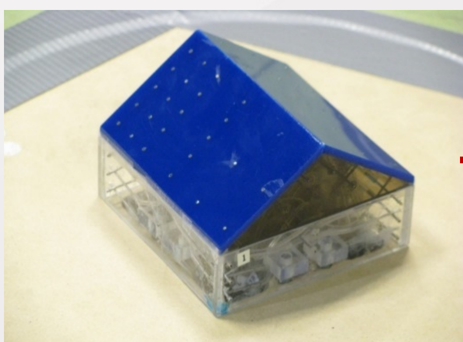
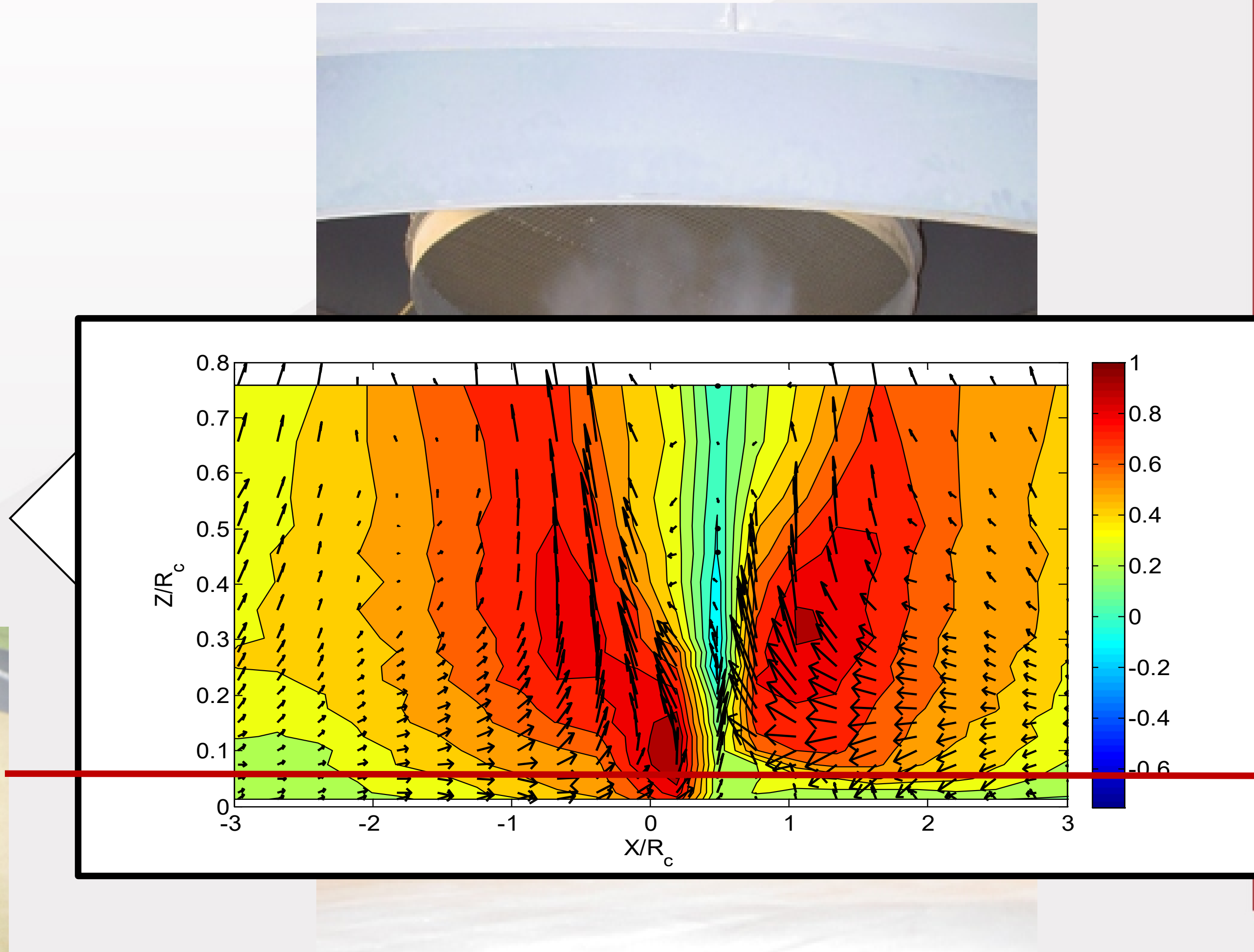
Tornado simulator tests often involve translating a vortex past a building model.

Translation



Tornado simulator tests often involve translating a vortex past a building model.





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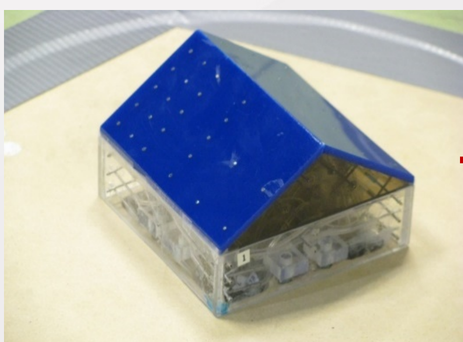
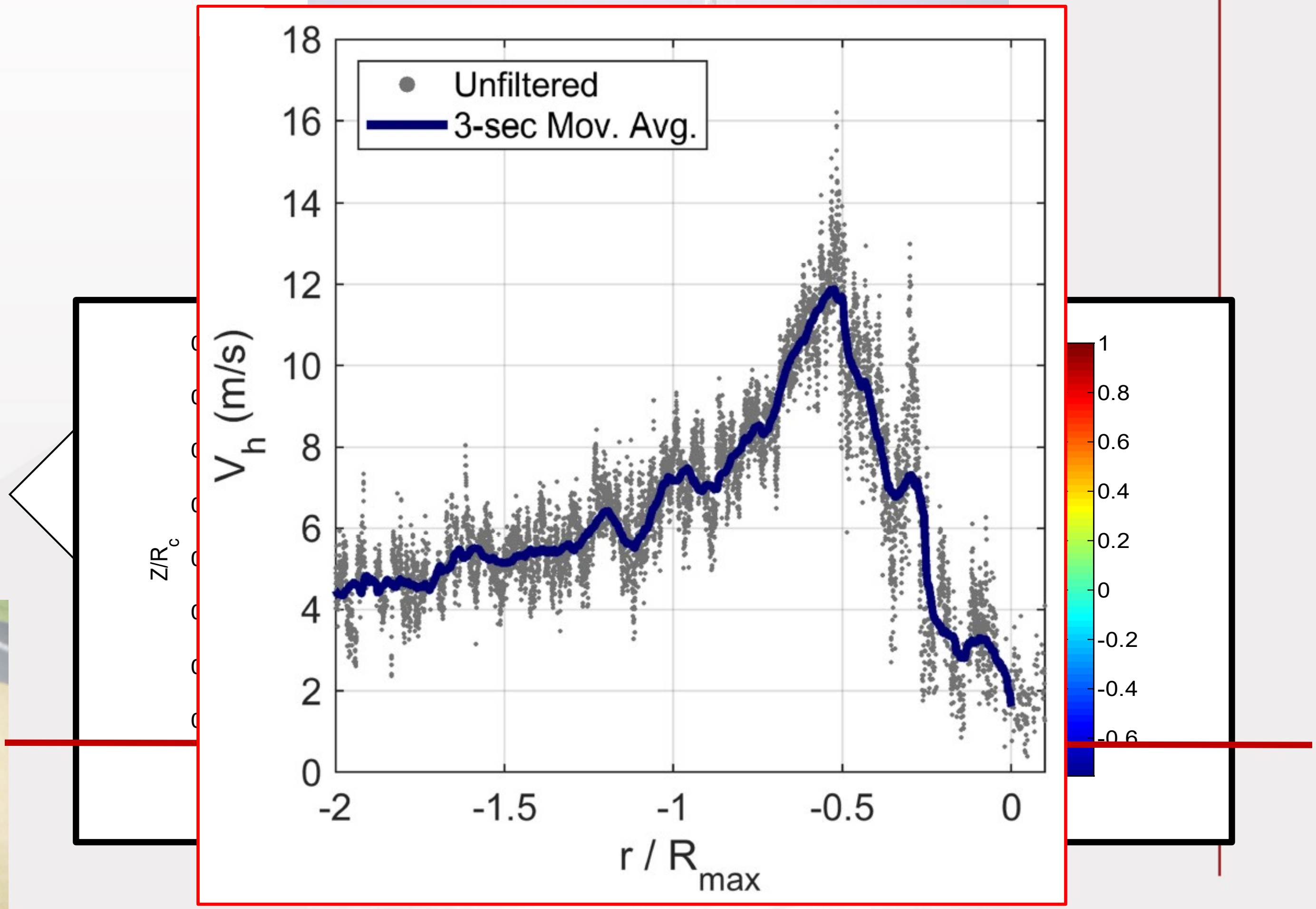
Tornado simulator tests often involve translating a vortex past a building model.





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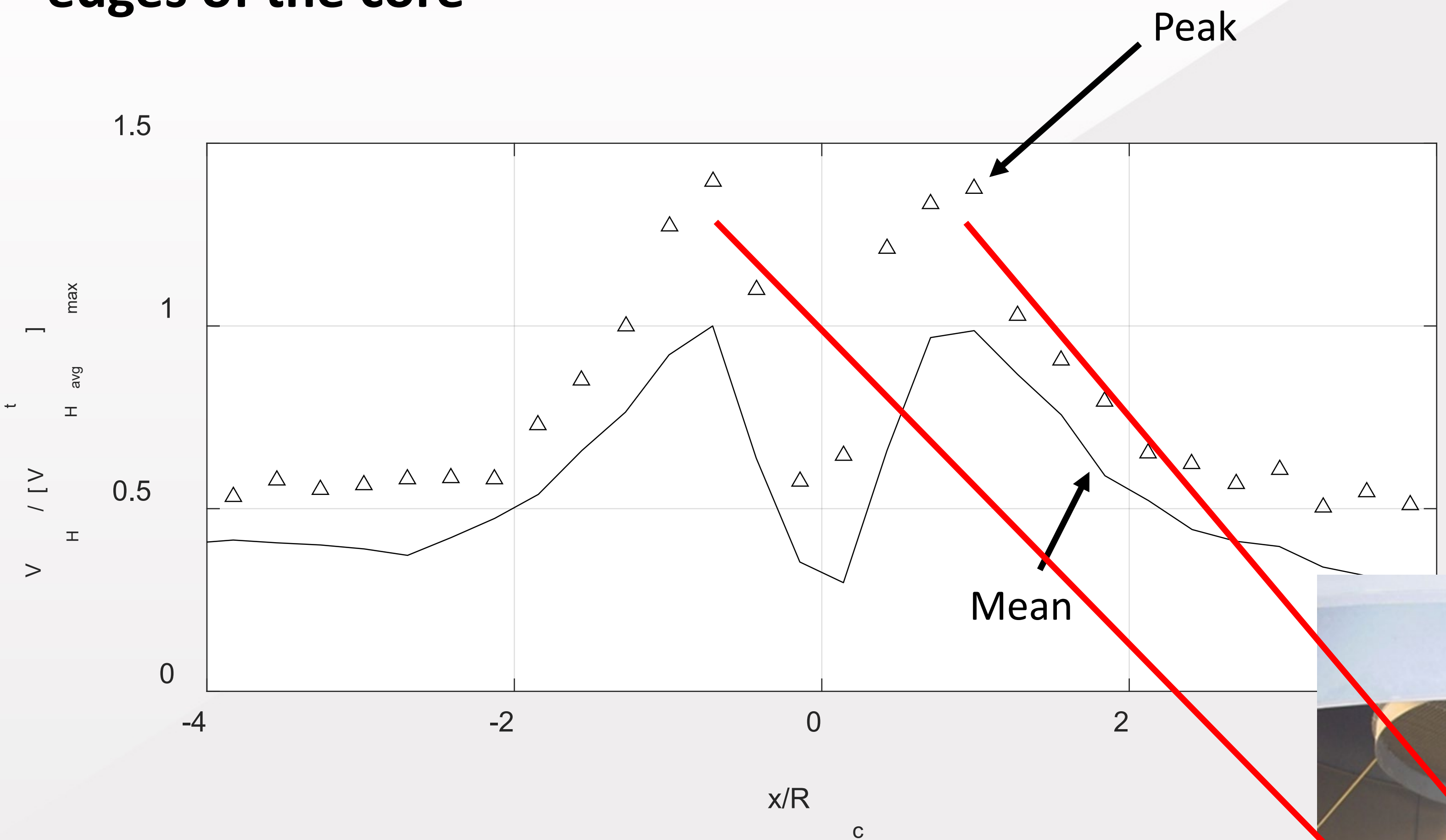
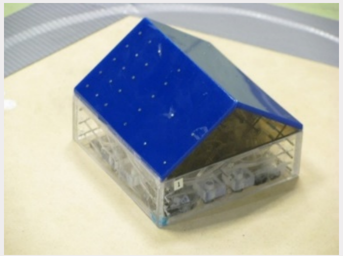
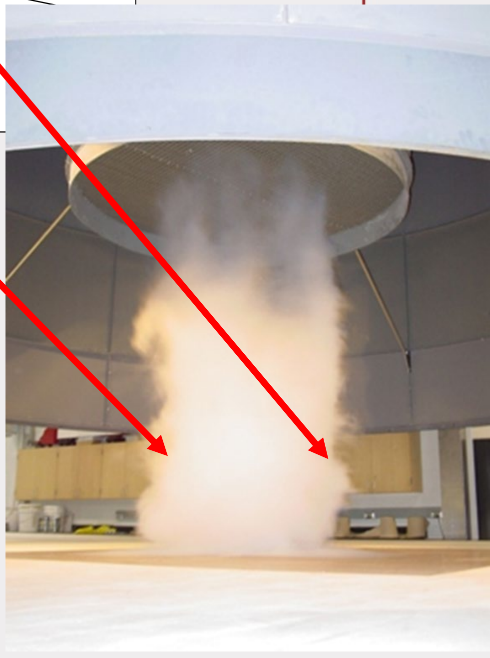
Plotting the horizontal component shows peak velocities near the edges of the core

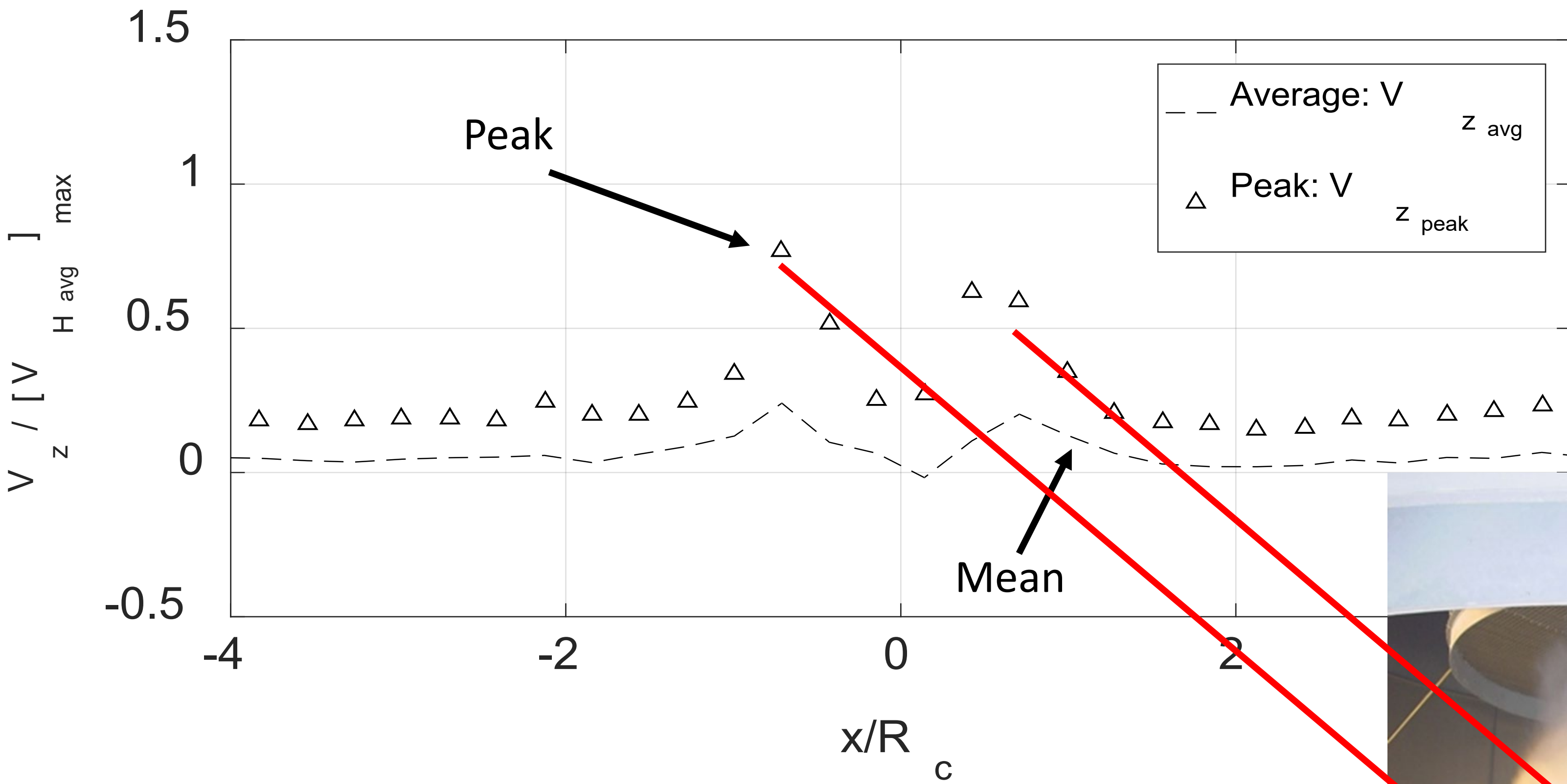


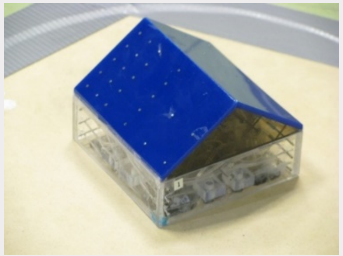


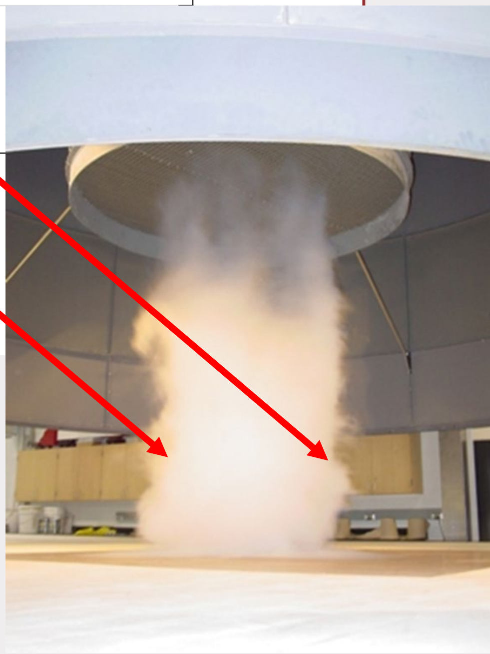
Translation



Plotting the vertical component shows a significant difference between tornado vortices and straight-line boundary layers

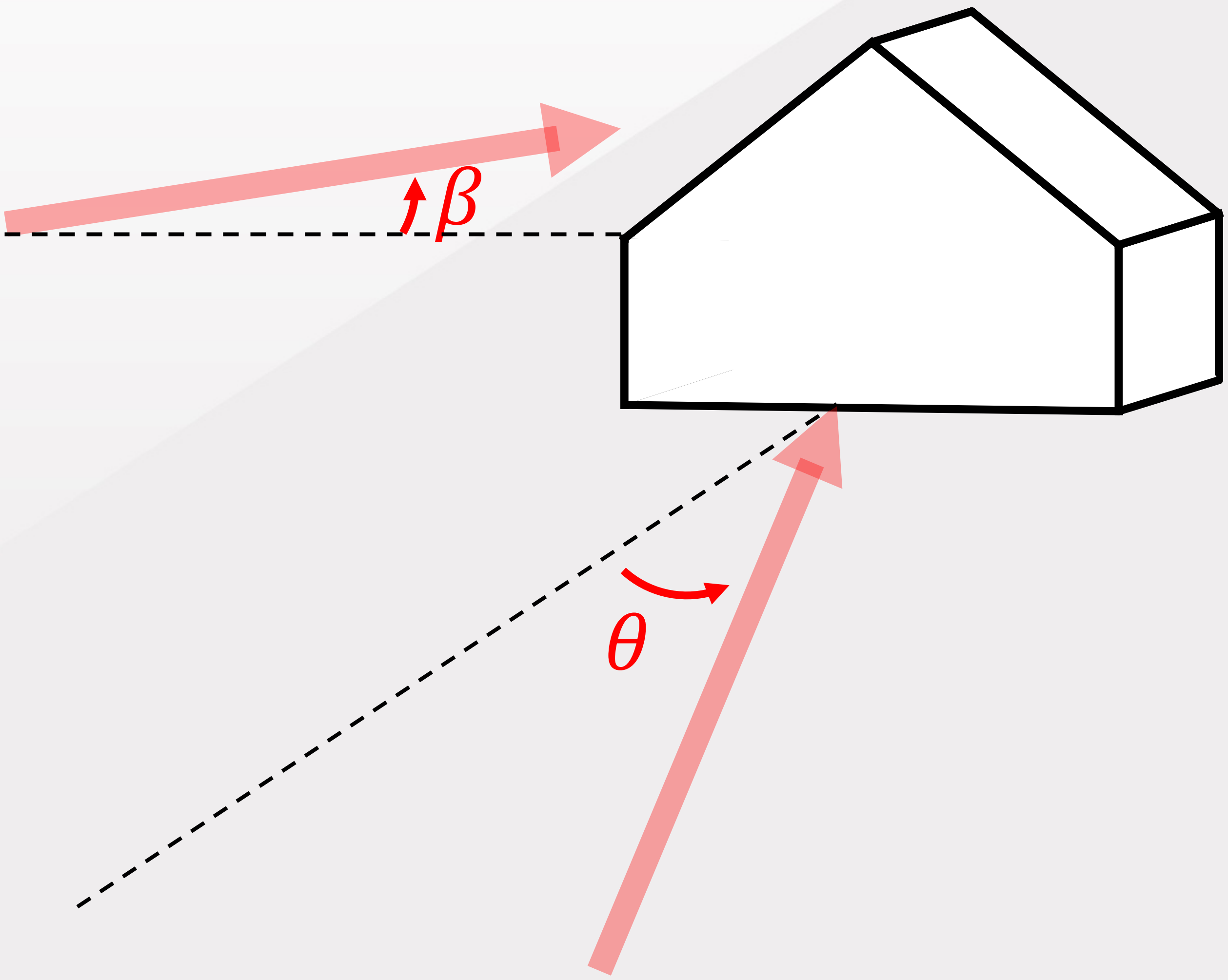




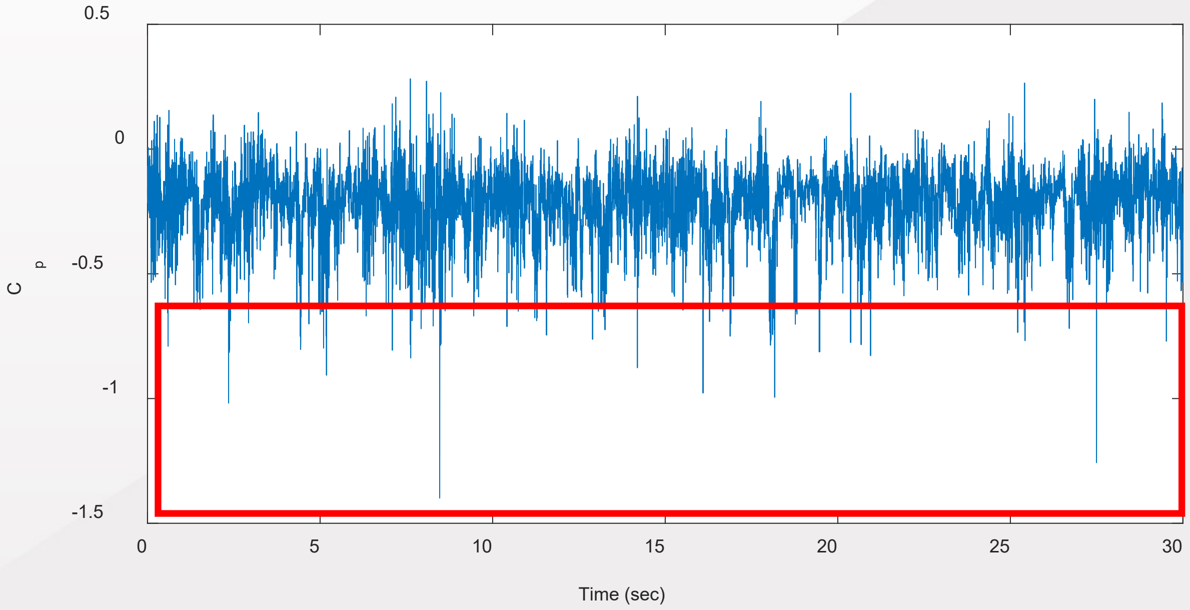


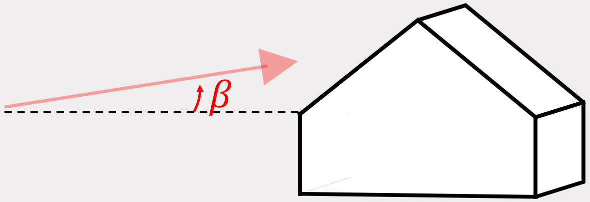
This means that a building will experience some range of vertical angles of attack, β

In addition to the incidence angle θ



Wind tunnels generate vertical angles of attack also, but historically we have not considered them explicitly





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But there are a lot of different tornadoes to consider…

Manchester, SD, 2003
National Geographic, Carsten Peter

VORTEX-99 team on May 3, 1999, in central Oklahoma
http://www.nssl.noaa.gov/headlines/dszpics.html

Binger, Oklahoma F4 tornado of 22 May 1981. NSSL
http://www.spc.noaa.gov/faq/tornado/torscans.htm

Tushka, Oklahoma tornado, April 14, 2011
http://www.srh.noaa.gov/images/oun/wxevents/20110414/stormphotos/austin-garfield/20110414_tushka2.jpg

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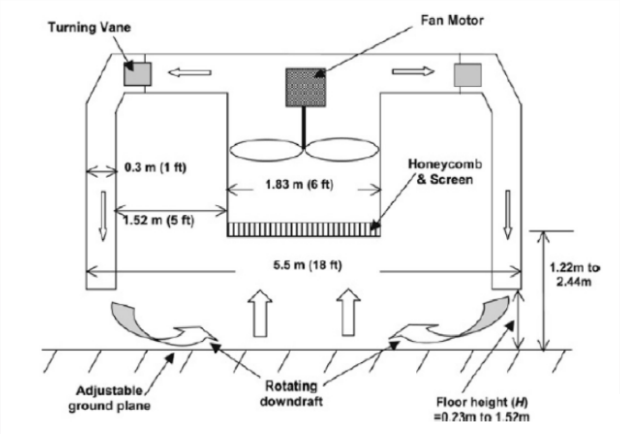
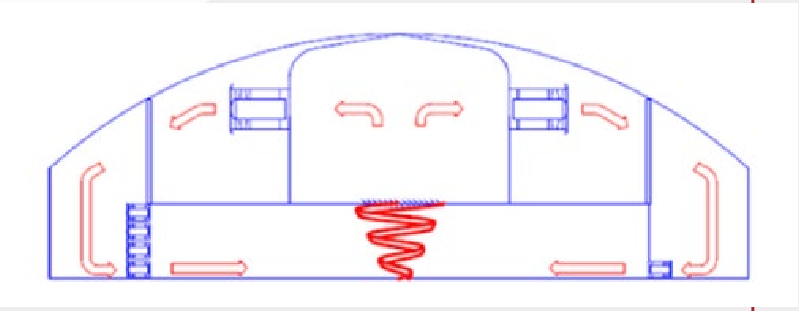
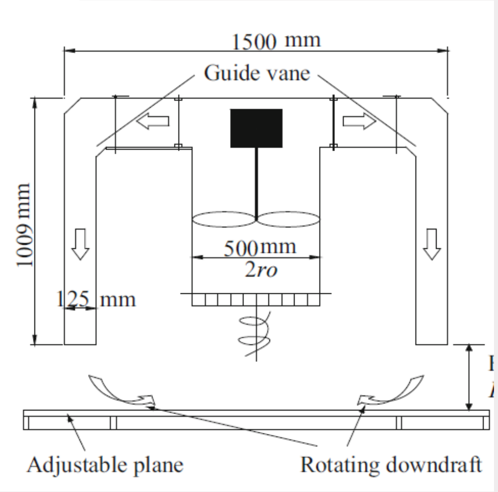
And there are a lot of different ways to simulate tornadoes…



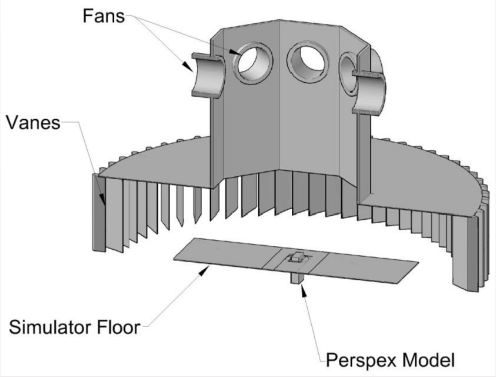
Iowa State



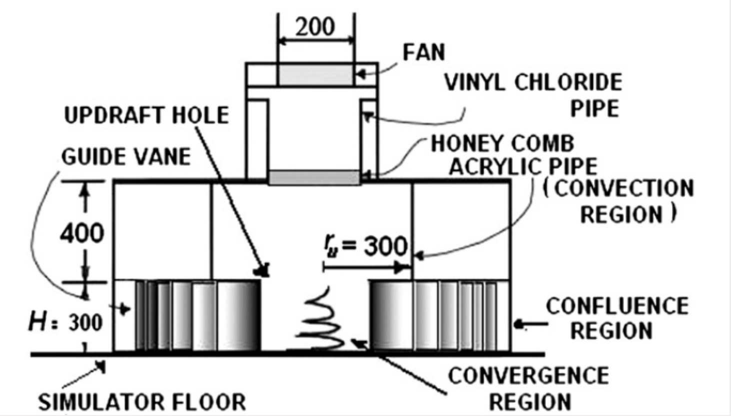
UWO



Tongji



Texas Tech



Tokyo Polytechnic

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The following framework can allow us to simulate many types of tornadoes and compare between many types of simulation approaches

$$p(\theta,\beta) = \underbrace{p_a(\theta,\beta)}_{\text{Aerodynamic pressure}} + \underbrace{p_0}_{\text{Static pressure}} - p_\infty$$

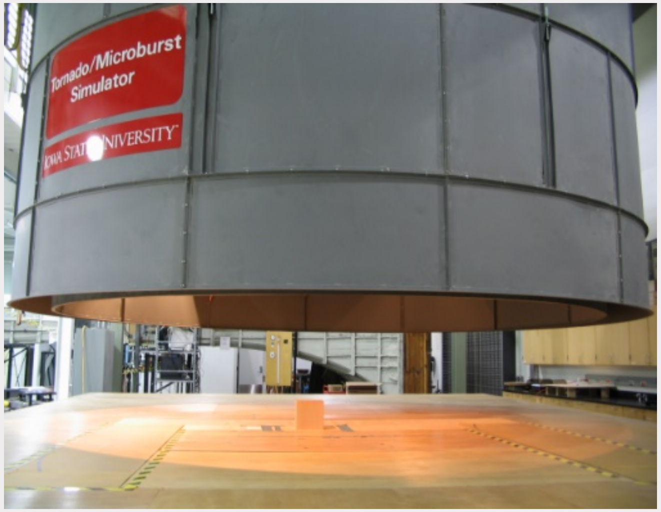
NOTE: These are instantaneous quantities!

We can convert these to pressure coefficients using an appropriate dynamic pressure

$$C_p(\theta, \beta) = C_{p_a}(\theta, \beta) + C_{p_0}$$

Aerodynamic pressure

Static pressure



We can convert these to pressure coefficients using an appropriate dynamic pressure

$$C_p(\theta, \beta) = C_{p_a}(\theta, \beta) + C_{p_0}$$

What parameters and scales are important when trying to experimentally estimate these pressure coefficients?

$$C_p(\theta, \beta) = C_{p_a}(\theta, \beta, Re, S_{uu}) + C_{p_0}(S, Re, V_t, z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$

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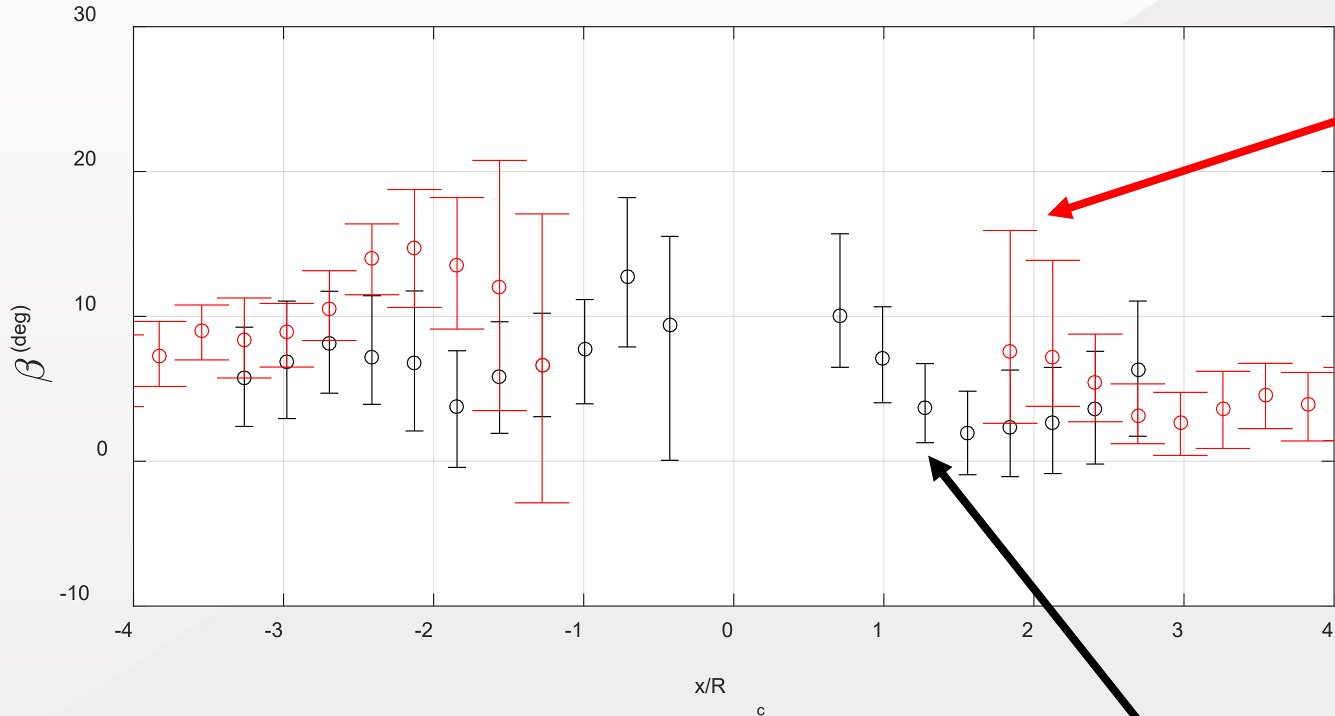
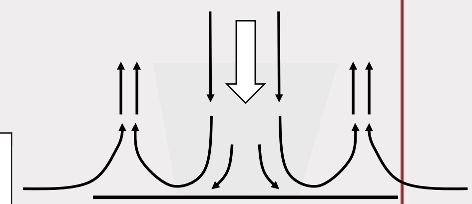
The swirl ratio, S, will affect the β range we see and the static pressure distribution

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

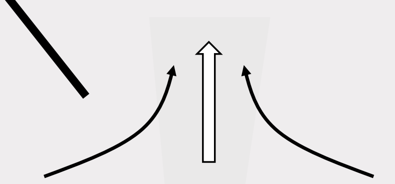
Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$

Higher swirl ratios produce larger angles of attack (β)

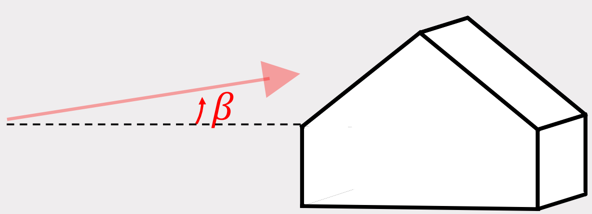




High swirl ratio



Low swirl ratio



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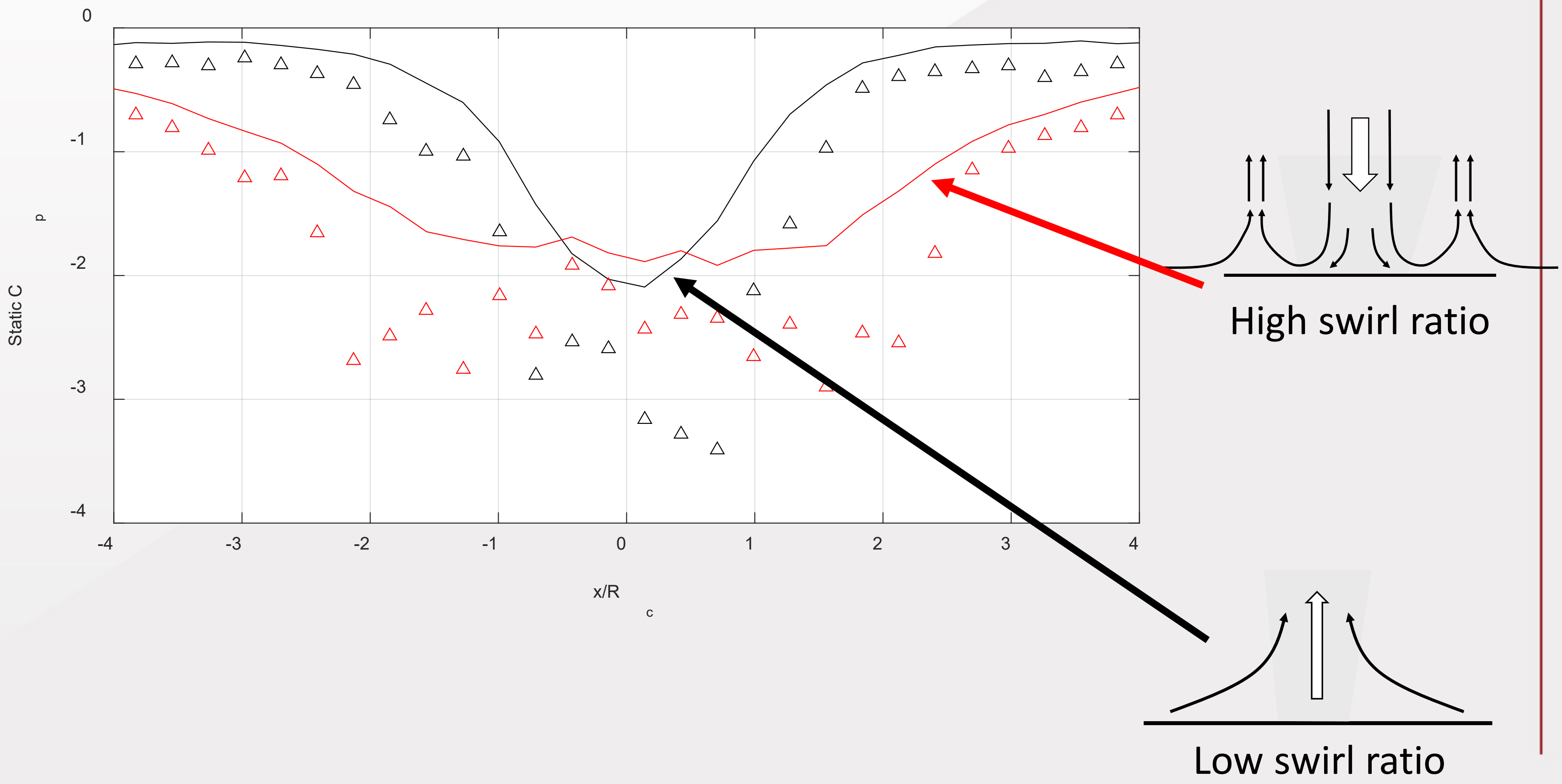
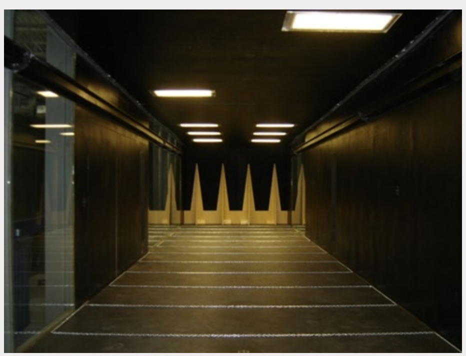
Swirl ratio also changes the static pressure profile

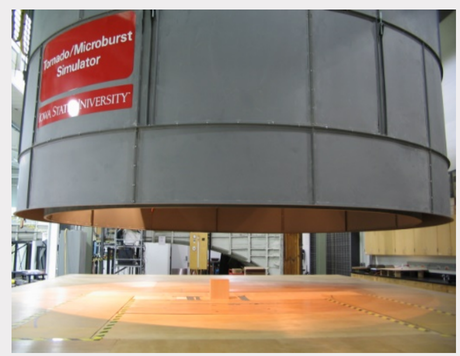


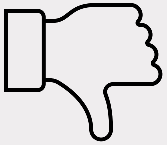
Which type of facility is best suited to study this?

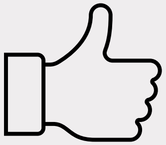
$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$









For $C_{p_0}(S)$

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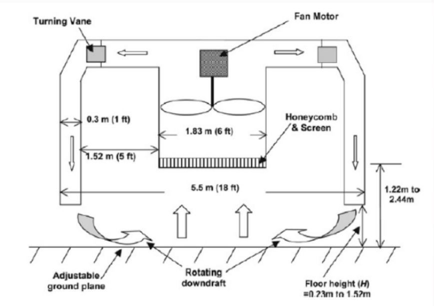
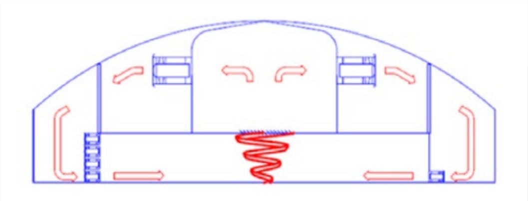
The geometry of the tornado simulators, G, will affect the kinematic similarity of simulations

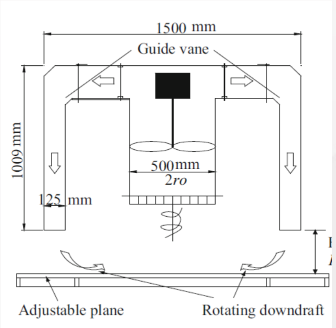
$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

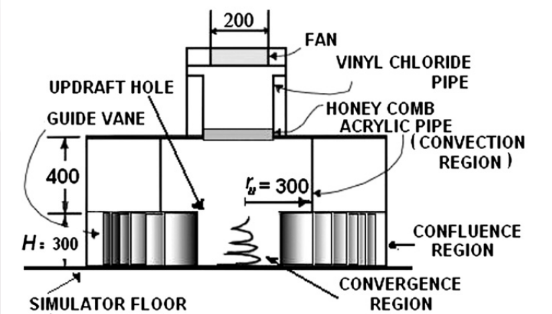
Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$

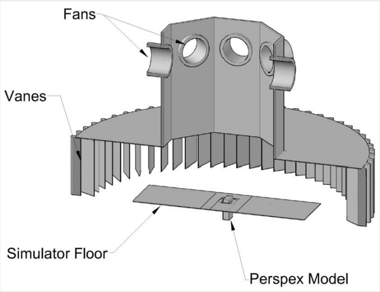
The geometry of tornado simulators affects how well they can meet kinematic similarity with full scale tornadoes









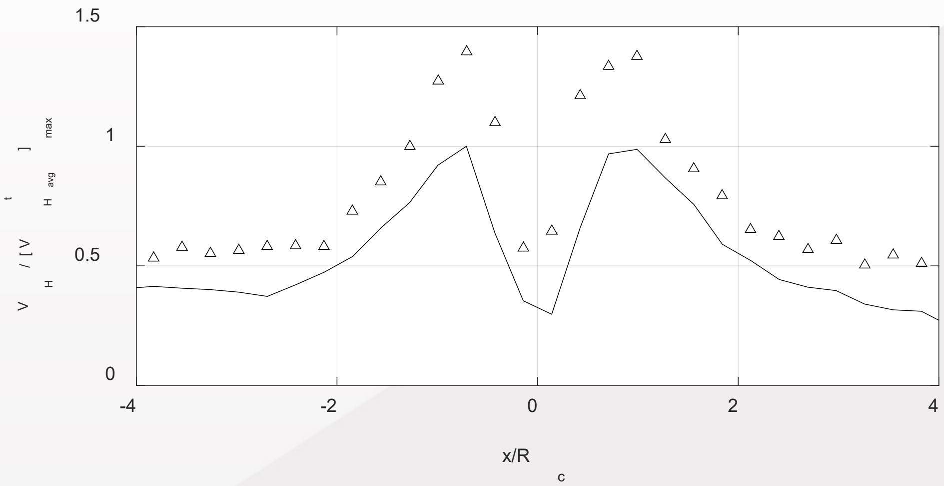


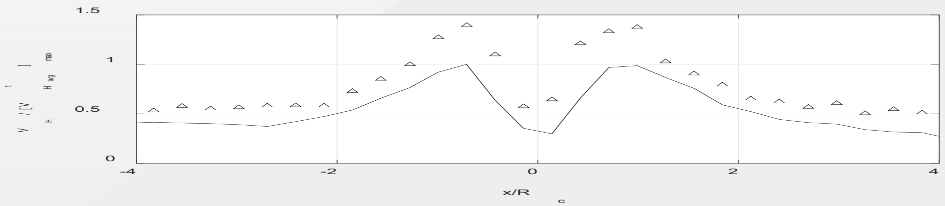
$$\frac{r_{V_m}}{z_{V_m}} \qquad \frac{r_{U_m}}{r_{V_m}}$$

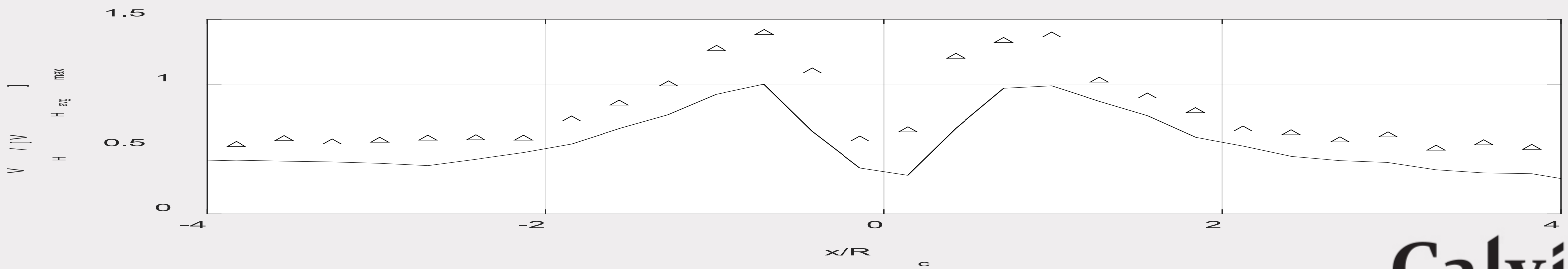
$$\frac{V_m}{U_m} \qquad \frac{z_{U_m}}{z_{V_m}}$$

$$\frac{V_t}{V_m}$$

This affects what profile a building see during testing







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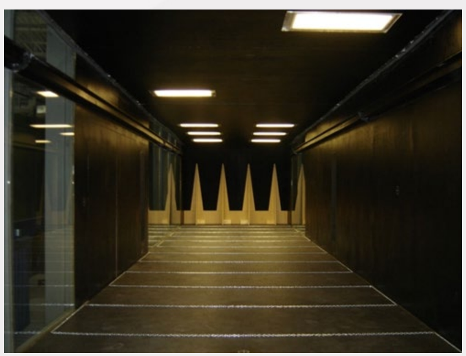
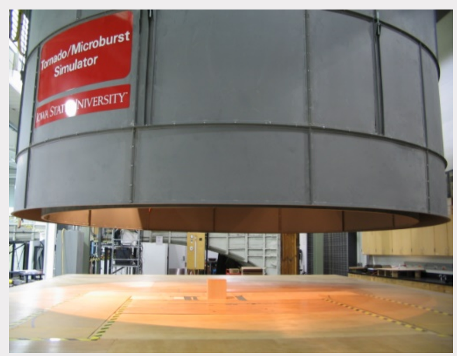
Which type of facility is best suited to study this?

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

Plus the following: $\color{red}{G}, S, \dot{\theta}, \dot{\beta}, z_0$





For $\beta(G)$
and $C_{p_0}(G)$

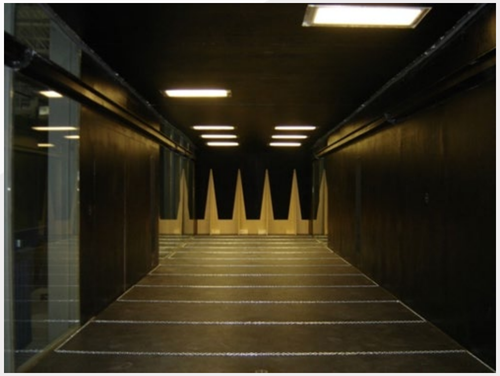
The Reynolds number will affect dynamic similitude for both bluff body aerodynamics and the static pressure field

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

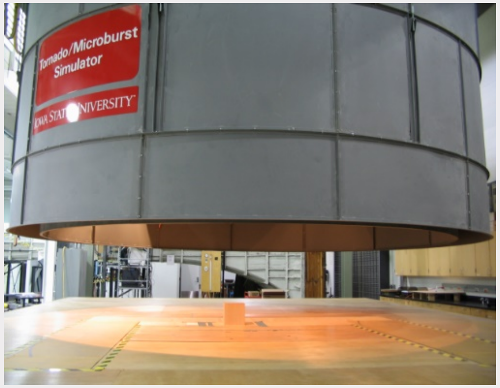
Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$

Minimum Reynolds number for sharp-edged bluff bodies is 4×10^4

Actual dynamic similarity is typically not possible with experimental facilities ($Re > 10^7$)



No problem for most ABLs



Need a fairly large tornado simulator to accomplish this

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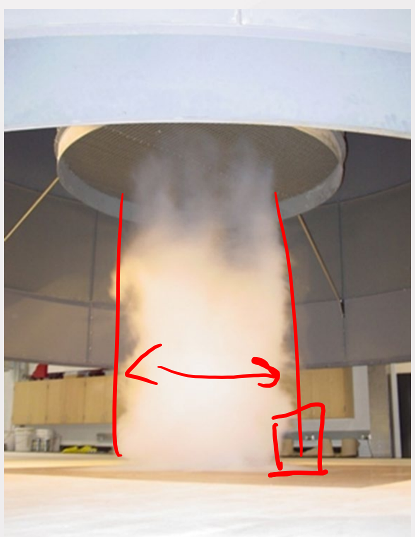
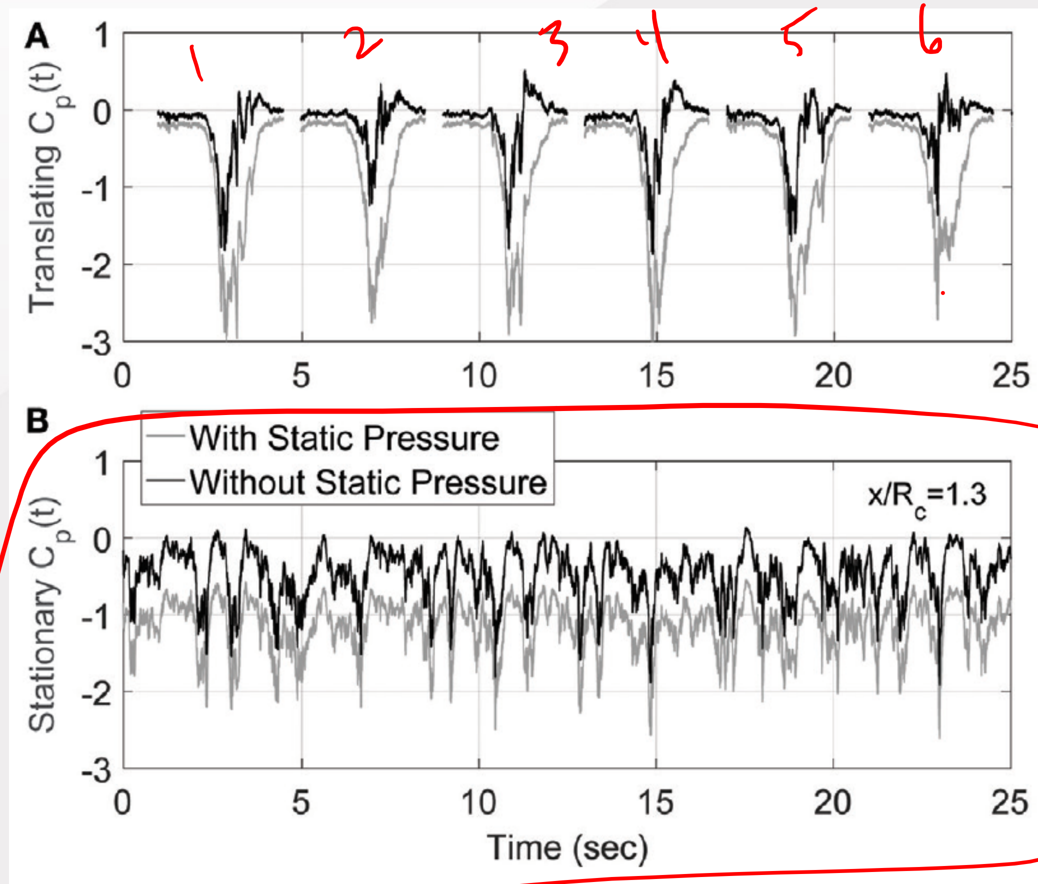
Tornado vortex wandering can be a problem in tornado simulators – will also Re dependent

Wandering will affect pressure measurements on building models





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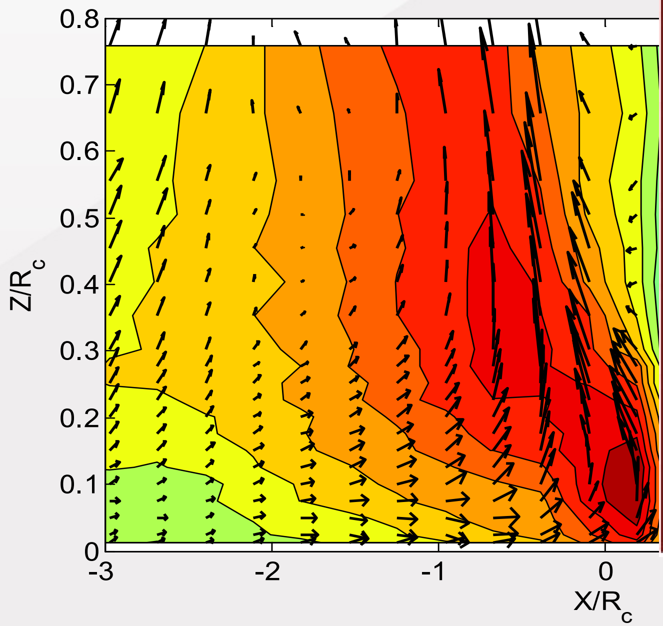
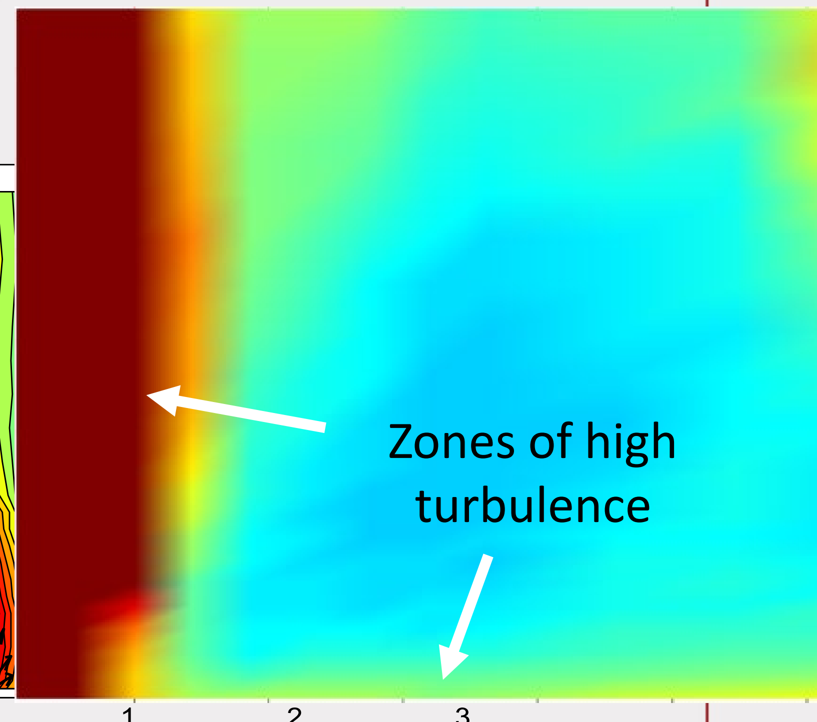
Tornado vortex wandering can also be a problem for estimating turbulence intensity



Turbulence intensity contour



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Which type of facility is best suited to study this?

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

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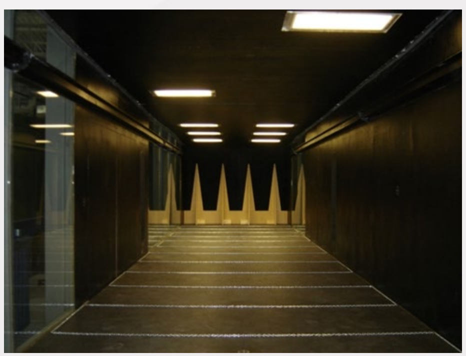
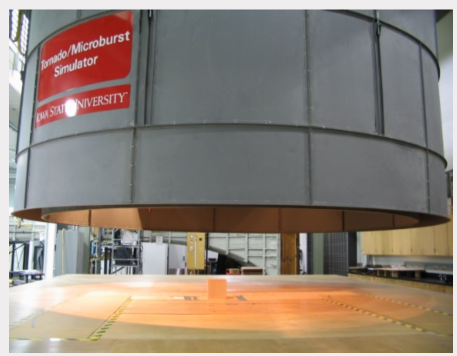
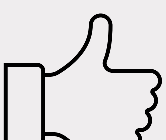
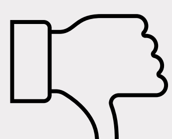






Wide range of Re



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Surface roughness effects are not well understood for tornado flow field

$$C_p(\theta, \beta) = C_{p_a}(\theta, \beta, Re, S_{uu}) + C_{p_0}(S, Re, V_t, z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$

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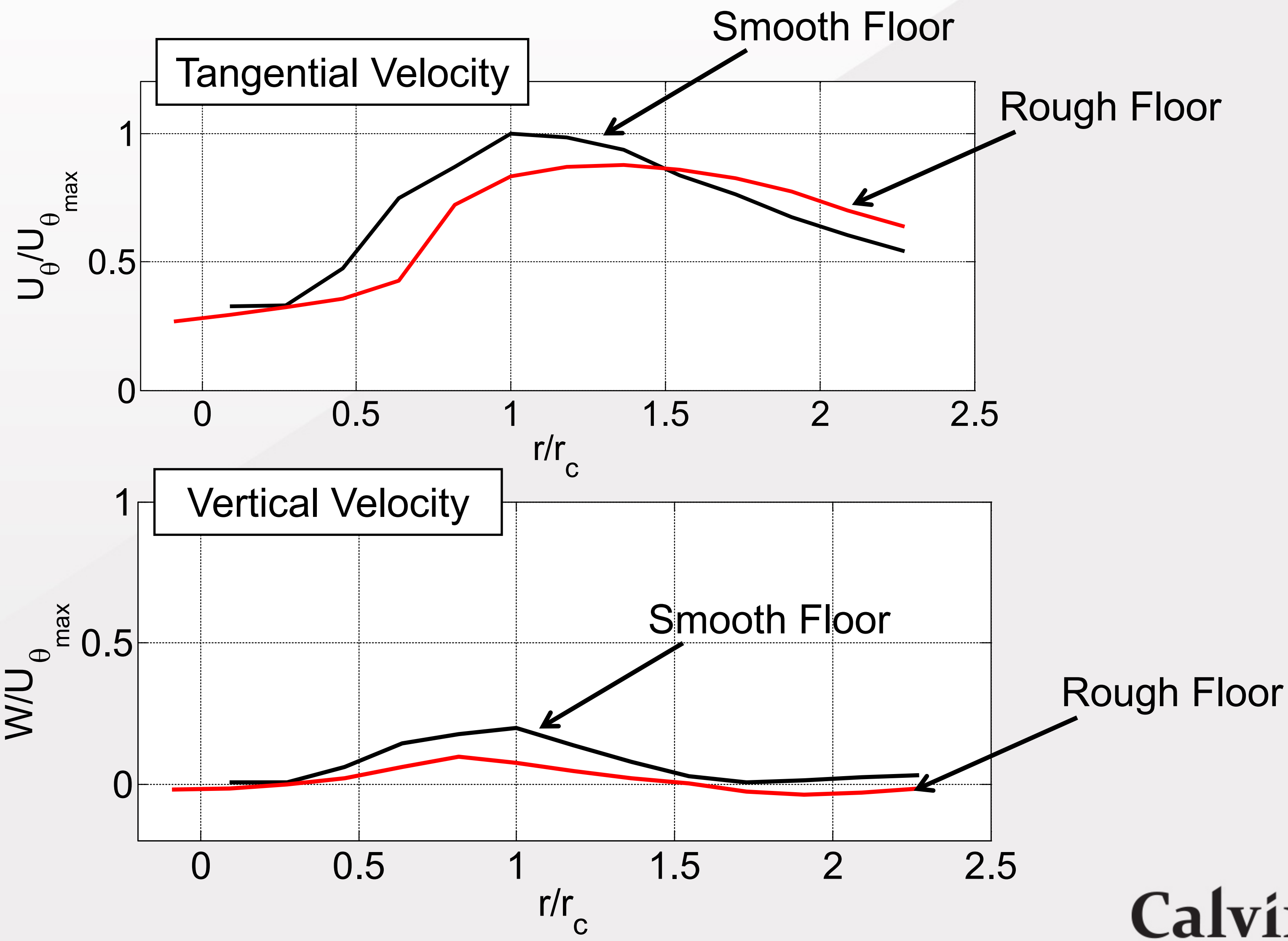
Surface roughness tends to flatten out the velocity field



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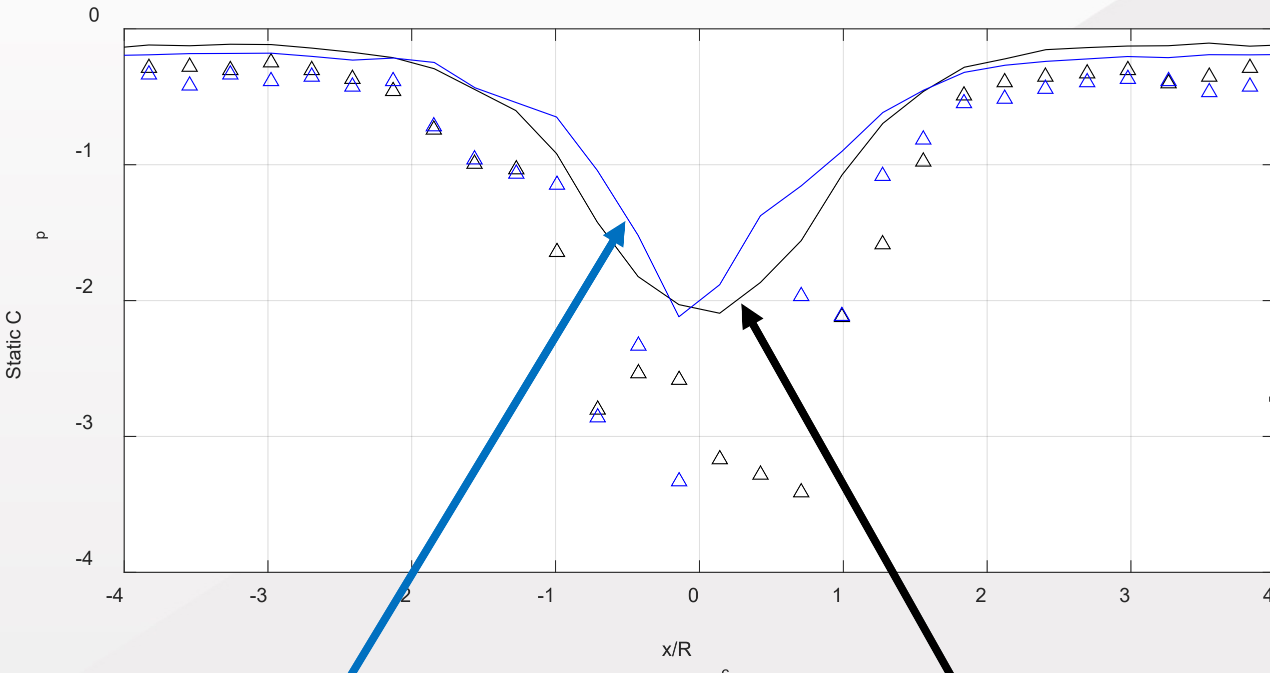
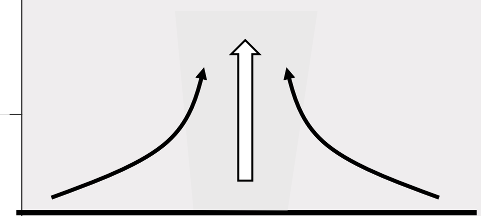
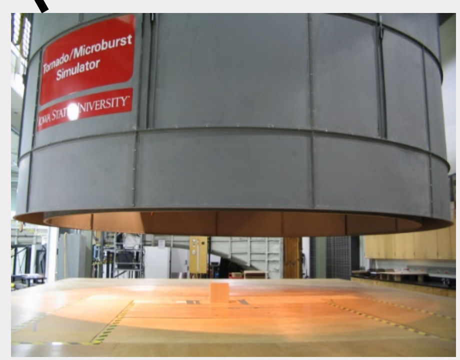
Surface roughness does not appear to change the static pressure profile significantly





Low swirl ratio

Rough Surface

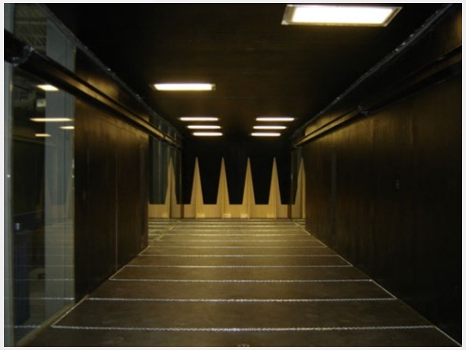


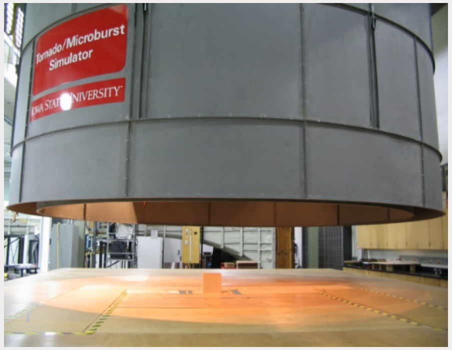
Smooth Surface

Which type of facility is best suited to study this?

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$





Pressure gradients?
Streamline curvature?

More study needed

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Turbulence spectra has a strong influence on bluff body aerodynamics

$$C_p(\theta, \beta) = C_{p_a}(\theta, \beta, Re, S_{uu}) + C_{p_0}(S, Re, V_t, z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$

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Turbulence spectra play a crucial role in getting the bluff body aerodynamics right.

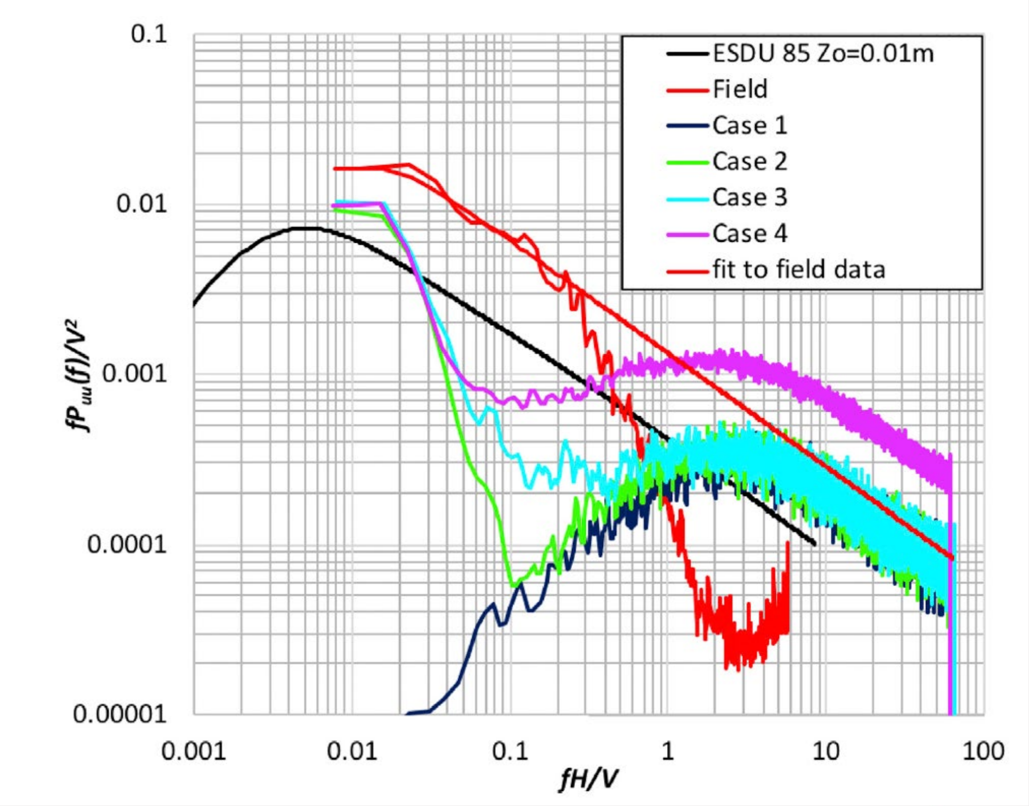
M&K (2018) found that energy levels around $0.1 < {}^{fH}/_{V} < 2$ are very important for the pressures in separated regions.

H is the building height
V is the mean velocity

How do we best quantify the spectra for transient tornado flows?

How does the pressure gradient alter these spectra?

What are the target spectra for a real tornado?



Morrison and Kopp (2018)

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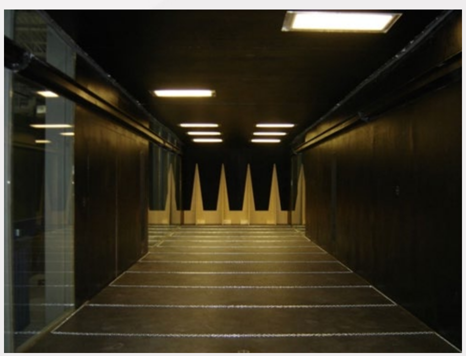
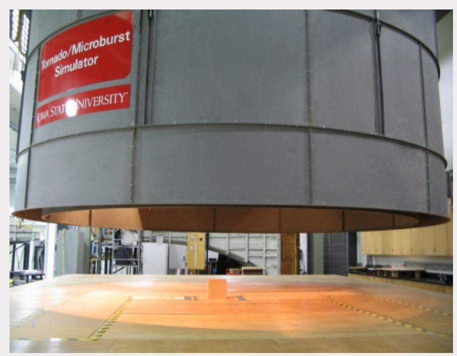
Which type of facility is best suited to study this?

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,{\color{red}S_{uu}}) + C_{p_0}(S,Re,V_t,z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$





Transient spectra?
Pressure gradients?

Transient spectra

Vortex translation may affect both the aerodynamics and the static pressure

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$

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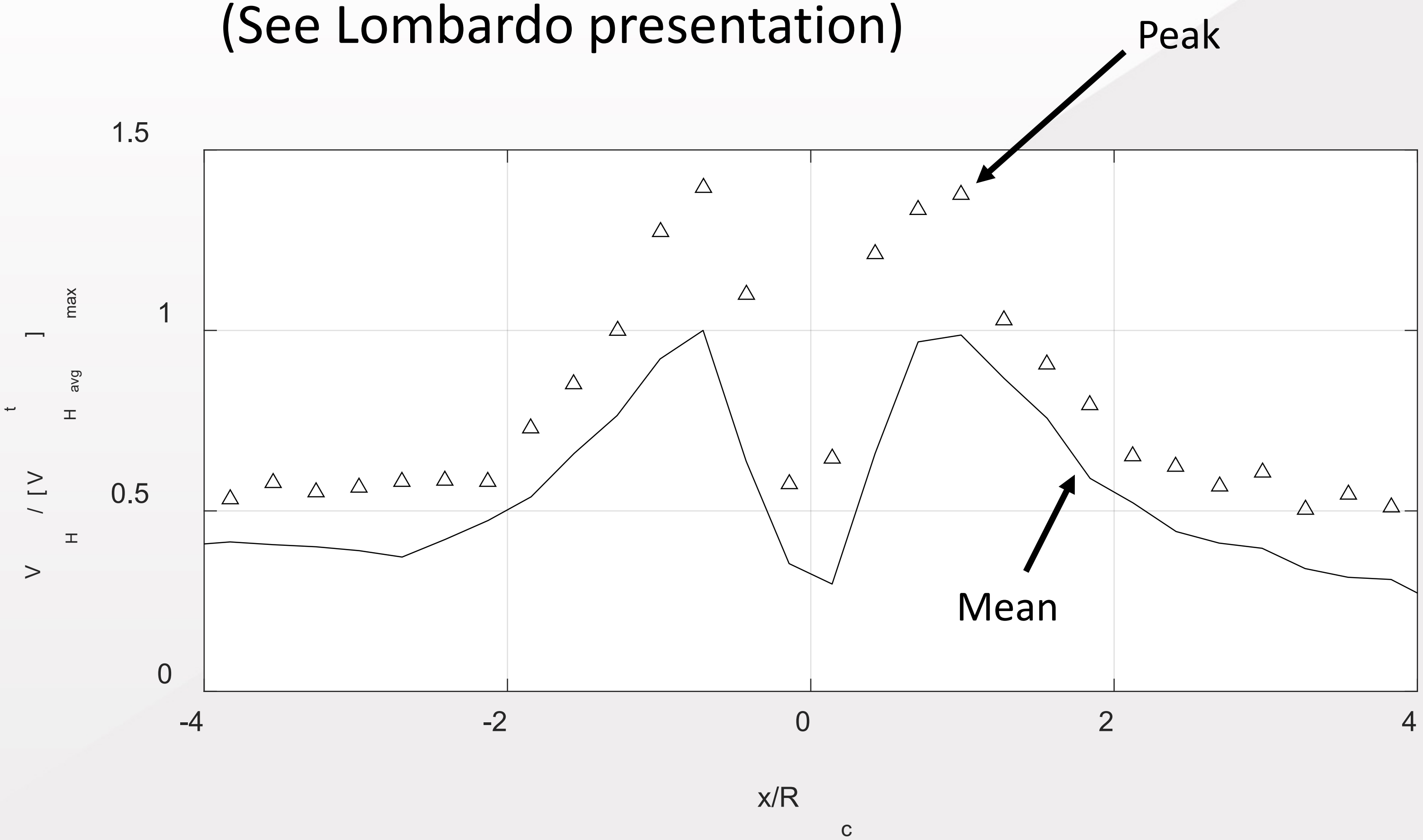
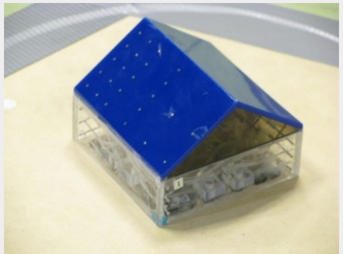
The translation speed of the vortex will determine time rates of change for V, θ, and β – we need full scale targets
(See Lombardo presentation)



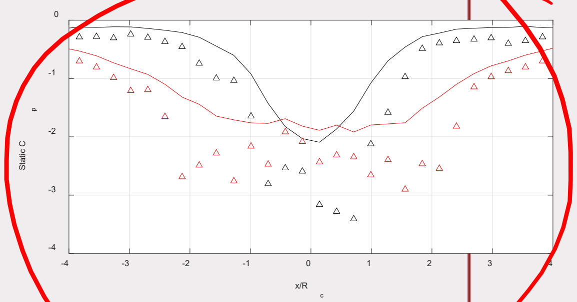


Translation

A translating vortex brings up an interesting issue that is usually not considered

Specifically, consider the unsteady potential term in the Bernoulli equation:

$$\frac{\partial \phi}{\partial t} + \frac{V^2}{2} + \frac{p}{\rho} = \frac{V_\infty^2}{2} + \frac{p_\infty}{\rho}$$



To explore this idea, we can use a simple potential flow model of a translating vortex …

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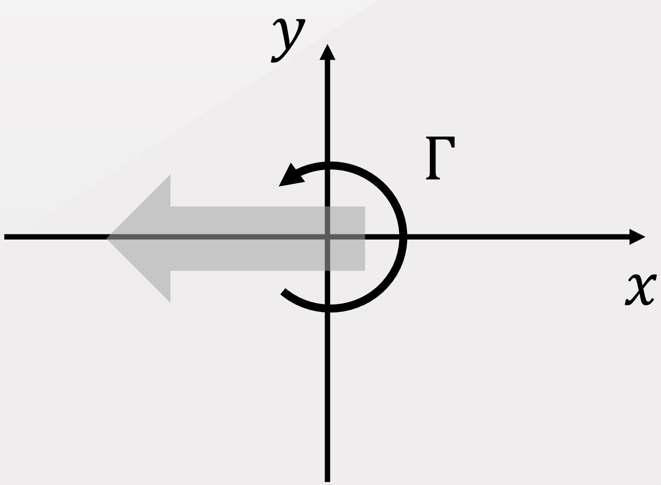
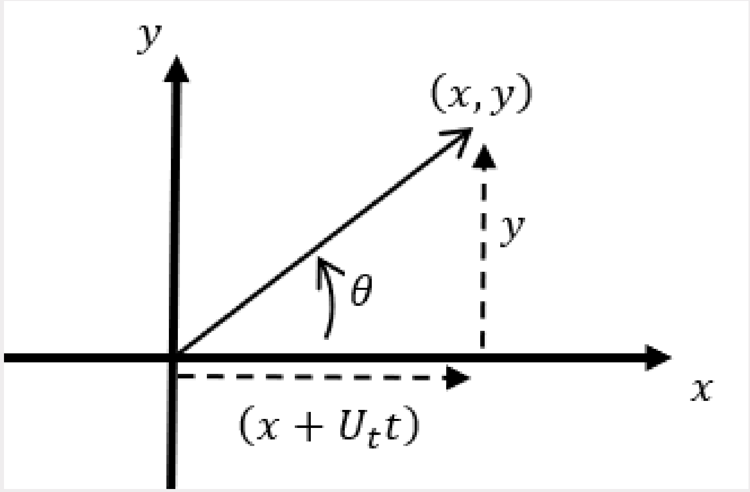
Consider a vortex translating with velocity U along the x axis.

The unsteady potential function can then be written as:

$$\phi = \frac{\Gamma}{2\pi}\theta = \frac{\Gamma}{2\pi} tan^{-1}\left(\frac{y}{x - Ut}\right)$$





It can be shown that the static pressure coefficient will then have a contribution from an unsteady term

$$\text{Static } C_p = -\frac{2\frac{\partial\phi}{\partial t}}{V_{\theta_{max}}^2} - \frac{V^2}{V_{\theta_{max}}^2}$$

$$= C_{p_{unsteady}} + C_{p_{steady}}$$

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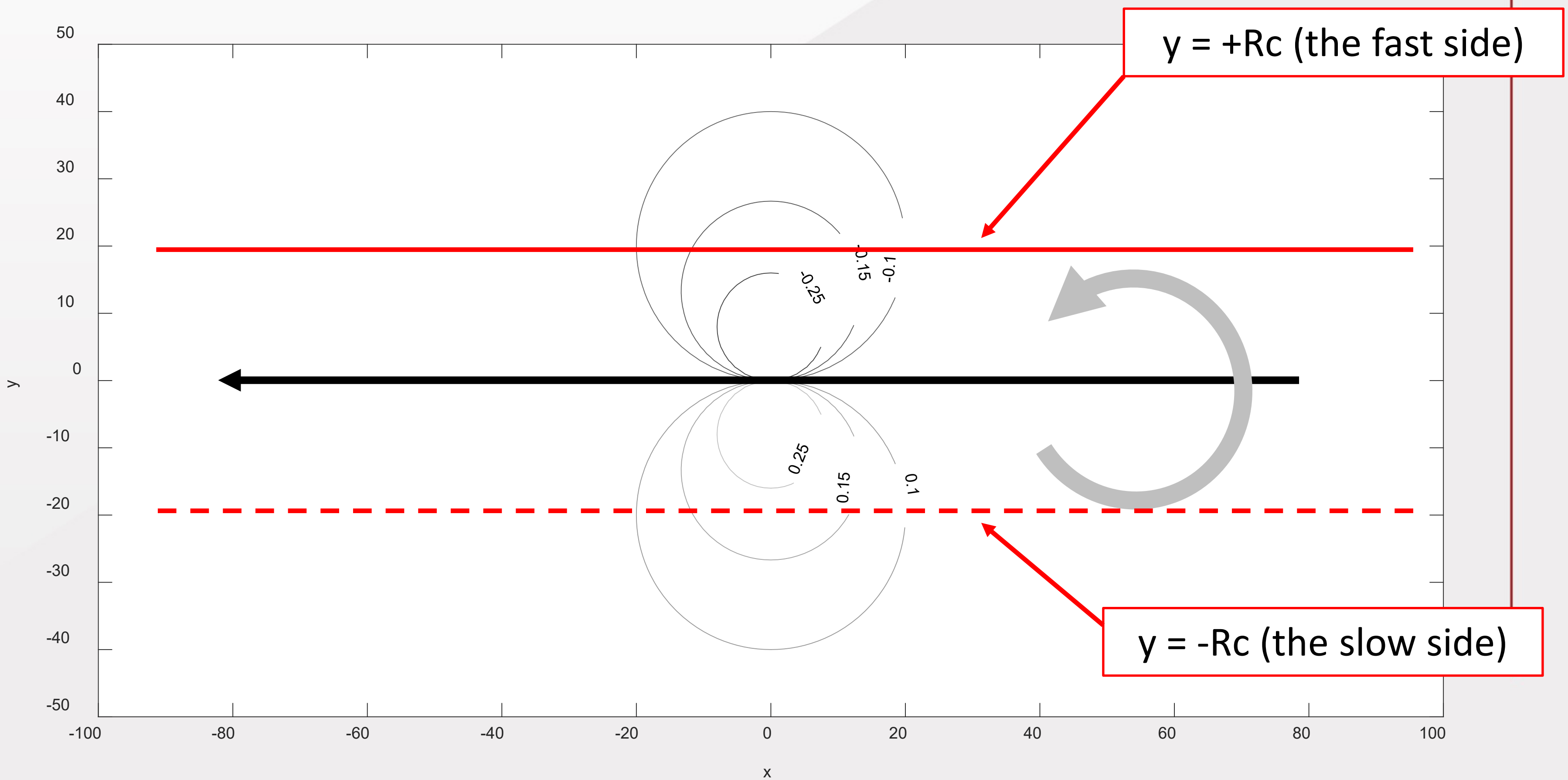
The unsteady term is zero on the translation axis – and has opposite sign on either side.



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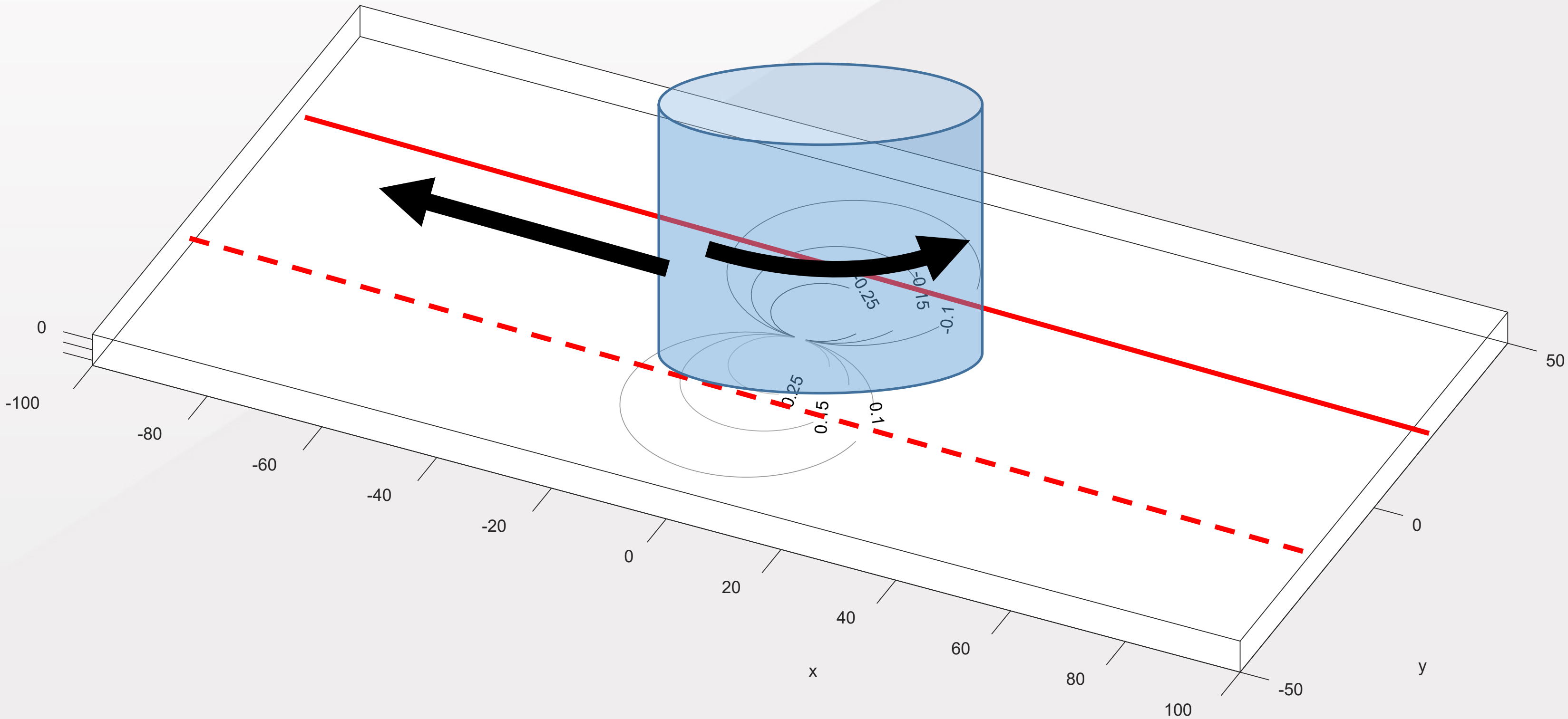
Structures on opposite sides of the vortex may have greater or lesser effect of static pressure depending on translation speed.



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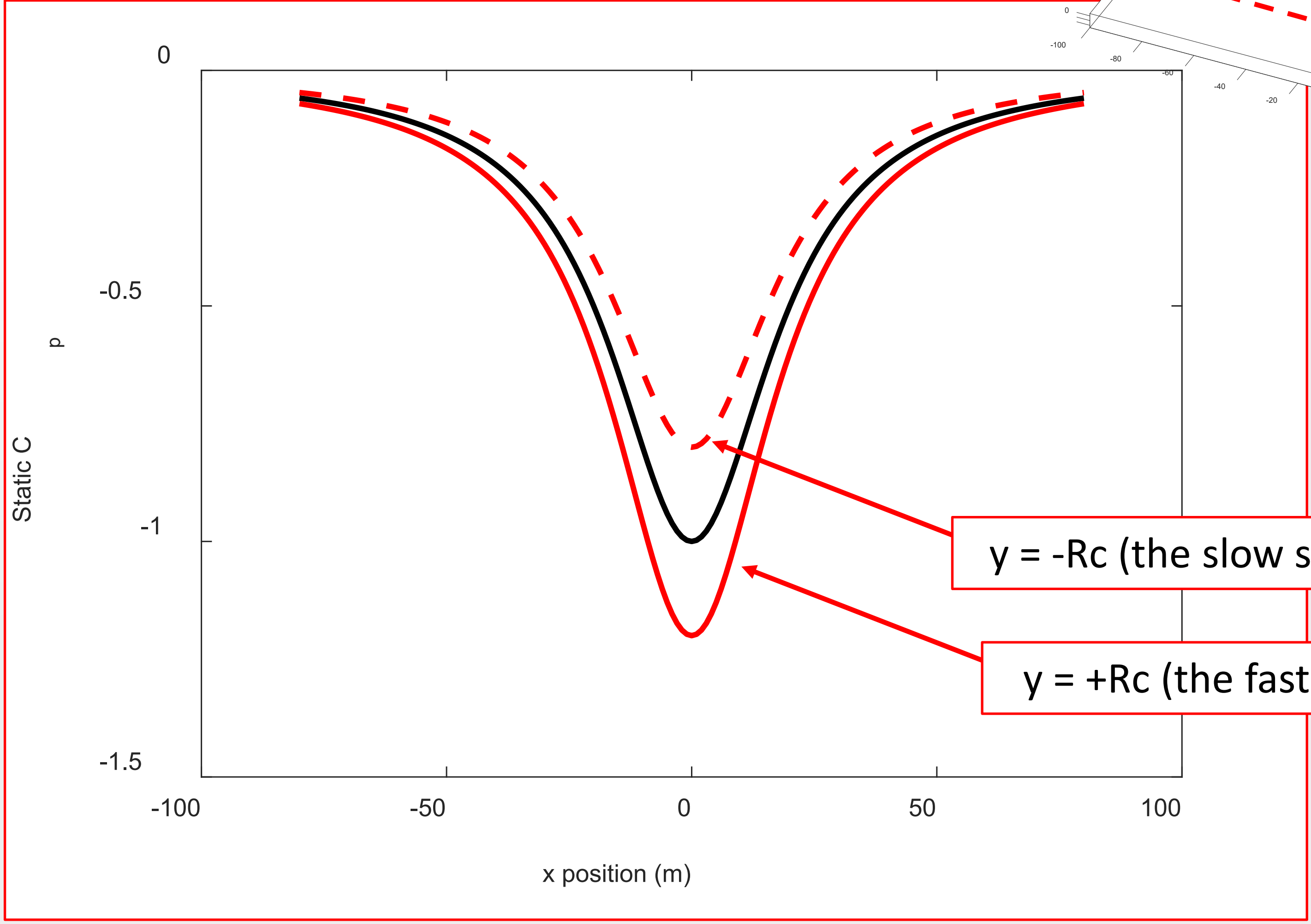
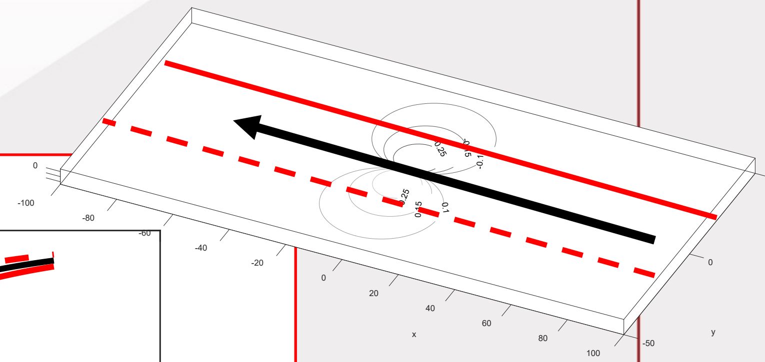
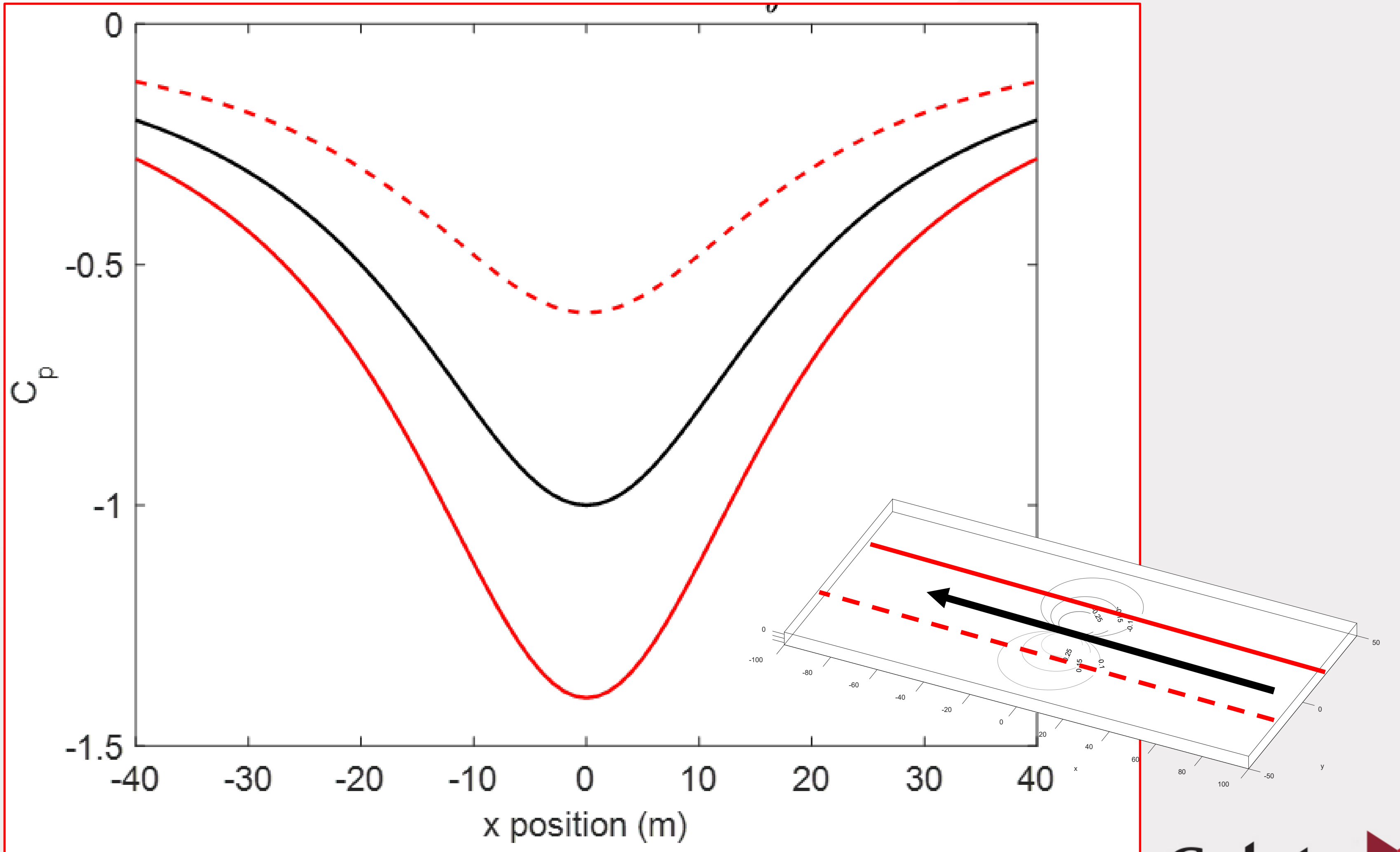
For a translation speed of 10% of the max tangential velocity, the unsteady adjustment to static Cp is ±20%





The effect grows to ±40% if the translation speed is 20% of the max tangential velocity



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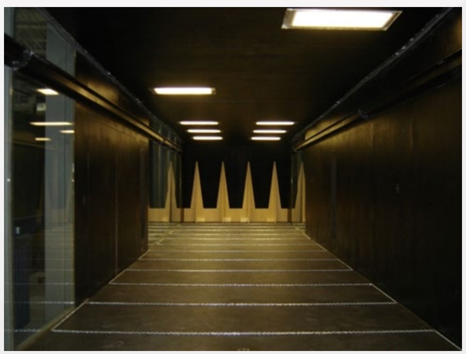
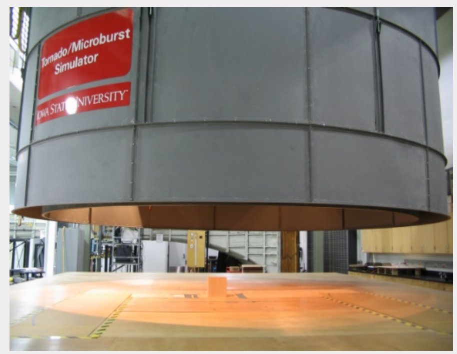
Which type of facility is best suited to study this?

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

Plus the following: $G, S, \dot{\theta}, \dot{\beta}, z_0$





$\dot{\theta}, \dot{\beta}, \dot{V}$ can be tested
Pressure gradients?

Unsteady static pressure

Translation speeds too slow

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Conclusions

Quantifying tornado-induced wind loading will require different types of flow simulation facilities that are good at different scales and different parameter ranges

However:

- We need full scale targets
- We are probably moving to a “post design event” era
- CFD can also be a part of the suite of tools

$$C_p(\theta,\beta) = C_{p_a}(\theta,\beta,Re,S_{uu}) + C_{p_0}(S,Re,V_t,z_0)$$

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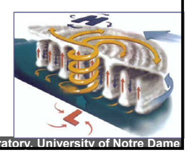
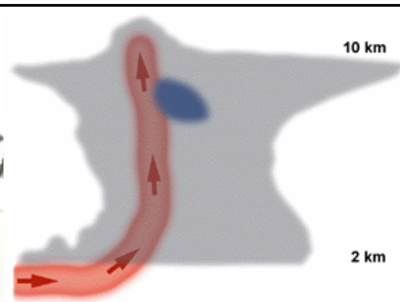
Gust Fronts, Vortical and Convective Systems, Rolls and Intermittency: Changing Dynamic of Wind Fields

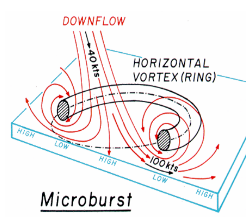
Ahsan Kareem

NatHaz Modeling Laboratory

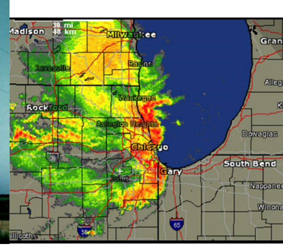
University of Notre Dame







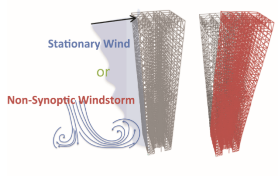
A Gust-Front

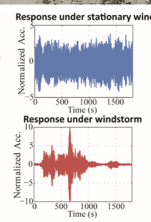


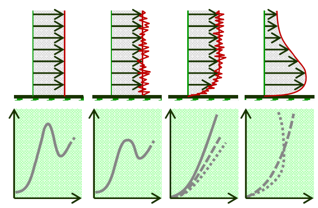
Gust Fronts, Vortical and Convective Systems, Rolls and Intermittency: Changing Dynamic of Wind Fields

Triple Emerging Fronts: The Three Nons

- •Non-Stationarity
- •Non-Linearity
- •Non-Gaussianity







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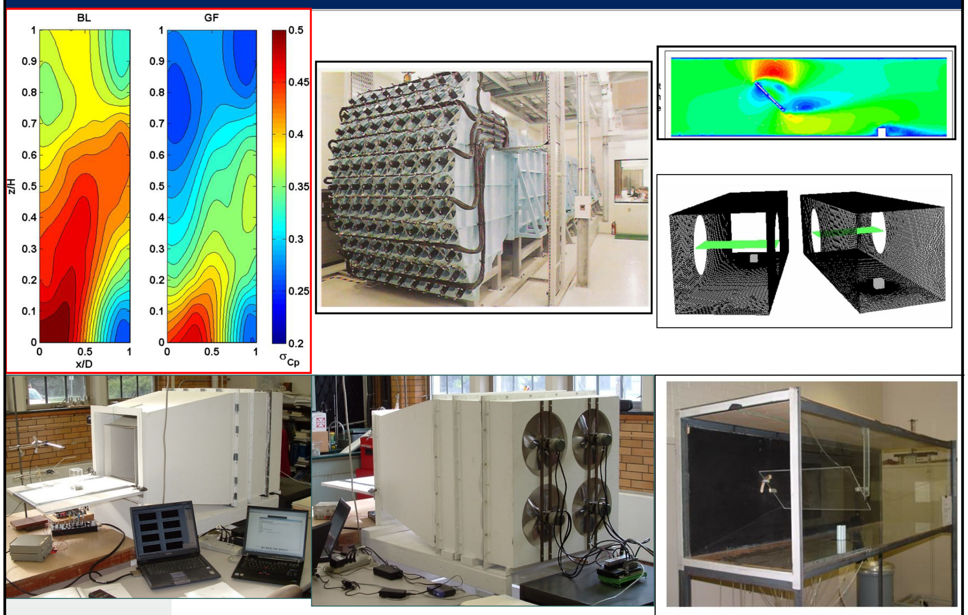
Changing Dynamic

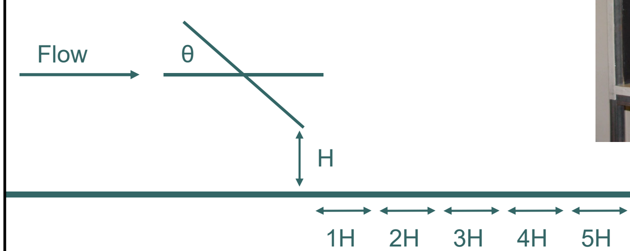
- Revisit the current design paradigm
  - Changing Kinematics of Flow
  - Changing Dynamics of Flow
  - Stationary vs. Transient Winds
  - Mechanical / Convective Turbulence
  - Changing Dynamic of Aerodynamics
  - Resulting Load Effects
- Gust Front Factor
- Turbulence/Intermittence/Synthetic Stochastic Emulation
- Vortical Flows/Urban Aerodynamics
- Accelerating Flows: Cd plus Cm

NatHaz Experimental/Computational Systems



Gust Simulator #1

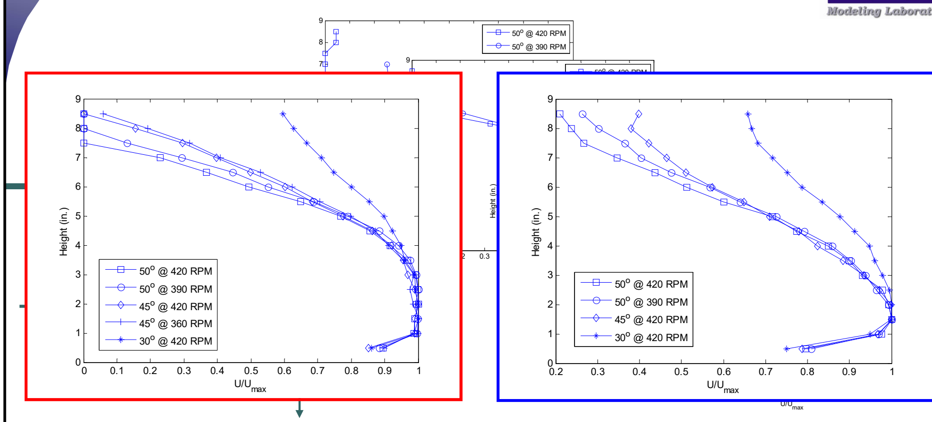
Notre Dame Modeling Laboratory



Results | FP$_{@HI}$

- Flat plate downburst outflow simulation
  - Flow profile was investigated up to 5 outlet diameters (H) and the plate angle was tested between 30° and 50°
    - Mean flow profile evolves into desired flow pattern at 3H – 4H
  - Simulated profile has good agreement with full scale data
    - Above and below the region of maximum outflow
  - Drawbacks
    - Plate motion not completely controlled
    - Fluid dynamics of a flat plate at high incidence (Stahl and Mahmood 1985)

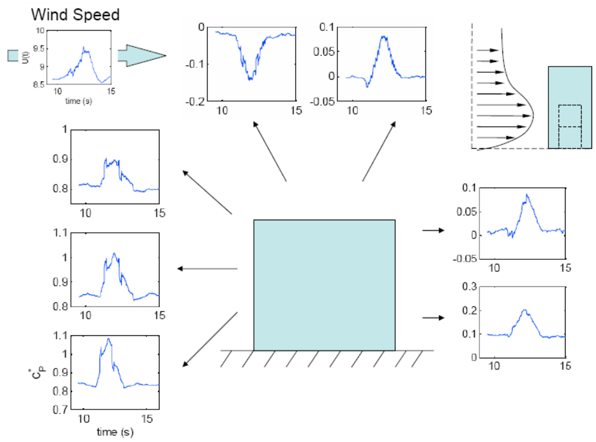
Results | FP$_{@HI}$



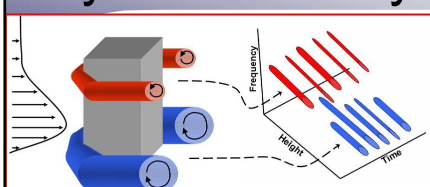
1H 2H 3H 4H 5H

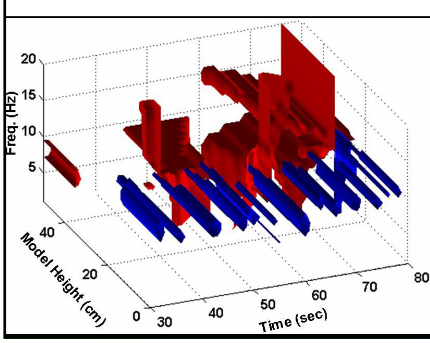
Results | FP$_{@HI}$

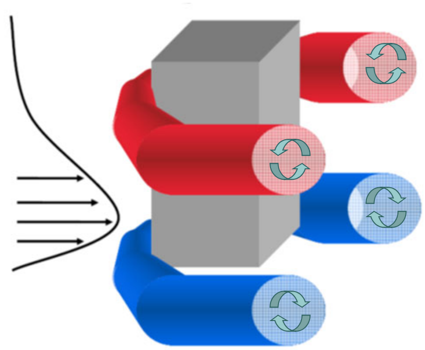
- Model 1 (1:1)
  - Top surface below max. outflow vel.
  - Roof, leeward pressures fluctuate in narrow range
  - Impact dominant on windward surface
- Model 2 (2:1)
  - Top surface at max. outflow vel.
  - Narrow range of fluctuations
  - Response trends similar on all faces
- Model 3 2x(2:1)
  - Top surface above the max. outflow vel.
  - Marked difference on rooftop trailing edge and leeward face
  - Changes in aerodynamics



Synthesis of Dynamics

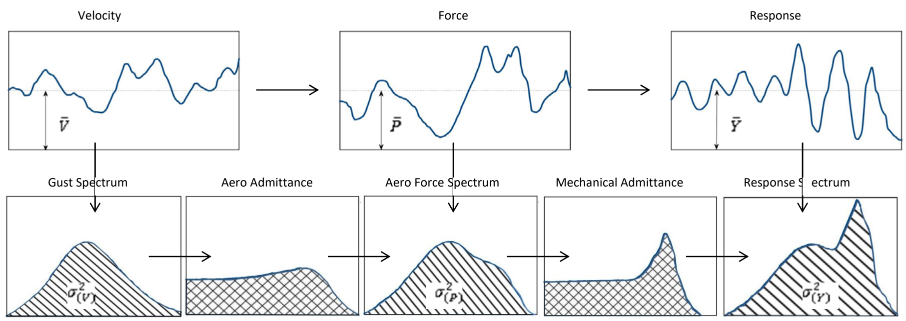






(Wang et al. 2005)

Wind-Loading-Response Dynamics
Time & Frequency Domain



Prevailing School of Practice

- Tacit assumption of
  - Linearity (Gaussian)
  - Stationarity/Homogeneity
- Real World is
  - Non-Linearity (Non-Gaussian)
  - Nonstationary/Non homogeneous

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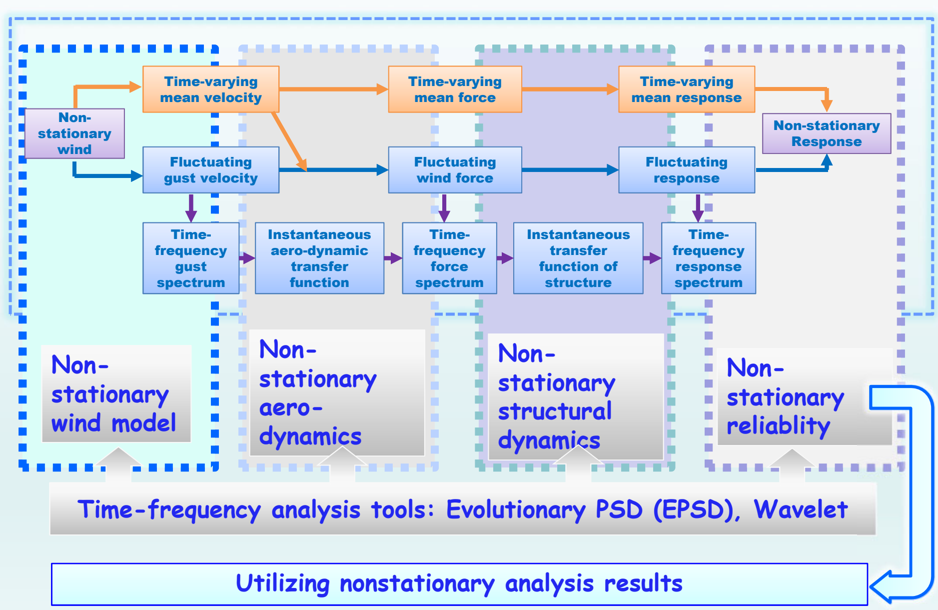
Generalized Wind Loading Chain



Assessing Data Stationarity

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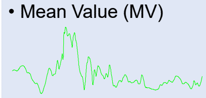
What does it mean for data to be stationary?
- Statistical properties time invariant over entire time series (Bendat and Piersol 2010)
  - For practicality, may consider only first two moments or use intervals
- Definition implies that non-stationary processes contain some structured organization in time

Why is data stationarity important?
- Allows for analysis in the frequency domain
  - Underlying stationary assumption when performing FT
- Many system ID and structural analysis techniques require it
  - HPBW
  - Frequency Domain Decomposition

How does non-stationarity manifest itself?
- Mean Value (MV)



- Variance (AM)

- Frequency (FM)

- MV/AM/FM

How do we test for stationarity?
- Assume non-stationarity manifests itself as time-varying trends in mean square values of data
  - Run test
  - Reverse arrangements test

- Tests determine only whether a signal is random (Cappa et al., 2001)
- May not be appropriate for assessing signals with time-varying frequency content (Beck et al., 2006)

Averaging Interval Approaches

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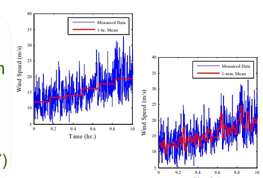
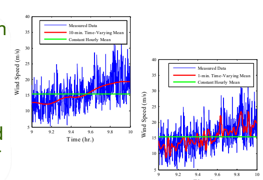
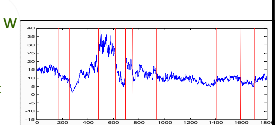
Fixed Averaging Interval for Stationary Data (FAI)
- Effective for atmospheric boundary-layer winds
- Longitudinal wind speed assumed to be stationary random process: $U(t) = \bar{U} + u(t)$
- User-defined interval:
  - 10-min. (AIJ Recommendations), 1-hr. (NBC), 3-sec. (ASCE7)



Fixed Averaging Interval for Non-Stationary Data (FAI-NS)
- Decompose data into time-varying mean and fluctuating component using DWT or EMD: $U(t) = \bar{U}(t) + u'(t)$
- User-defined interval must still be specified
- After detrend, fluctuating component may be assumed as zero-mean stationary Gaussian or Gaussian-like process



Variable Averaging Interval (VAI)
- Data-driven: determine intervals based on measured wind data itself
- Find variable blocks which are uncorrelated:
  - Time dependent memory method (TDMM)
  - Trend-detection method
  - Decorrelation scale
  - Statistical method: t-test
  - Confidence interval
  - Penalized contrast (PC)
- Linear detrend using least square regression fit



NatHaz Comparison : boundary-layer vs. Gust-front

Boundary-layer

- Stationary
  : Time-invariant
- Vertical profile
  : Power / Logarithmic law
- Codes and standards
  : Gust loading factor (G_{GLF})
  : Gust effect factor (G_f)
  - ASCE 7

$$F_{Design,B-L} = F_{ASCE7} = (static\ force) \cdot G_f$$

Gust-front

- Nonstationary
  : Time-dependent
- Vertical profile
  : Nose-shape profile
- Codes and standards
  : Introducing new factor

$$F_{Design,G-F} = F_{ASCE7} \cdot [?]$$

Gust-front factor NatHaz Modeling Laboratory, University of Notre Dame

NatHaz GLF, GFF and Generalized GFF

- Conventional GLF - Stationary model

[Constant mean] + [Stationary fluctuations]
: Constant peak factor, g & Constant RMS response, σ

- GLF

$$G_{GLF} = \frac{\max[x_{B-L}(z,t)]}{\mathrm{mean}[x_{B-L}(z,t)]}$$

- GFF approach - Nonstationary model

[Time-dependent mean] + [Nonstationary fluctuations]
: Time-dep. peak factor, $g(t)$ & Time-dep. RMS response, $\sigma(t)$
: Utilizing in conjunction with ASCE 7

- GFF

$$G_{G-F} = \frac{\max[x_{G-F}(z,t)]}{\max[x_{B-L}(z,t)]}$$

- Generalized GFF approach

-Nonstationary model, akin to conventional GLF
: Accounting for dynamic effects of gust-front winds

- Generalized GFF

$$G_{G,G-F} = \frac{\max[x_{G-F}(z,t)]}{mean[x_{G-F}(z,t)]}$$

Gust-front factor NatHaz Modeling Laboratory, University of Notre Dame

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Relationship Nouveau

Kinematic Effects (Velocity Pressure Coefficient)

$K_{z,G-F}, I_1$

Rise-Time Effects (Pulse Dynamics Factor)

$I_2 = \frac{\hat{R}}{\bar{R}}$

Gust-front factor : $G_{G\text{-}F}$

$$F_{Design} = F_{ASCE7} \cdot K_{z,G-F} \cdot G_{G-F}$$

$$G_{G-F} = I_1 \cdot I_2 \cdot I_3 \cdot I_4$$

Nonstationary Turbulence Effects (Structural Dynamics Factor)

$$I_3 = \frac{[1 + \max(\tilde{y}_{G-F}) / \max(\bar{y}_{G-F})]}{G_{GLF}}$$

Transient Aerodynamics Effects (Load Modification Factor)

$$I_4 = \frac{f(C_D; C_M)_{transient}}{f(C_D)_{steady}}$$

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Features of Gust-front factor framework

Relationship nouveau | Robust & Versatile | Usability-based framework

Usability-Based framework

: Dealing with sophisticated computations

: Offering easy analysis/design step …

: Accommodates user expertise

Web-based design

http://gff.ce.nd.edu

NatHaz Preliminary Uncertainty Analysis (I)

- Six uncertain parameters considered
  - $V_{3\text{-}s}$ = 3-sec gust; z_{max} = vertical profile parameter; t_d = time function parameter; c_1 = turbulence parameter; n_0 = fundamental frequency of structure; ξ = damping ratio
  - Coeff. of Variations (COV) of 0.2 except n_0 = 0.05 & ξ = 0.4
- Wind load factor (γ_w)
  - To assess the level of uncertainties associated with the wind induced load effects (base moment, in this study)

$$\boxed{\gamma_w = \left(\frac{\mu_W}{W_n}\right)\frac{\exp\left[\beta\varepsilon_\ell\sqrt{\ln\left(1+V_W^2\right)}\right]}{\sqrt{1+V_W^2}}}$$

Wind load factors for dynamically sensitive structures with uncertainties (Kwon et al. 2015)

NatHaz Preliminary Uncertainty Analysis (II)

- Load factor is significant for gust front winds
  - Synoptic winds: ASCE 7 = 1.6; Kwon et al. 2015 = 1.9
- $V_{3\text{-}s}$ is predominant (red)
  - Z_{max} is the second influential parameter
- The effects of turbulence intensity (c_1) is rather marginal as compared to $V_{3\text{-}s}$ & Z_{max}
- Dynamic effects by gust front winds are less significant than static/quasi-static and kinematic effect (relatively small contributions from c_1, n_0, ξ)

Example: CAARC standard tall building

	Inputs		Load factor (γ_w)	Base moment		Generalized GFF $G_{G,G\text{-}F}$	
	Mean	COV		Mean [2]	COV	Mean	COV
Exposure C							
All[1]	–	–	3.270	2.296	0.629	1.448	0.073
$V_{3\text{-}s}$	40 m/s	0.20	2.315	2.151	0.427	1.448	0.007
z_{max}	60.35 m	0.20	1.269	2.027	0.124	1.449	0.005
t_d	200 sec	0.20	1.022	2.065	0.011	1.446	0.011
c_1	0.134	0.20	1.141	2.067	0.062	1.447	0.062
n_0	0.17 Hz	0.05	1.002	2.068	0.001	1.448	0.001
ζ	0.01	0.40	1.005	2.069	0.002	1.448	0.002
Exposure B							
All[1]	–	–	3.115	2.499	0.600	1.661	0.094
$V_{3\text{-}s}$	40 m/s	0.20	2.292	2.377	0.419	1.660	0.006
z_{max}	80.47 m	0.20	1.186	2.227	0.092	1.661	0.005
t_d	200 sec	0.20	1.027	2.277	0.013	1.658	0.013
c_1	0.201	0.20	1.185	2.278	0.008	1.659	0.080
n_0	0.17 Hz	0.05	1.0047	2.279	0.002	1.660	0.002
ζ	0.01	0.40	1.003	2.280	0.002	1.660	0.002

All: all uncertain parameters are considered

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Urban Aerodynamics (The Black Swans)

Vortical Flows in street canyons

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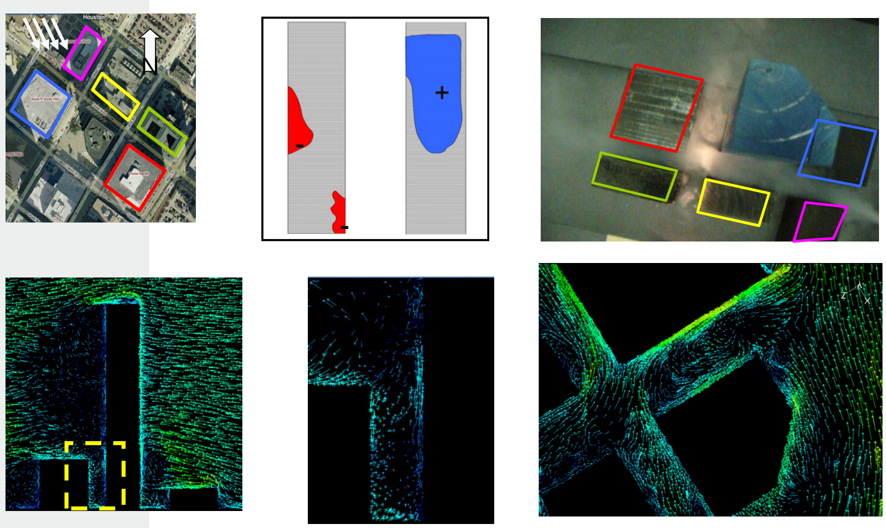
Flow Field



Impact of Extreme Wind Events

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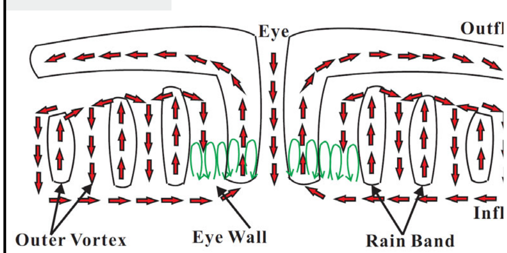

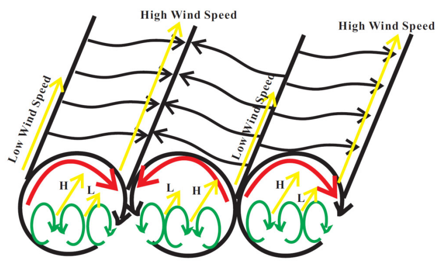

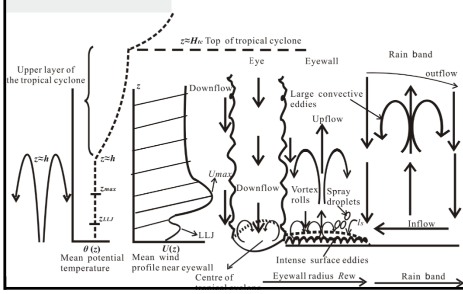

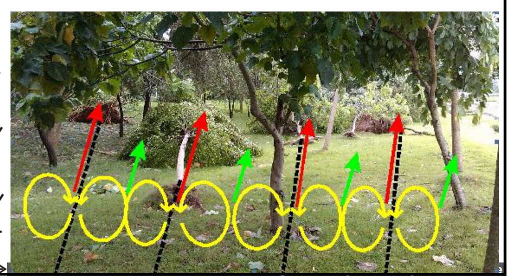

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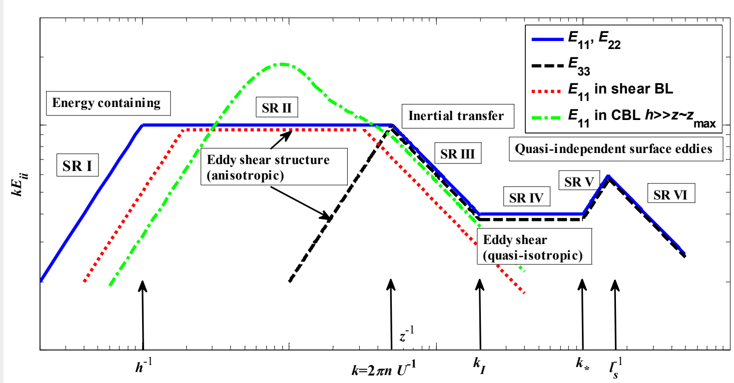
CONCEPTUAL FRAMEWORK FOR TURBULENCE SPECTRA IN TC WINDS

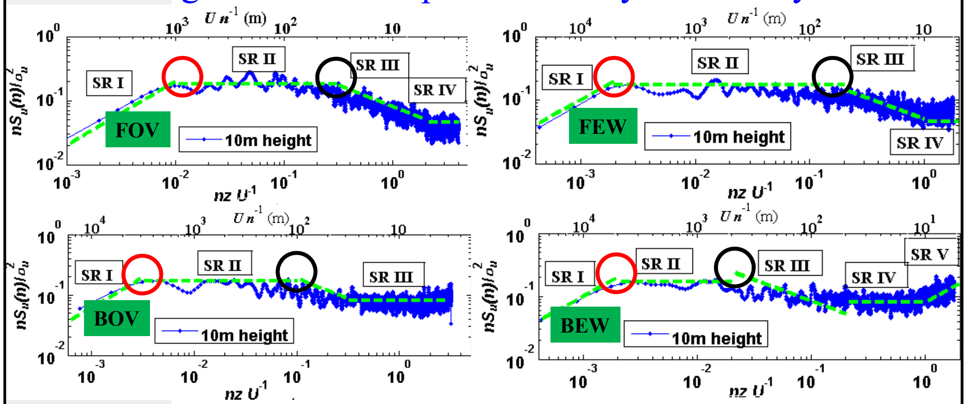


Dirac….”A theory with mathematical beauty is more likely to be correct than an ugly one that fits some experimental data’

NatHaz

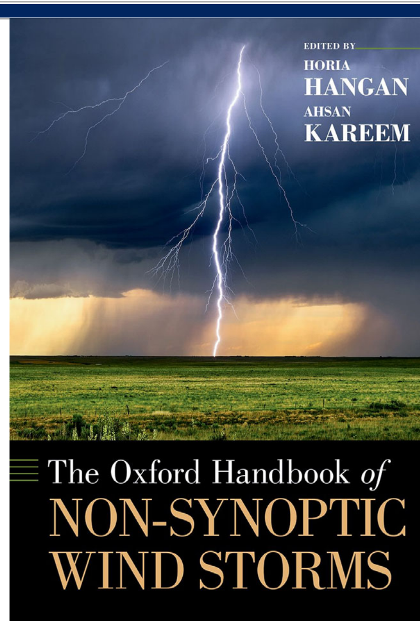
FIELD MEASURED TURBULENCE SPE CTRA

Longitudinal wind spectra in Eddy surface layer



- There are two dominant scales in the longitudinal spectra at the eddy surface layer. The first scale is related to the Euleria n integral scale, which is changed with the roughness length, height and mean wind speed; the second scale is related to t he height of measurement conducted, it increase significantly with increase of mean wind speed and height.
- SR II is a self-similar spectral range, where the main mechanism is formation of elongated shear eddy structures. Since these eddies only interact weakly with each other in this surface layer, this transfer process does not involve an eddy to e ddy (or 'staircase-like') energy cascade

NatHaz



Narrowband Components in Two-Celled Vortices Generated in a Tornado Simulator

Delong Zuo
National Wind Institute
Texas Tech University

Boundary Layer Wind Tunnel Simulation of Transient and Non-synoptic Wind Events Workshop
University of Florida, May 19, 2021

Motivation

Knowledge Gaps

- Understanding of turbulence and fluctuating pressure in tornado-like flows
- Understanding of the differences between tornadic loading and loading by boundary-layer type winds on structures

Objectives

- Physical simulation of tornado-like vortices
- Evaluation of tornado-like loading on structures

VorTECH at Texas Tech University

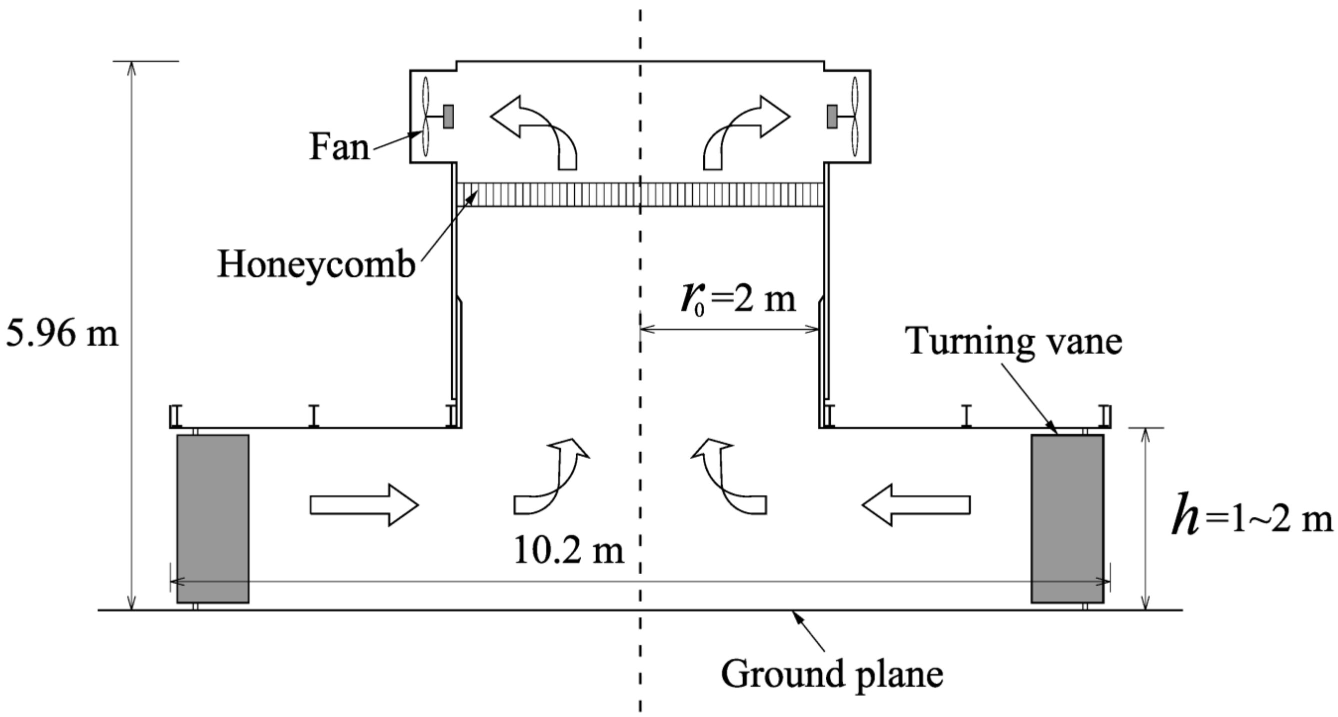
Key Features

- Ward-type simulator
- Diameter of testing chamber: 10.2 m
- Diameter of updraft hole: 4 m
- Height of (64) turning vanes: 1 m to 1.7 m
- Translation of floor: up to 1.46 m/s constant speed over at least 4 m

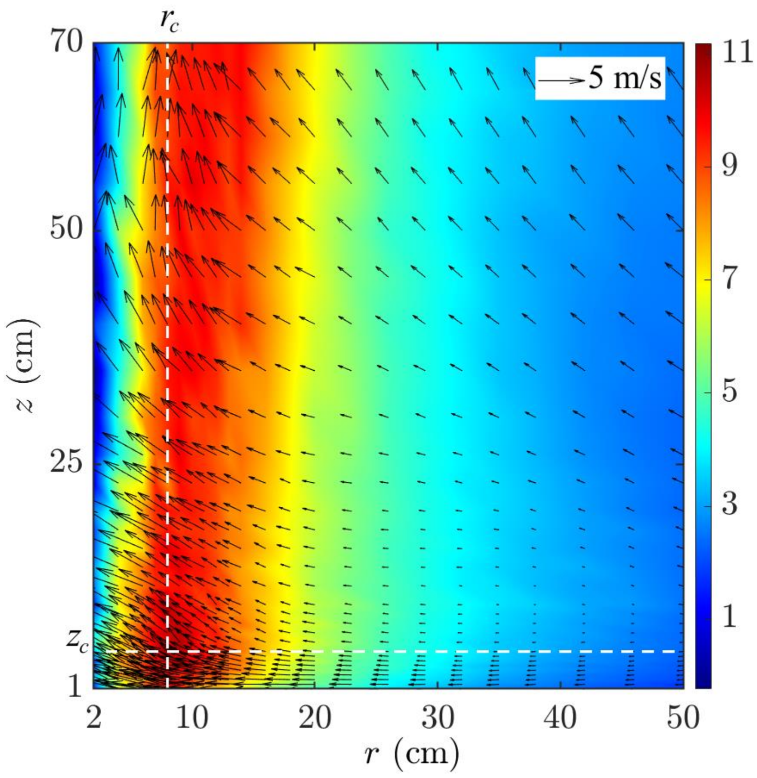
Governing Parameters

Governing Parameters of Tornado Simulation

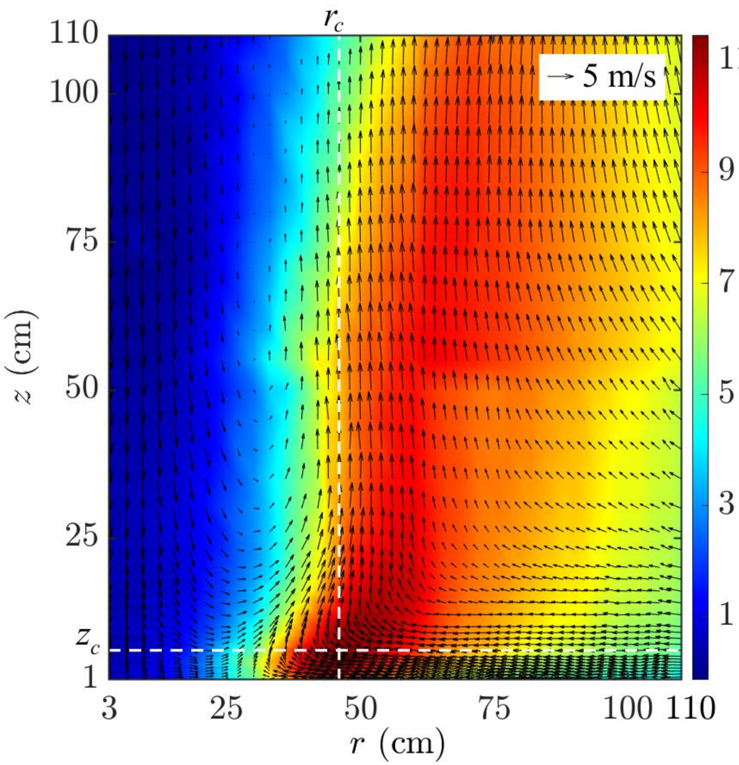
Parameter	Definition	Achievable in VorTECH
Aspect ratio	$a=h/r_0$	$0.5\leq a \leq 0.85$
Swirl ratio	$S=\Gamma r_0/(2Qh)$	$0< S <3.6$
Radial Reynolds number	$Re_r=Q/(2\pi v)$	$\leq 7.21\times 10^5$



Example Mean Velocity Fields of Vortices

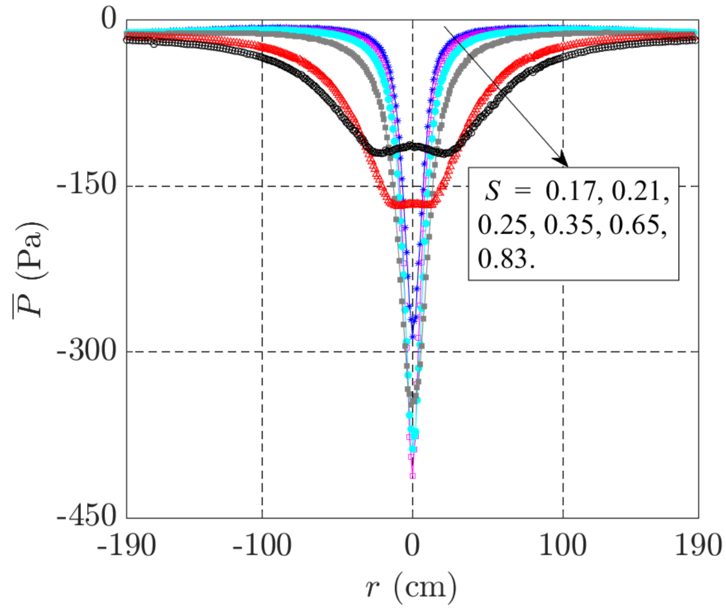


$S = 0.17;\quad Re_r = 6.46\times10^5$

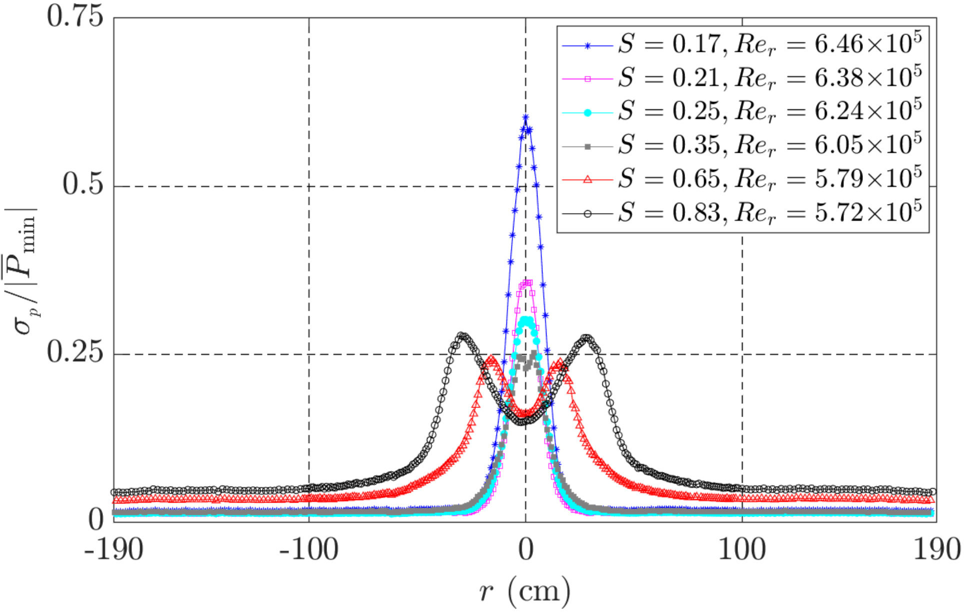


$S = 0.83;\quad Re_r = 5.72\times10^5$

Transition of Surface Pressure Characteristics

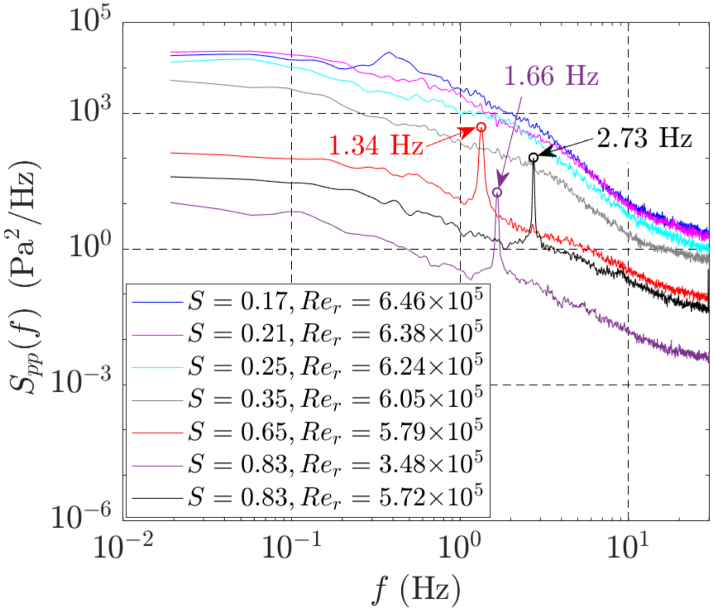


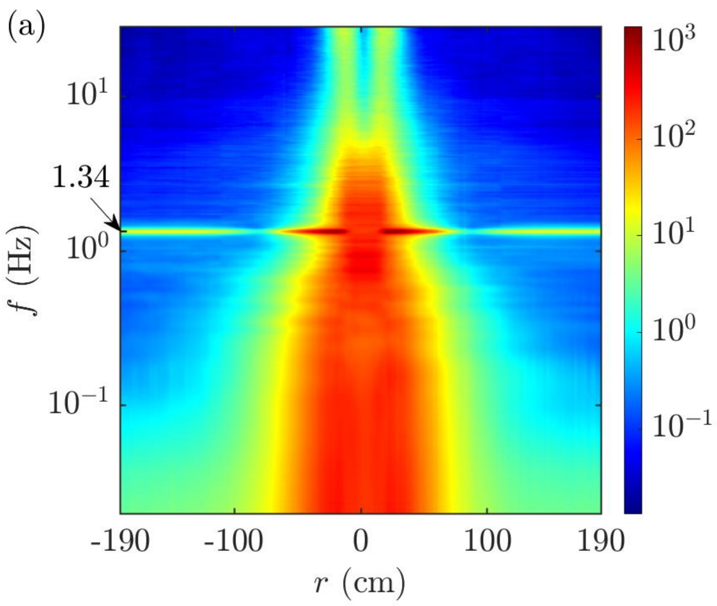
Radial Profile of Mean Pressure Deficit



Radial Profile of Standard Deviation of Pressure Deficit

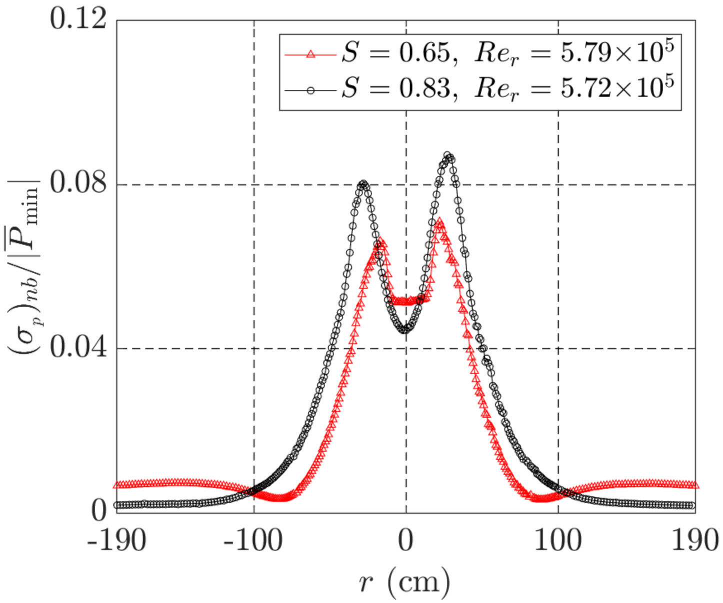
Narrowband Components in Surface Pressure

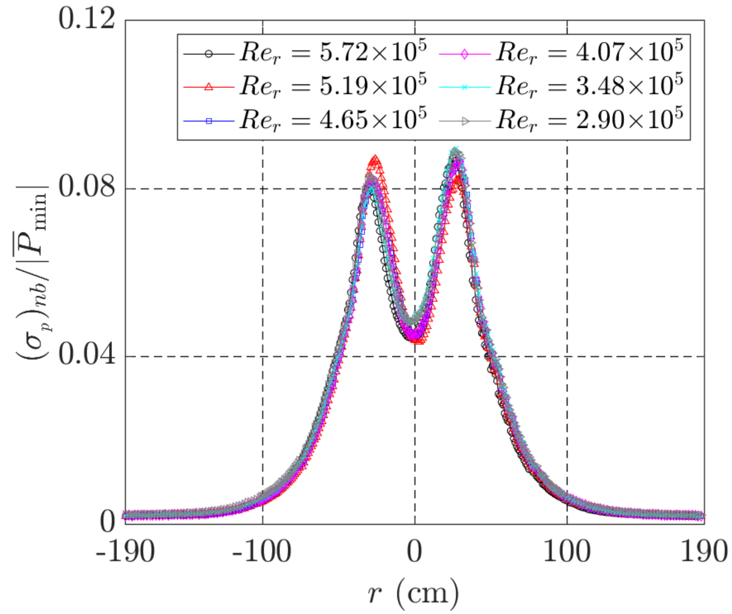


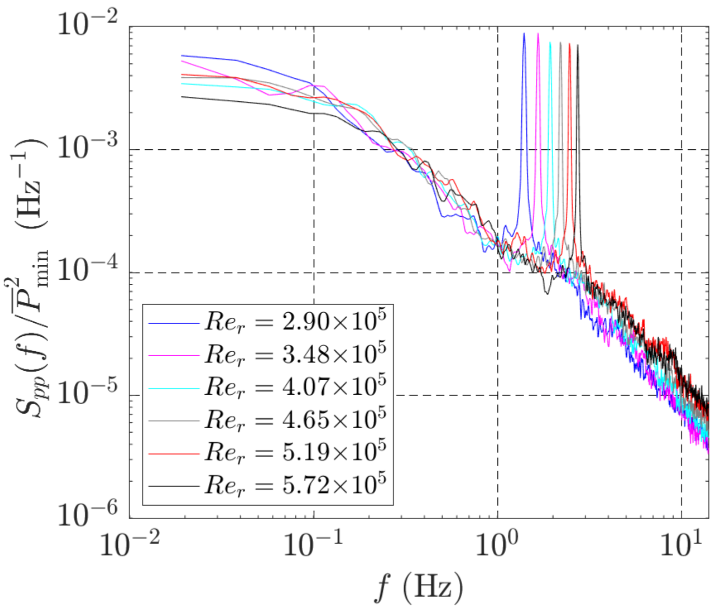


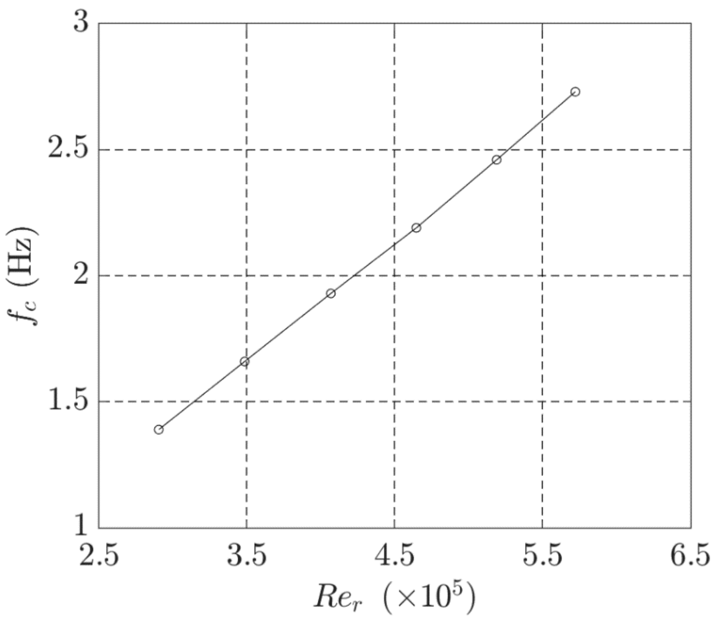
$S = 0.65; \quad Re_r = 5.79\times10^5$

Dependence of Narrowband Components on Controlling Parameters

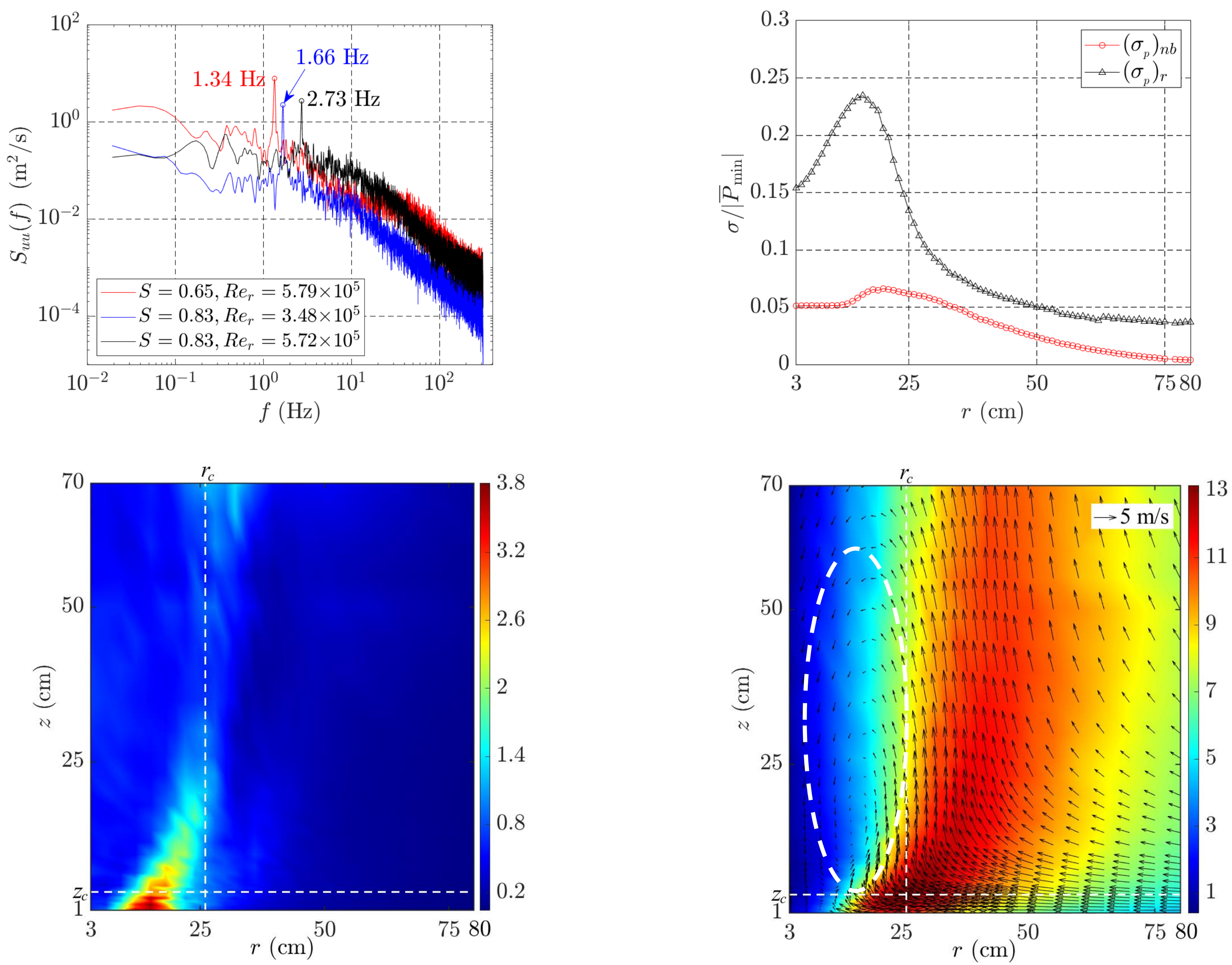




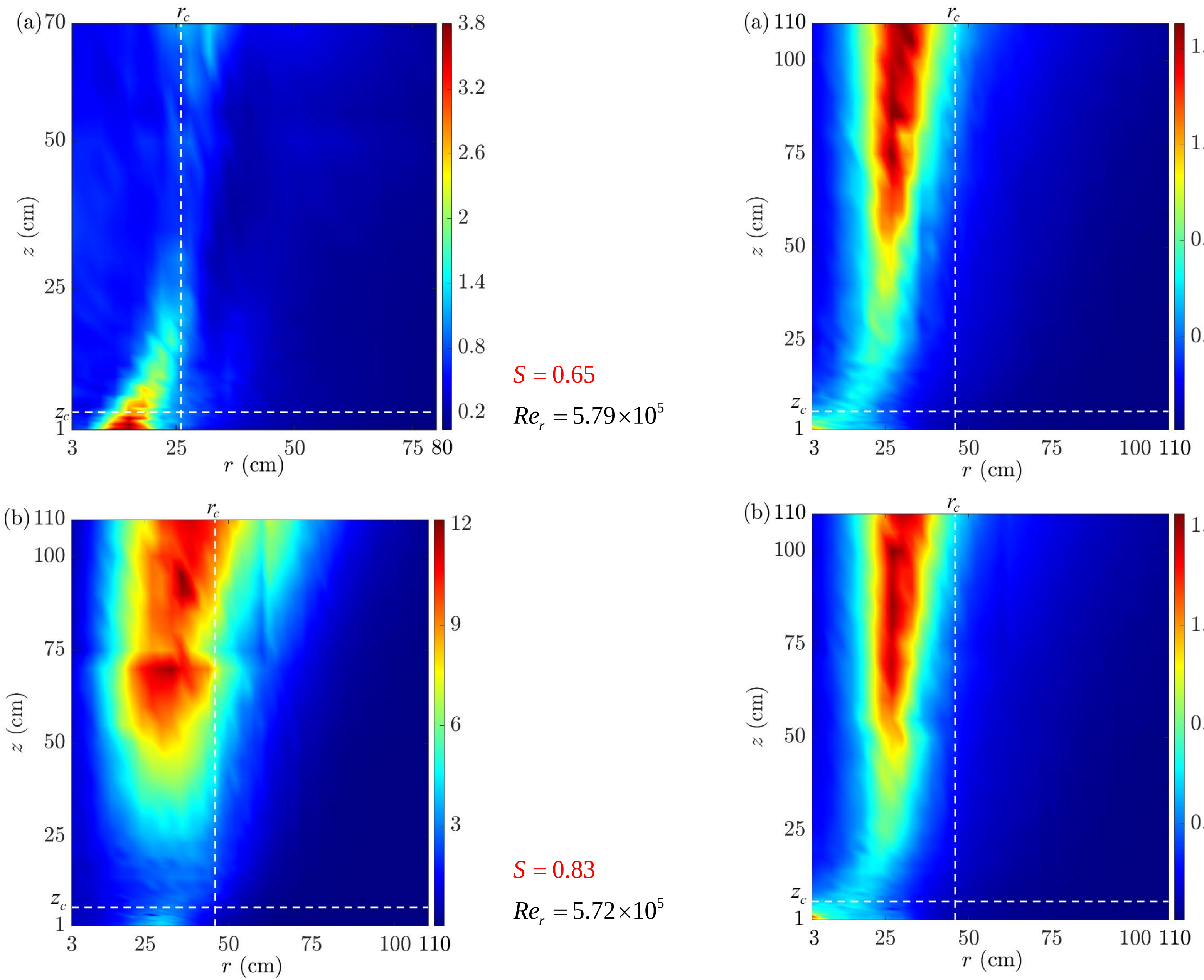




Narrowband Components in Flow Velocity



Dependence of Narrowband Components on Controlling Parameters



$S = 0.65$

$Re_r = 5.79\times10^5$

$S = 0.83$

$Re_r = 5.72\times10^5$

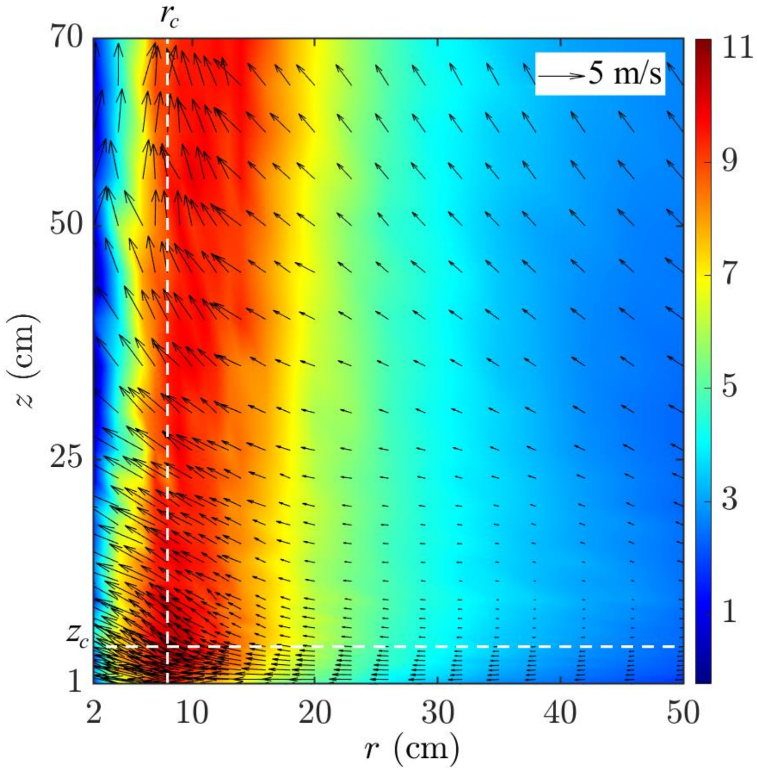
$S = 0.83$

$Re_r = 3.48\times10^5$

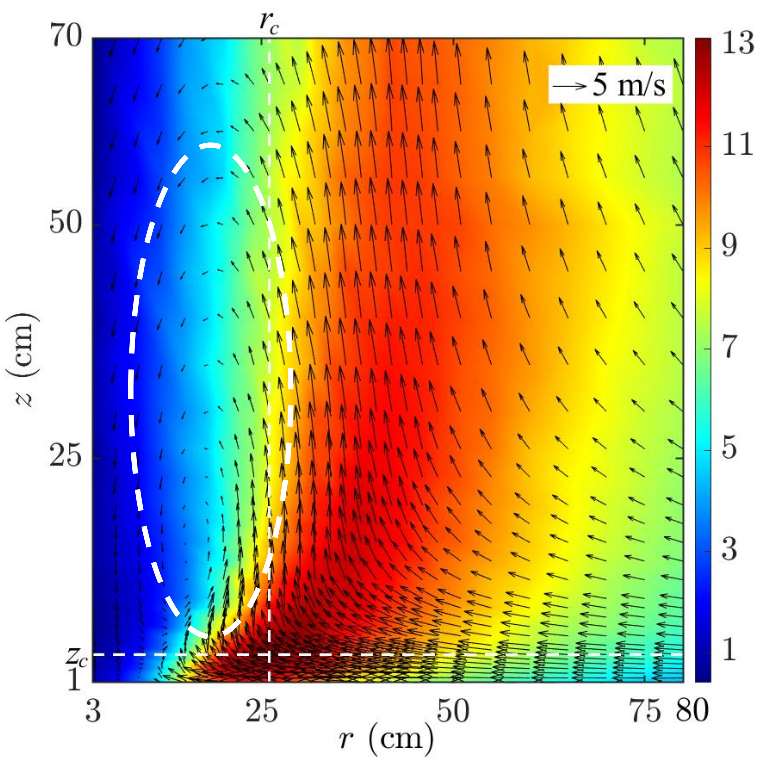
$S = 0.83$

$Re_r = 5.72\times10^5$

Single-Celled Vortex vs. Two-Celled Vortex



$S = 0.17; \quad Re_r = 6.46\times10^5$



$S = 0.65; \quad Re_r = 5.79\times10^5$

UF NHERI Virtual Workshop
Transient and Non-synoptic Wind Events
May 19, 2021

AI-EMPOWERED WIND TUNNEL FOR TRANSIENT AERODYNAMICS

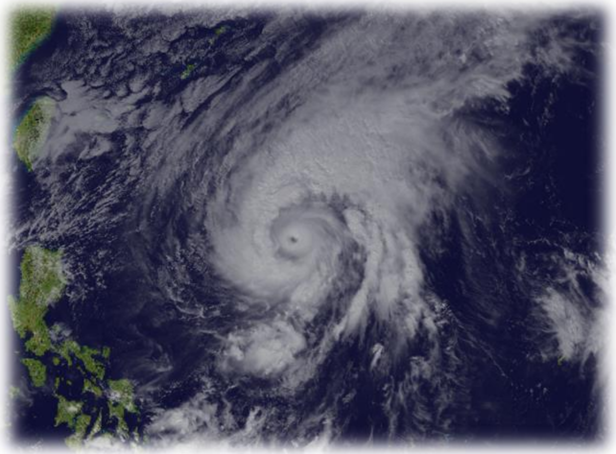
Teng Wu
University at Buffalo

University at Buffalo
Institute of Bridge Engineering
School of Engineering and Applied Sciences

MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS

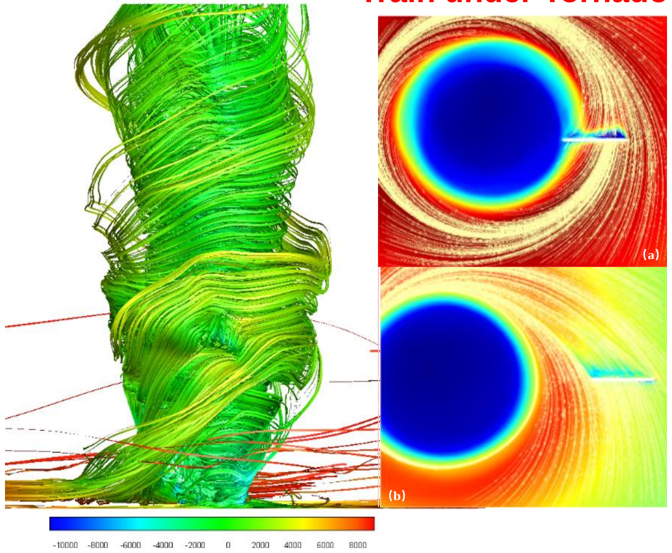
Background

Teng Wu
05/19/2021

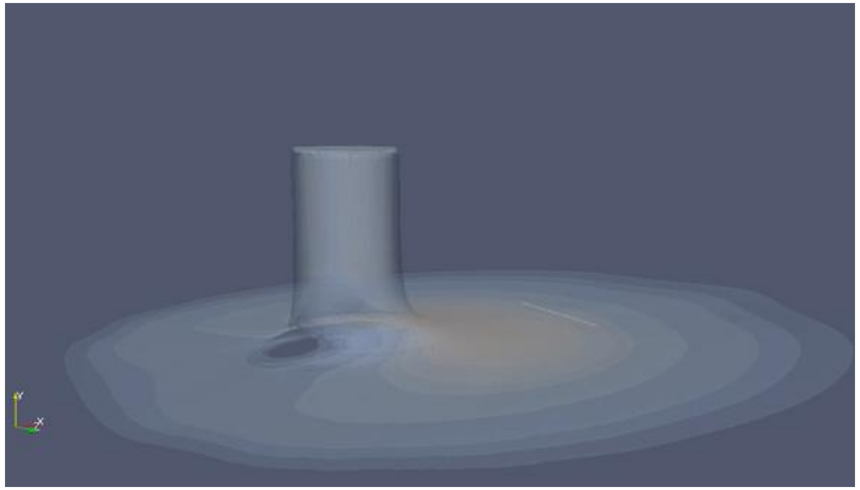


Numerical Simulation

Train under Tornado



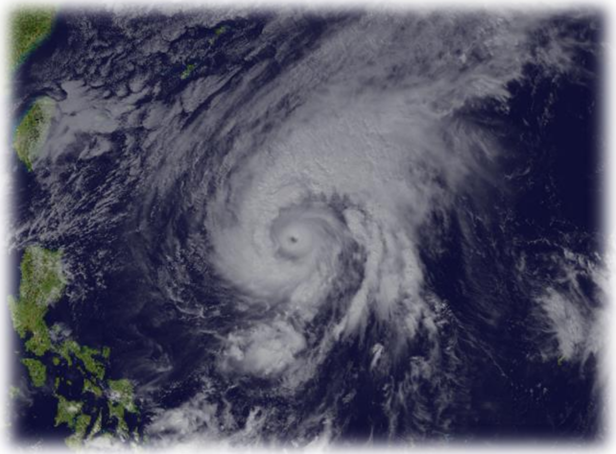
Bridge under Downburst



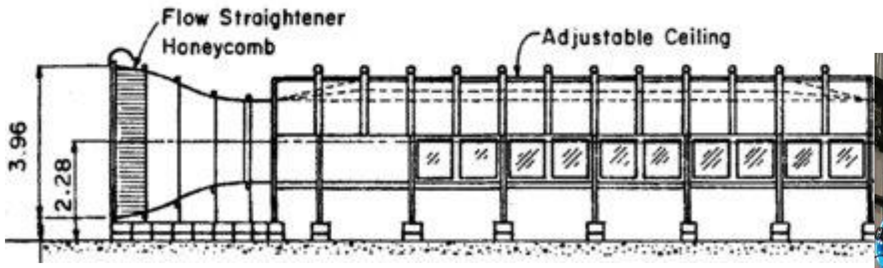
Zero-thickness Flat Plate

Background

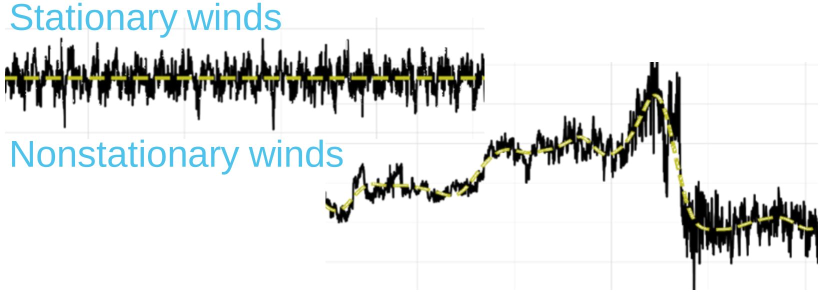
Teng Wu
05/19/2021



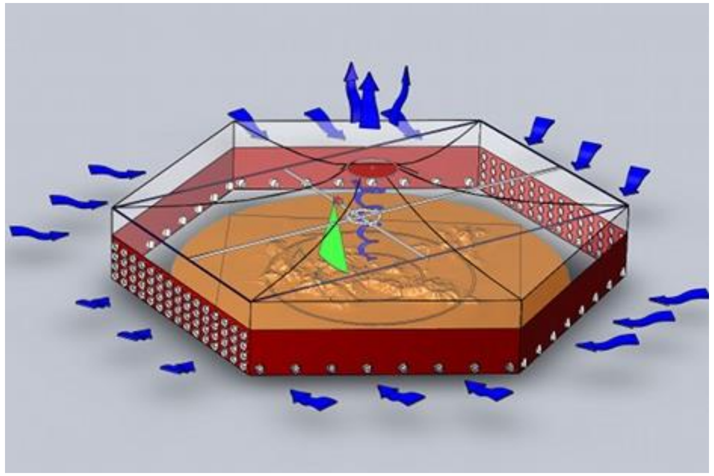
Physical Modeling



The first-of-its-kind Boundary Layer Wind Tunnel

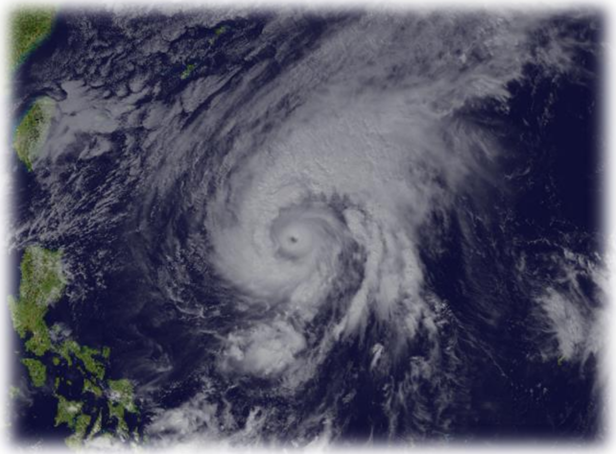


WindEEE @ Western University



AI-Empowered Transient Wind Simulation

Teng Wu
05/19/2021



Physical Modeling

Multiple-fan wind tunnel @ UB

A power section:
A fan matrix, 8 by 8 individually controlled fans with low-inertia high-speed Yaskawa AC servo motors, followed by honeycombs and a vibration isolation module

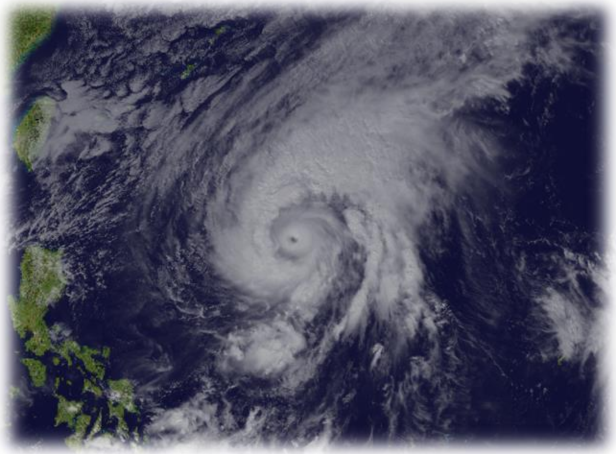
A moveable settling chamber:
Three damping screens

Six interchangeable sections:
A maximum overall length of 9m, including a test section for vertical structure and a test section for horizontal structure

- The selected motors together with customized fan blades and fan fairings permit **a wind speed change of 4 m/s in less than 0.3 s** (measured at cross section center 0.8 m from the power section exit)
- It also permits **a maximum frequency response of approximately 12 Hz**
- Maximum rotation speed: **6000 RPM**
- Maximum wind speed: **20m/s**
- Turbulence intensity: less than **1.5%**

AI-Empowered Transient Wind Simulation

University at Buffalo
The State University of New York
WindHub
Teng Wu
05/19/2021

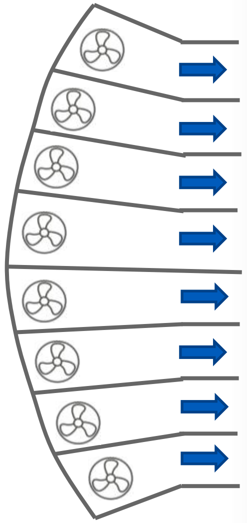


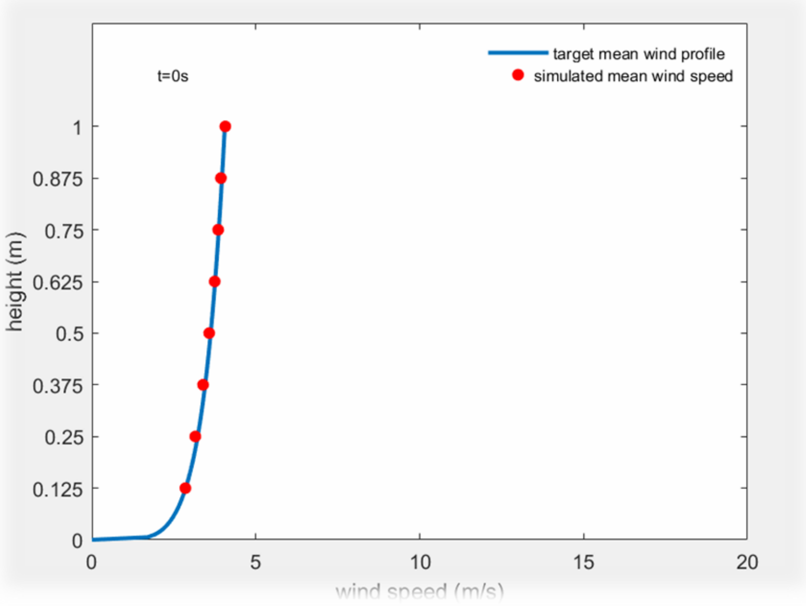
Physical Modeling

Multiple-fan wind tunnel @ UB

Control output:
RPM change for next time step $\Delta \boldsymbol{R}(t+\Delta t)$

Control input:
Measured wind speed at current time step $\boldsymbol{U}_{measure}(t)$;
Target wind speed for next time step $\boldsymbol{U}_{target}(t+\Delta t)$;
Previous command histories $[\Delta \boldsymbol{R}(t), \Delta \boldsymbol{R}(t-\Delta t), \Delta \boldsymbol{R}(t-2\Delta t), \ldots \Delta \boldsymbol{R}(t-n_{lim}\Delta t)]$.





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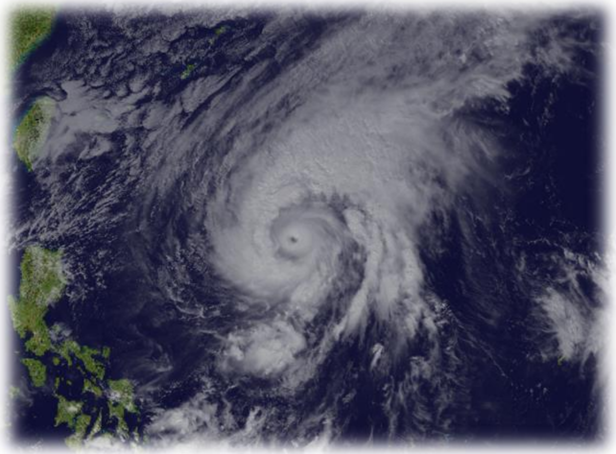
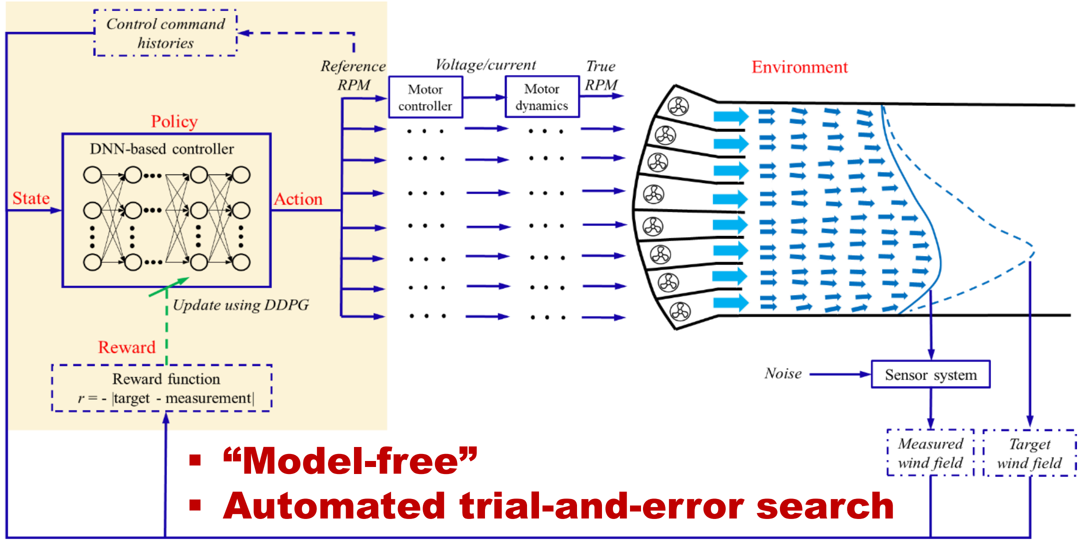


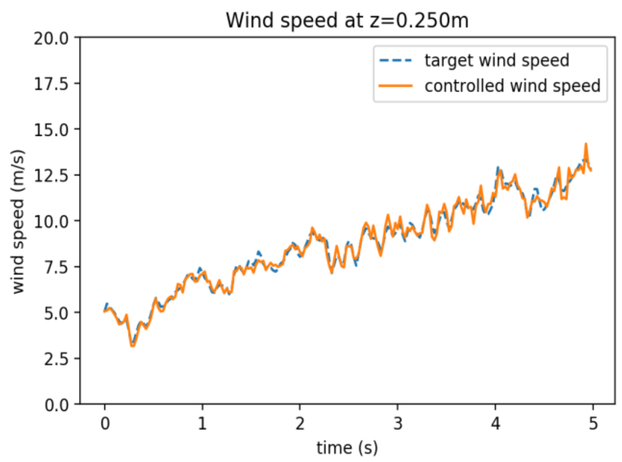
Physical Modeling

Multiple-fan wind tunnel @ UB

Deep Reinforcement Learning-based Control System



- **"Model-free"**
- **Automated trial-and-error search**



Li, S., Snaiki, R. and Wu, T., 2021. Active Simulation of Transient Wind Field in a Multiple-Fan Wind Tunnel via Deep Reinforcement Learning. *Journal of Engineering Mechanics*, In Press.

AI-Empowered Transient Aerodynamics Simulation

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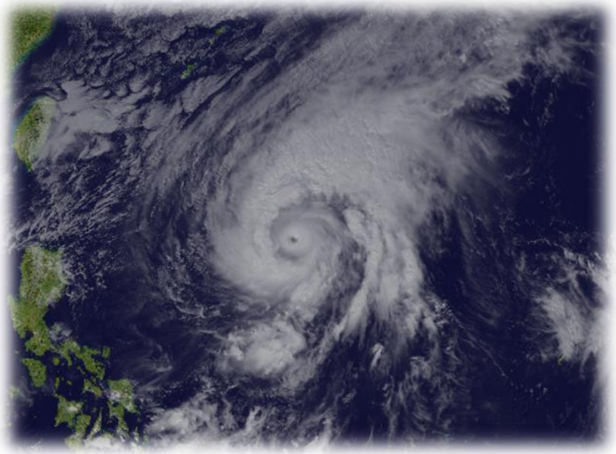

Physical Modeling

Multiple-fan wind tunnel @ UB

Performance-Based Wind Engineering

- Large Motion
- Structural Nonlinearity
- Complex Dynamics

AI-Empowered Transient Aerodynamics Simulation

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The State University of New York
WindHub

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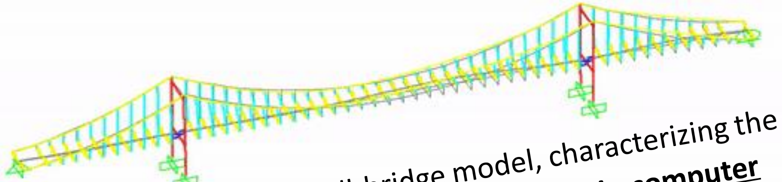
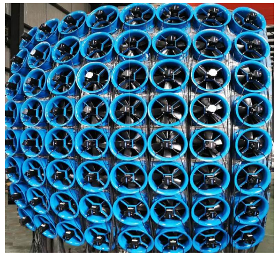


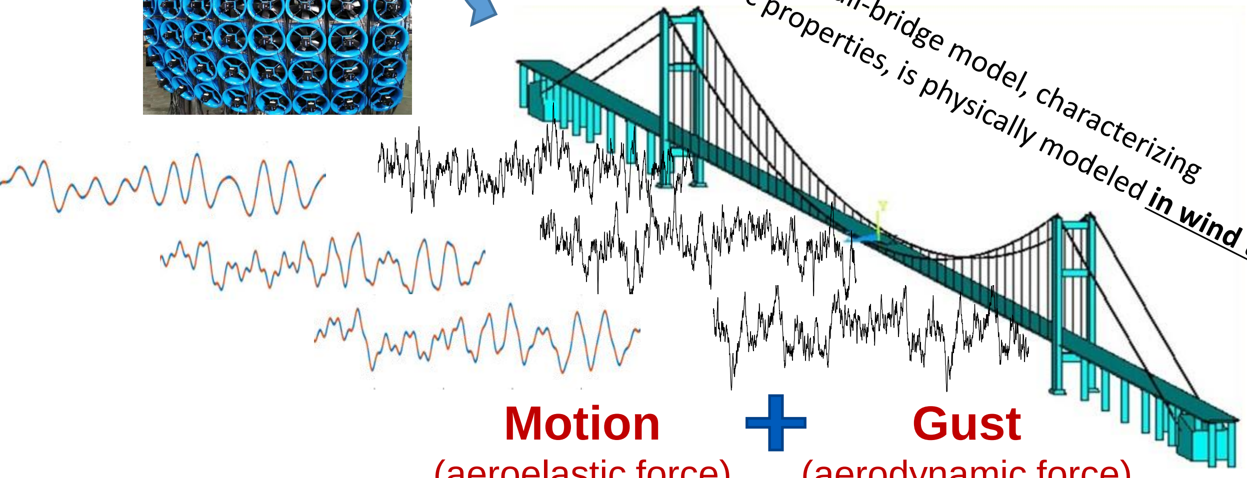
"Skeleton" of the full-bridge model, characterizing the dynamic properties, is numerically simulated **in computer**

Displacements

Interactions between skeleton and skin are accomplished through a system consisting of sensors, a network of actuators, and controllers



"Skin" of the full-bridge model, characterizing aerodynamic properties, is physically modeled **in wind tunnel**

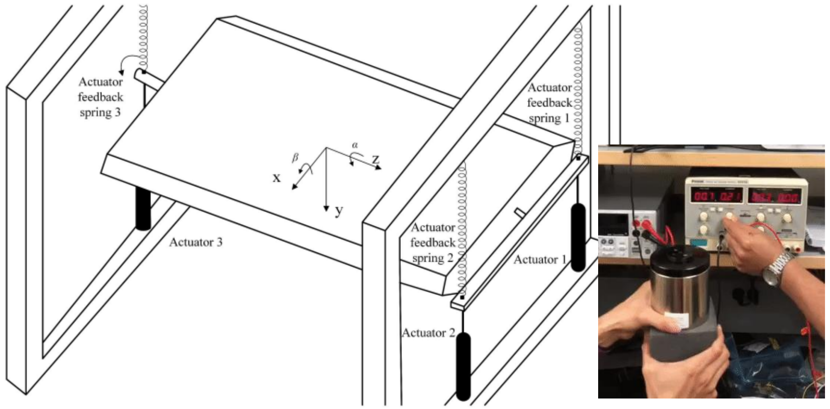


Aerodynamic & aeroelastic forces

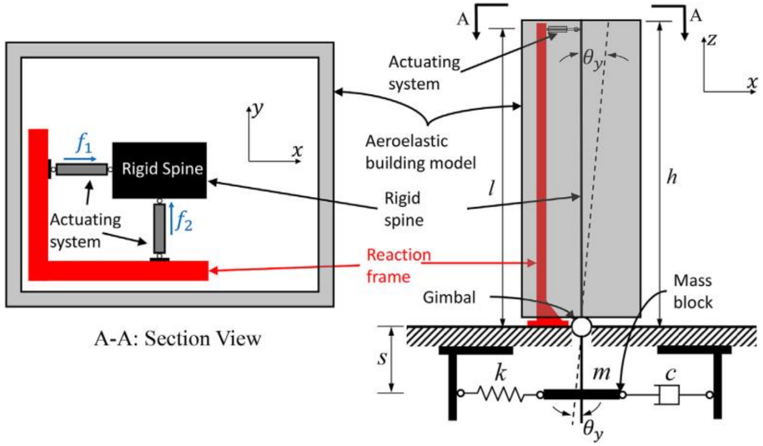
Motion (aeroelastic force) + **Gust** (aerodynamic force)

Real-Time **Aerodynamics** Hybrid Simulation

Digital Twin in Wind Engineering



Wu, T., Li, S. and Sivaselvan, M., 2019. Real-Time Aerodynamics Hybrid Simulation: A Novel Wind-Tunnel Model for Flexible Bridges, *Journal of Engineering Mechanics*, 145(9), 04019061.



Wu, T. and Song, W., 2019. Real-Time Aerodynamics Hybrid Simulation: Wind-Induced Effects on a Reduced-Scale Building Equipped with Full-Scale Dampers. *Journal of Wind Engineering and Industrial Aerodynamics*, 190, 1-9.

AI-Empowered Transient Aerodynamics Simulation

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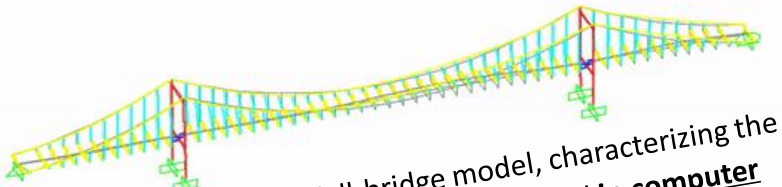
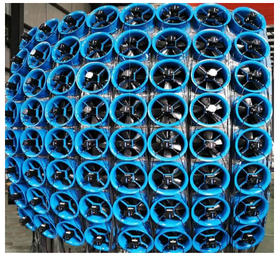


"Skeleton" of the full-bridge model, characterizing the dynamic properties, is numerically simulated **in computer**

Interactions between skeleton and skin are accomplished through a system consisting of sensors, a network of actuators, and controllers

Displacements



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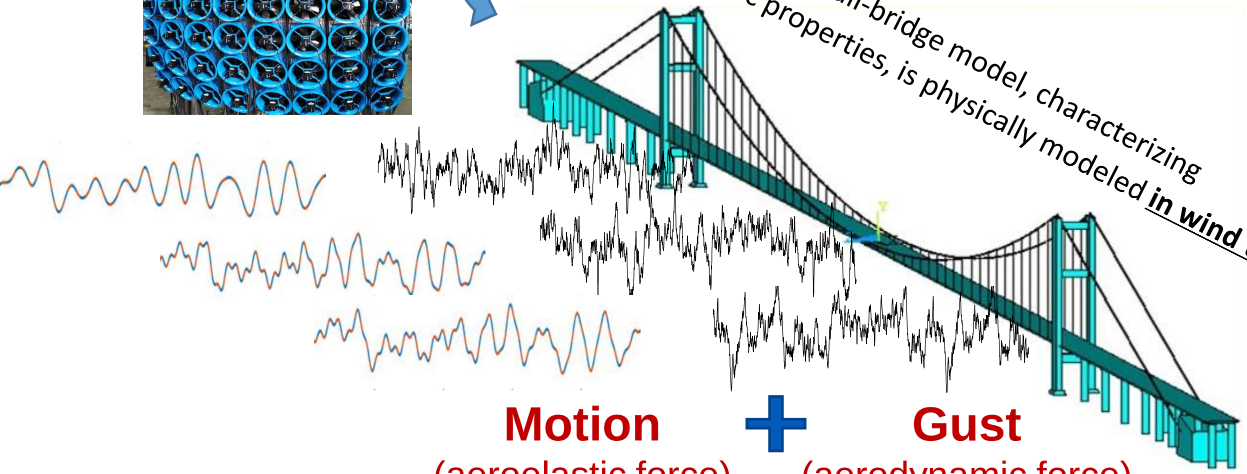


Aerodynamic & aeroelastic forces

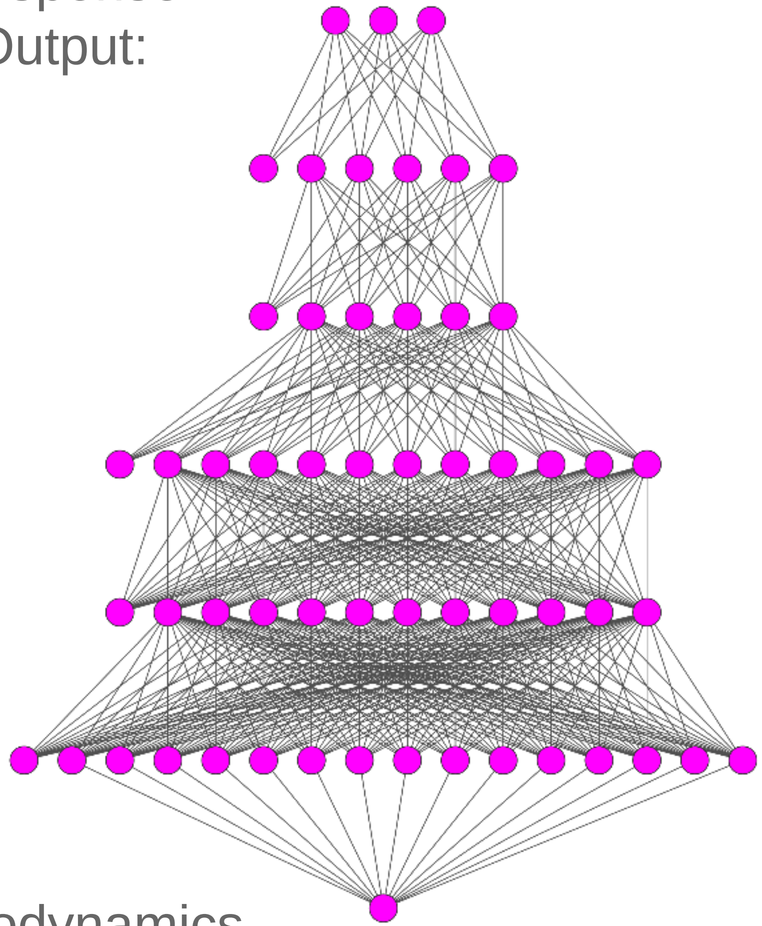
Motion
(aeroelastic force)

+

Gust
(aerodynamic force)

Real-Time **Aerodynamics** Hybrid Simulation

Structural Response Output: $u(t), \dot{u}(t), \ddot{u}(t)$



Aerodynamics Load Input: $f(t)$

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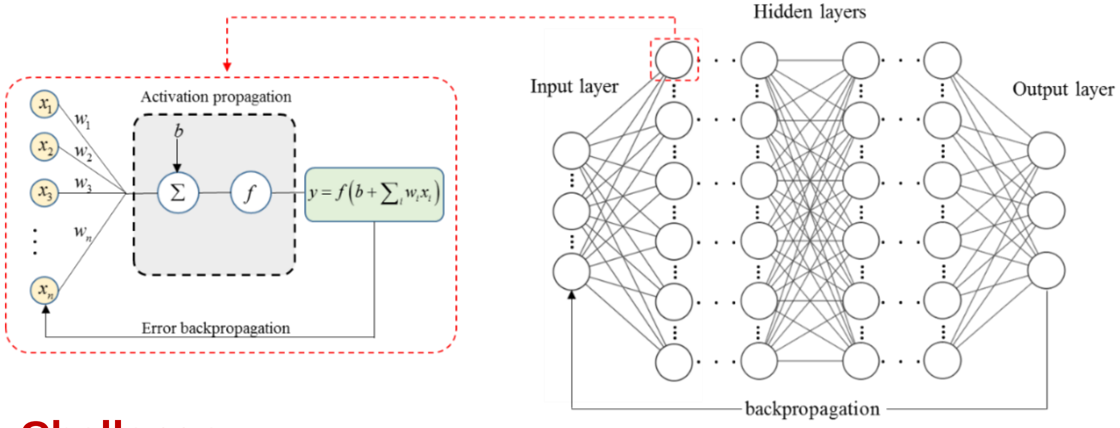
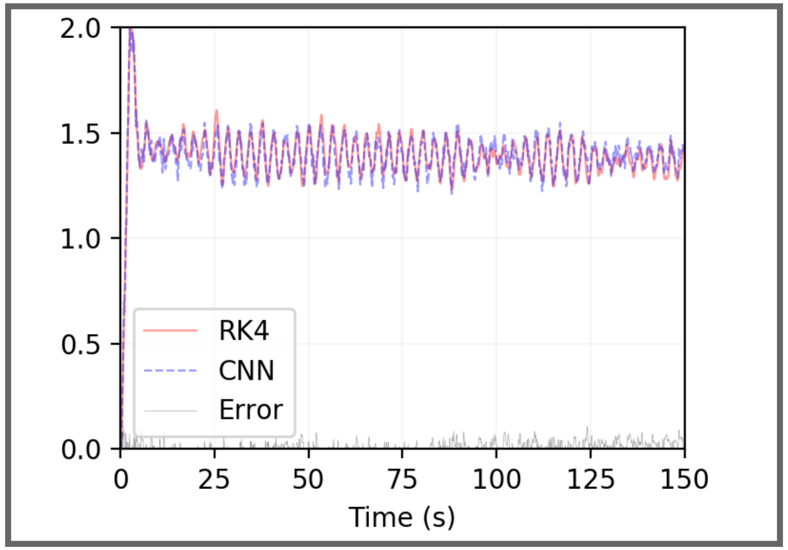
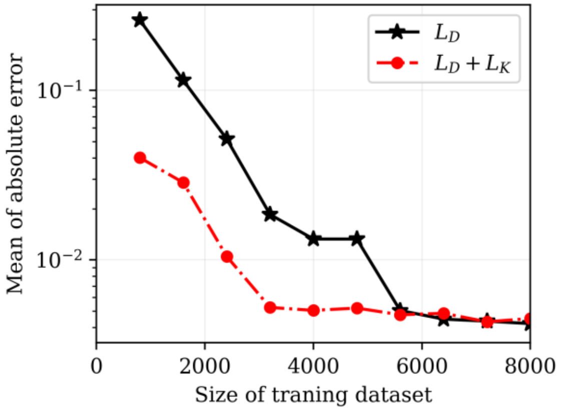


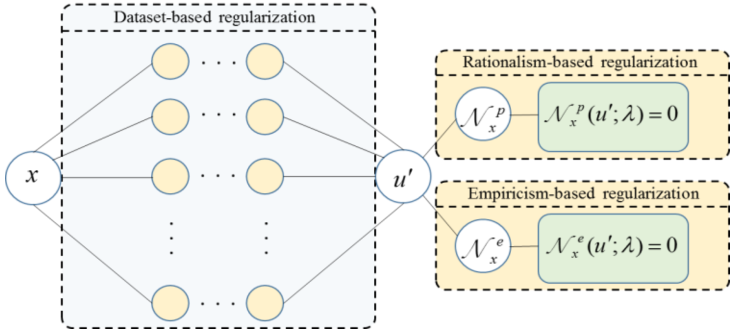


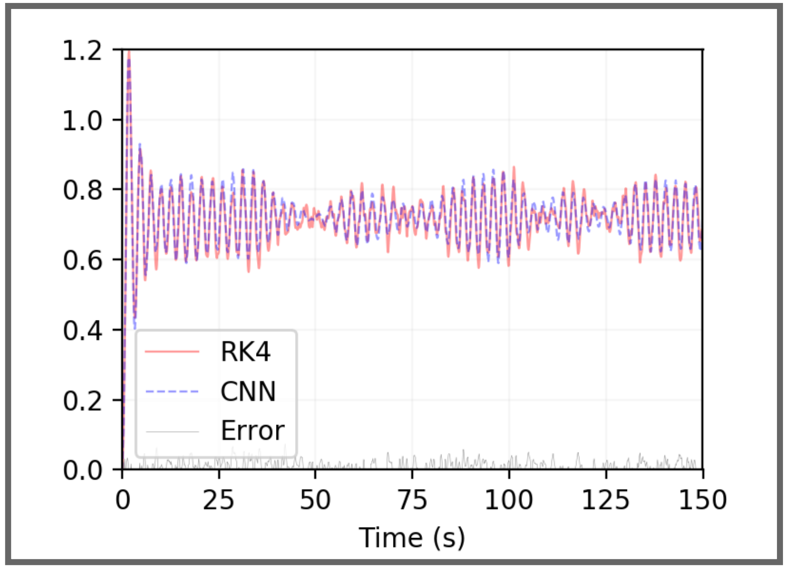


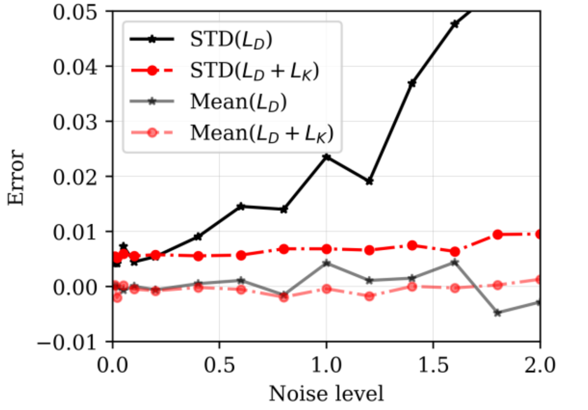
Challenge

- A large number of high-quality data needed for the training purpose is not available
- Black box makes deep neural network not easy to reasonably interpret & not robust to accurately interpolate/extrapolate

Knowledge-enhanced deep learning







Wang, H. and Wu, T., 2020. Knowledge-enhanced Deep Learning for Wind-induced Nonlinear Structural Dynamic Analysis. *Journal of Structural Engineering*, 146(11), 04020235.

AI-Empowered Transient Aerodynamics Simulation

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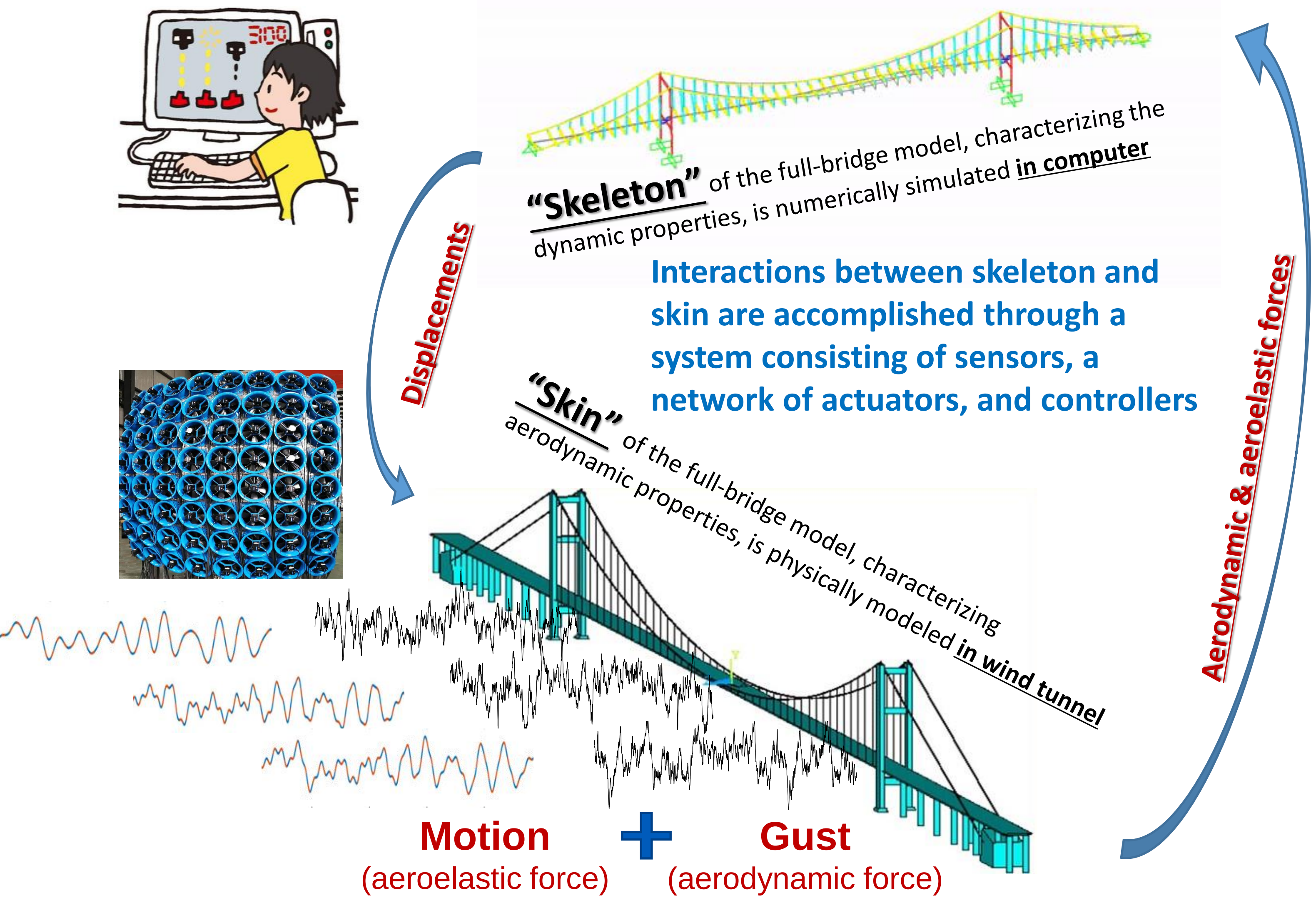
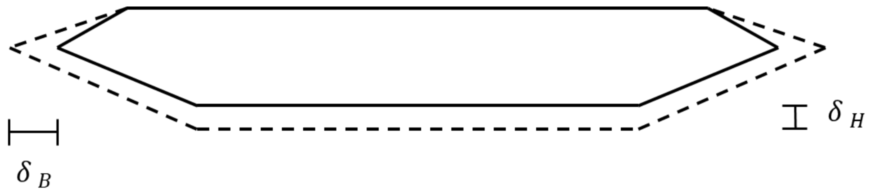
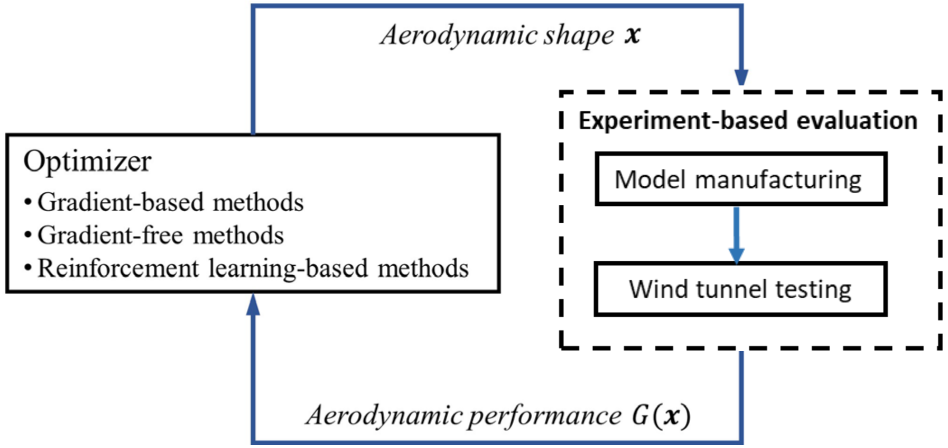


Shape Optimizer for Aerodynamic Mitigation



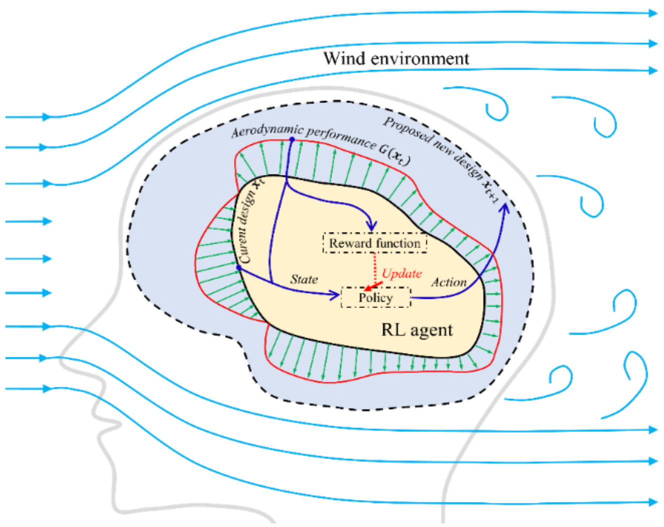


Real-Time **Aerodynamics** Hybrid Simulation

AI-Empowered Transient Aerodynamics Simulation

Teng Wu
05/19/2021

Deep reinforcement learning



Effective policy (i.e., shape search and update rule) with a goal to efficiently achieve the globally optimal solution (i.e., maximizing aerodynamic mitigation) can be learnt by an agent (i.e., structure) through interacting with its environment (i.e., wind) based on an automated trial-and-error process (i.e., no costly hand tuning of optimizer parameters)

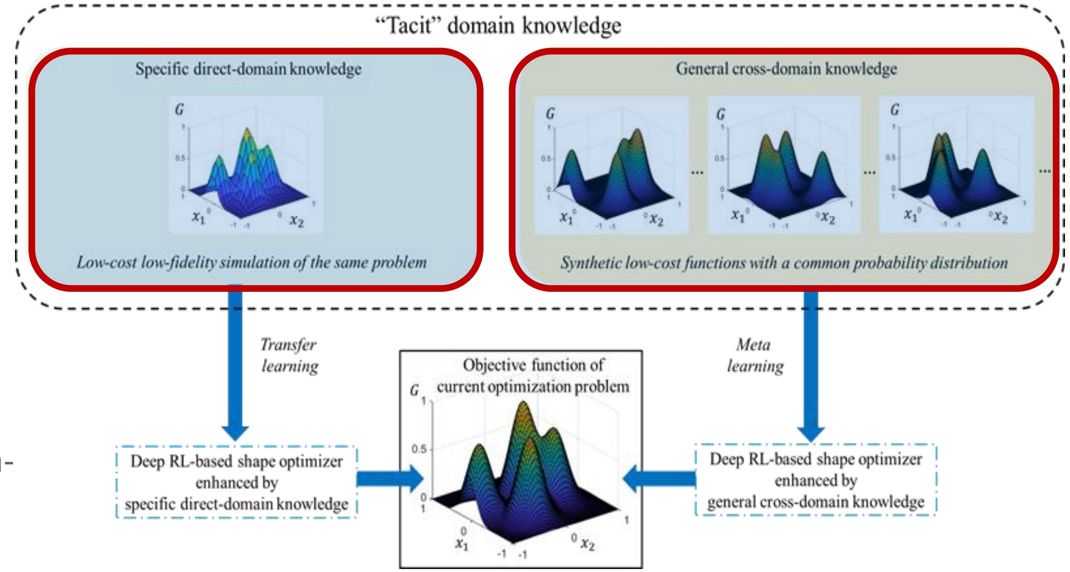
- **Equation-based "explicit" domain knowledge**

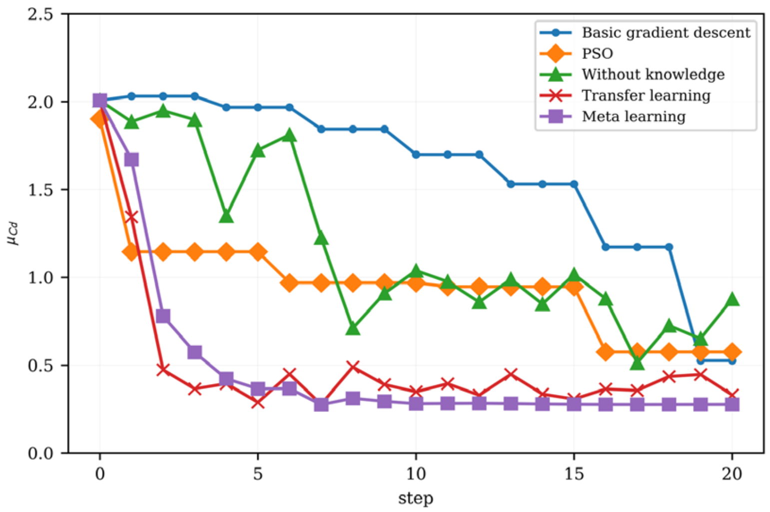
No-free-lunch theorem for search and optimization indicates that a universal law and associated governing equations for the optimization system may not exist

- **Equation-free "tacit" domain knowledge**

- **Specific direct-domain knowledge**
  (Low-fidelity simulations of current optimization problem)

- **General cross-domain knowledge**
  (A group of inexpensive tasks generated from a common probability distribution that reflects important high-level structures of current optimization problem)





Li, S., Snaiki, R. and Wu, T., 2021. A Knowledge-Enhanced Deep Reinforcement Learning-Based Shape Optimizer for Aerodynamic Mitigation of Wind-Sensitive Structures. *Computer-Aided Civil and Infrastructure Engineering*, In Press.

UF NHERI Virtual Workshop
Transient and Non-synoptic Wind Events
May 19, 2021

Thank you!

Presented by Dr. Teng Wu

Other contributors:

Dr. Reda Snaiki
Mr. Haifeng Wang
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Generation of tornado-like vortices

for wind engineering applications

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Boundary Layer Wind Tunnel Simulation of Transient and Non-synoptic Wind Events
University of Florida NSF NHERI Experimental Facility
May 19, 2021

Western
WindEEE Research Institute
Engineering, Energy & Environment

Institute for Catastrophic Loss Reduction
Building resilient communities

Alan G. Davenport Wind Engineering Group

Climate stressors / consequences

tornado

heat wave, energy consumption, UHI

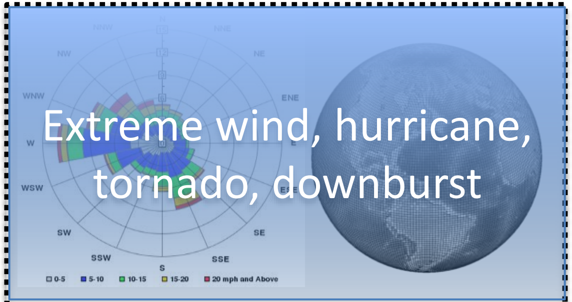
Hurricanes *Source: NY Times*

snow

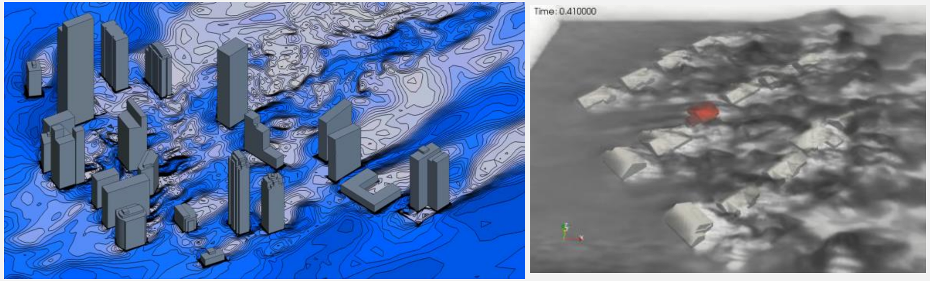
"In 2019, Canada's insurers paid more than $1 billion in wind damage claims" - ICLR

Alan G. Davenport "Wind Loading Chain" explained in CWE

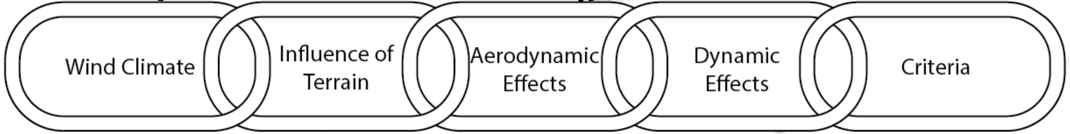
Prof. A.G. Davenport
(1932–2009)



Airport data Climate models

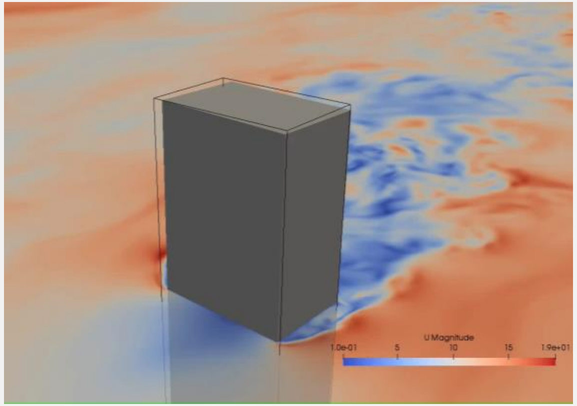


Interaction of the built environment with wind



Wind loading, top floor acceleration, deflection, thermal performance of a façade, pedestrian level wind, etc.

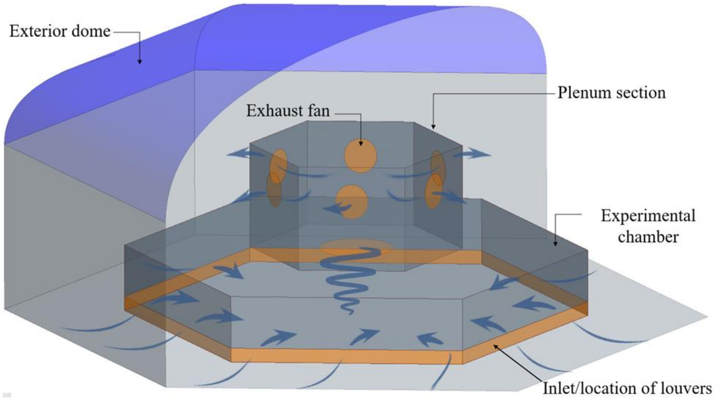
Ground roughness model

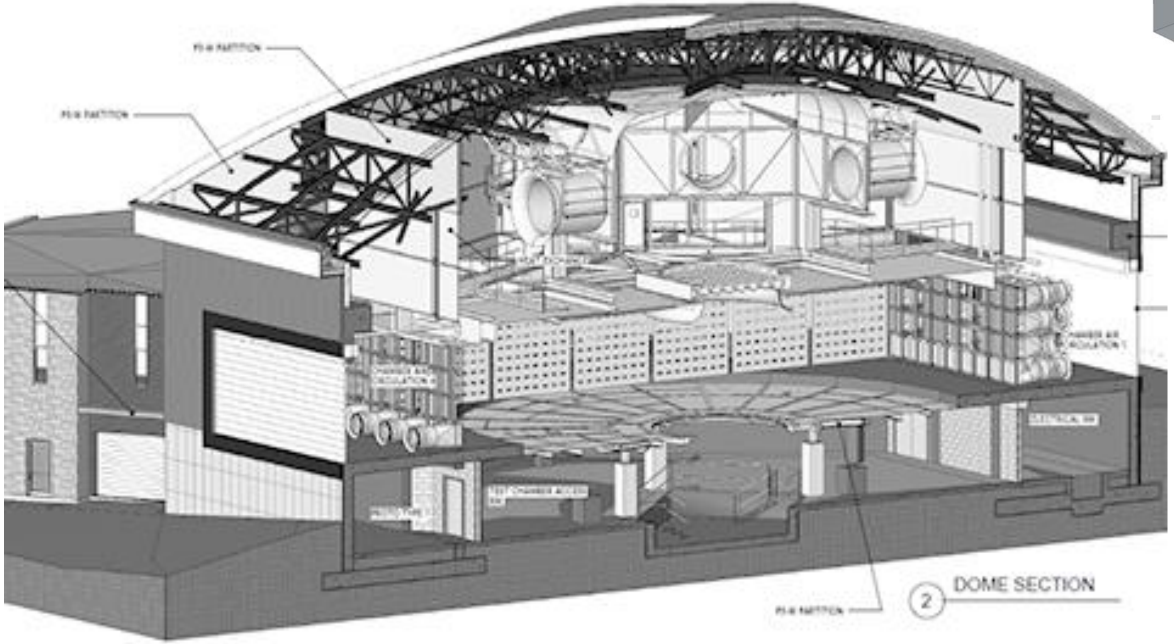


Wind induced dynamic excitation

WindEEE dome

- *3.4 MW power*
- 5 m lift & turntable, 106 fans
- 1600 floor roughness elements
- 5 m diameter storm systems
- 2 m/s wind storm translation





WindEEE Research Rates

- $4500 per day *for testing*
- $1500 per day *for test setup*

WindEEE Commerical Rates

- $1000 per day *for testing*
- $3000 per day *for test setup*

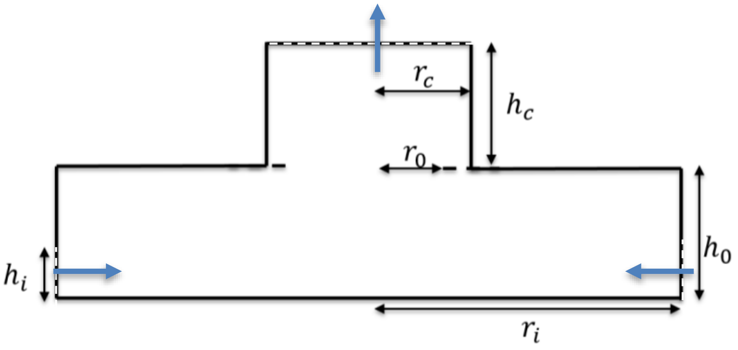
Characterization of tornado-like vortex

- Applying Buckingham pi theorem to a "WindEEE type" tornado vortex chamber
- F($\Gamma, Q, \upsilon, r_0, r_c, r_i, h_0, h_i, h_c$): Nine dimensional quantities with two fundamental units (m, s) would lead to seven independent non-dimensional terms
- Γ is the free stream circulation, Q is the system flow rate, υ is the kinematic viscosity, $r_0, r_c, r_i, h_0, h_i, h_c$ are the characteristic dimensions of the vortex chamber as shown

$$\boldsymbol{\Pi_1 = \frac{\Gamma r_0}{Q}} \qquad \Pi_2 = \frac{\upsilon r_0}{Q} \qquad \Pi_3 = \frac{h_0}{r_0} \qquad \boldsymbol{\Pi_4 = \frac{h_i}{r_0}}$$

$$\Pi_5 = \frac{h_c}{r_0} \qquad \Pi_6 = \frac{r_i}{r_0} \qquad \Pi_7 = \frac{r_c}{r_0} \qquad \boldsymbol{{\Pi_2}^* = \frac{\Pi_2}{\Pi_3} = \frac{Q'}{\upsilon}}$$

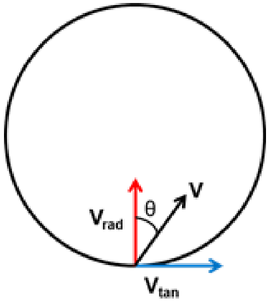
$a = \frac{r_0}{h_i}$	$S = \frac{r_0 \Gamma}{Q}$	$Re = \frac{Q'}{2\pi\upsilon}$
Aspect ratio	*Swirl ratio*	*Reynolds number*



Characterization of tornado like vortex

- **Swirl ratio** is considered the most important parameter - controls the flow-structure

$$S = \frac{\Gamma r_0}{2Q} = \frac{\left(\oint \vec{V}.\overrightarrow{dl}\right) r_0}{2\iint \vec{V}.\overrightarrow{dA}} = \frac{(2\pi r_i V_\theta) r_0}{4\pi r_i h_i V_r} = \frac{V_\theta r_0}{2V_r h_i} = \frac{\tan(\theta)}{2a}$$



$$S = \frac{\Gamma L}{2Q}$$

- Formulation: depends on the physical boundaries of the vortex chamber

- Relating this to a flow derived value is needed to apply to real tornadoes

- “Maximum circulation” based formulation: Baker and Church (1979), Haan et al. (2007), Mishra et al. (2008) Lee and Wurman (2004), Kosiba and Wurman (2010), Refan (2014), Refan et al. (2017)

$$S = \frac{\Gamma_\infty r_0}{2Q} = \frac{\left(\oint \vec{V}.\overrightarrow{dl}\right) r_0}{2Q} = \frac{2\pi r_{c,max} V_{\theta,max} r_0}{2Q}$$

Characterization of tornado like vortex

$$S = \frac{\Gamma L}{2Q} = \frac{\left(\oint \vec{V}.\overrightarrow{dl}\right) L}{2Q} = \frac{\iint ((\nabla \times \vec{V})).\overrightarrow{dA}\, L}{2Q} = \frac{\iint \vec{\xi}.\overrightarrow{dA}\, L}{2Q}$$

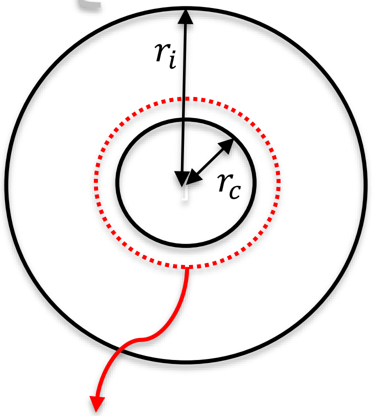
Regarded as the maximum circulation in previous studies

By definition r_c, is the location of maximum tangential velocity $(V_{\theta,max})$

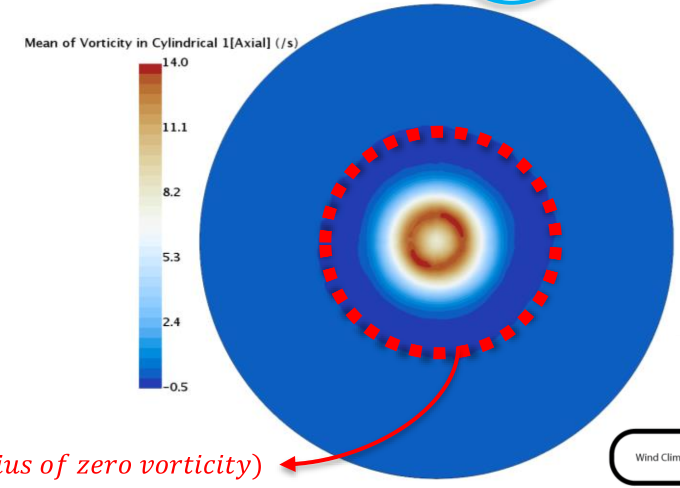
$$\frac{2\pi r_{c,max} V_{\theta,max} r_0}{2Q}$$

Would yield constant value for $r_c < r < r_i$ if the outer flow-field is irrotational like predicted by idealized models (Rankine)

	$\Gamma_{r=r_c}$	$\Gamma_{r=r_{crit}}$	$\Gamma_{r=r_i}$	$\Delta\Gamma$
S=0.3	73.6 m^2/s	93.9 m^2/s	94.2m^2/s	20.6m^2/s
S=0.5	126.6 m^2/s	155.5 m^2/s	157.1 m^2/s	30.5 m^2/s
S=0.8	229.8 m^2/s	251.3 m^2/s	251.3 m^2/s	21.5m^2/s



r_{crit} *(radius of zero vorticity)*



r_{crit} *(radius of zero vorticity)*

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Numerical simulation

- Thermodynamics disregarded
- Continuity and incompressible N-S equations
- Large Eddy Simulations (LES)
- WALE subgrid model

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0$$

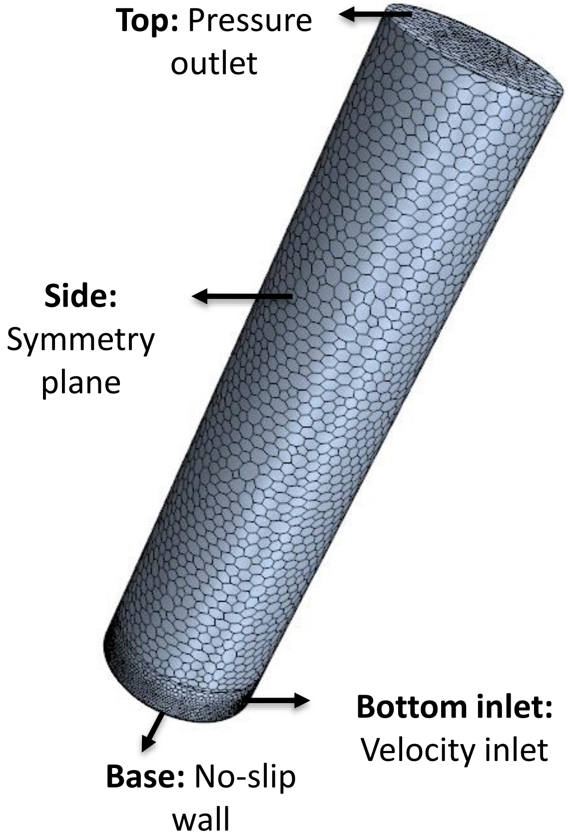
$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right)$$

$$\frac{\partial(\rho \widetilde{u_i})}{\partial x_i} = 0$$

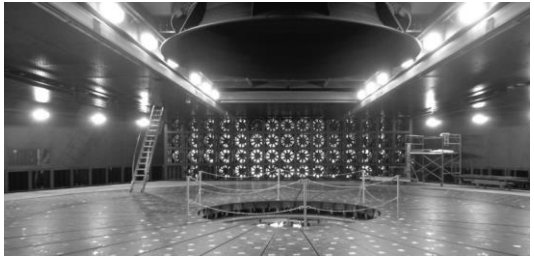
$$\frac{\partial(\rho \widetilde{u_i})}{\partial t} + \frac{\partial(\rho \widetilde{u_i}\widetilde{u_j})}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \widetilde{u_i}}{\partial x_j} + \mu_t \frac{\partial \widetilde{u_i}}{\partial x_j}\right)$$

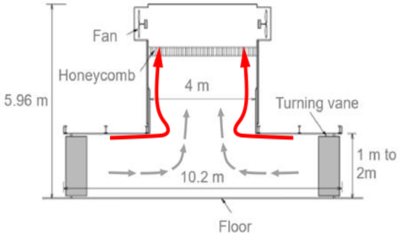
$$\mu_t = \rho\,(\Delta)^2 S_w$$

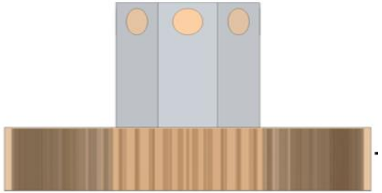
$$\Delta = \min\left(\kappa d, C V^{\frac{1}{3}}\right), C = 0.54$$



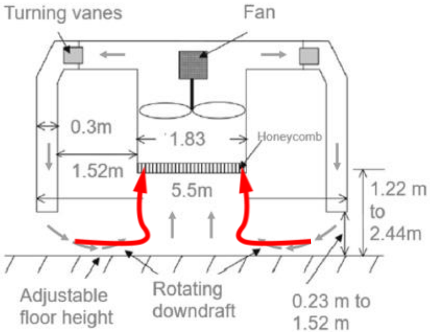
Engineering tornado modeling - How do we link the numerical simulations to experimental simulations?

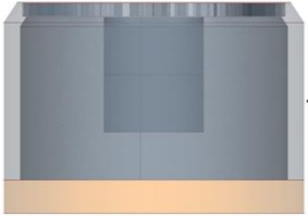




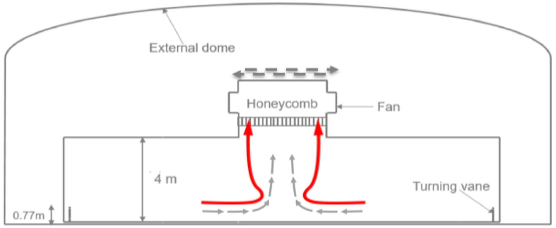


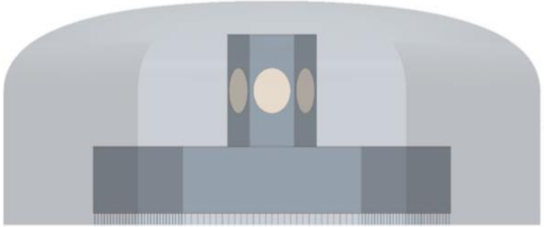
VorTECH (TTU)



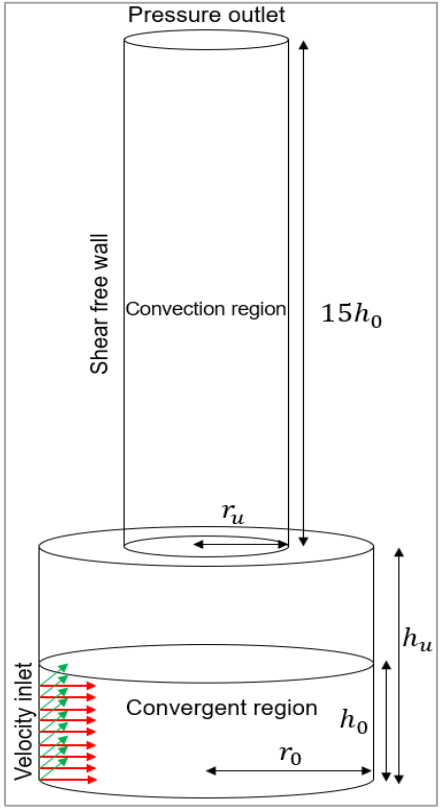


Tornado Simulator (ISU)

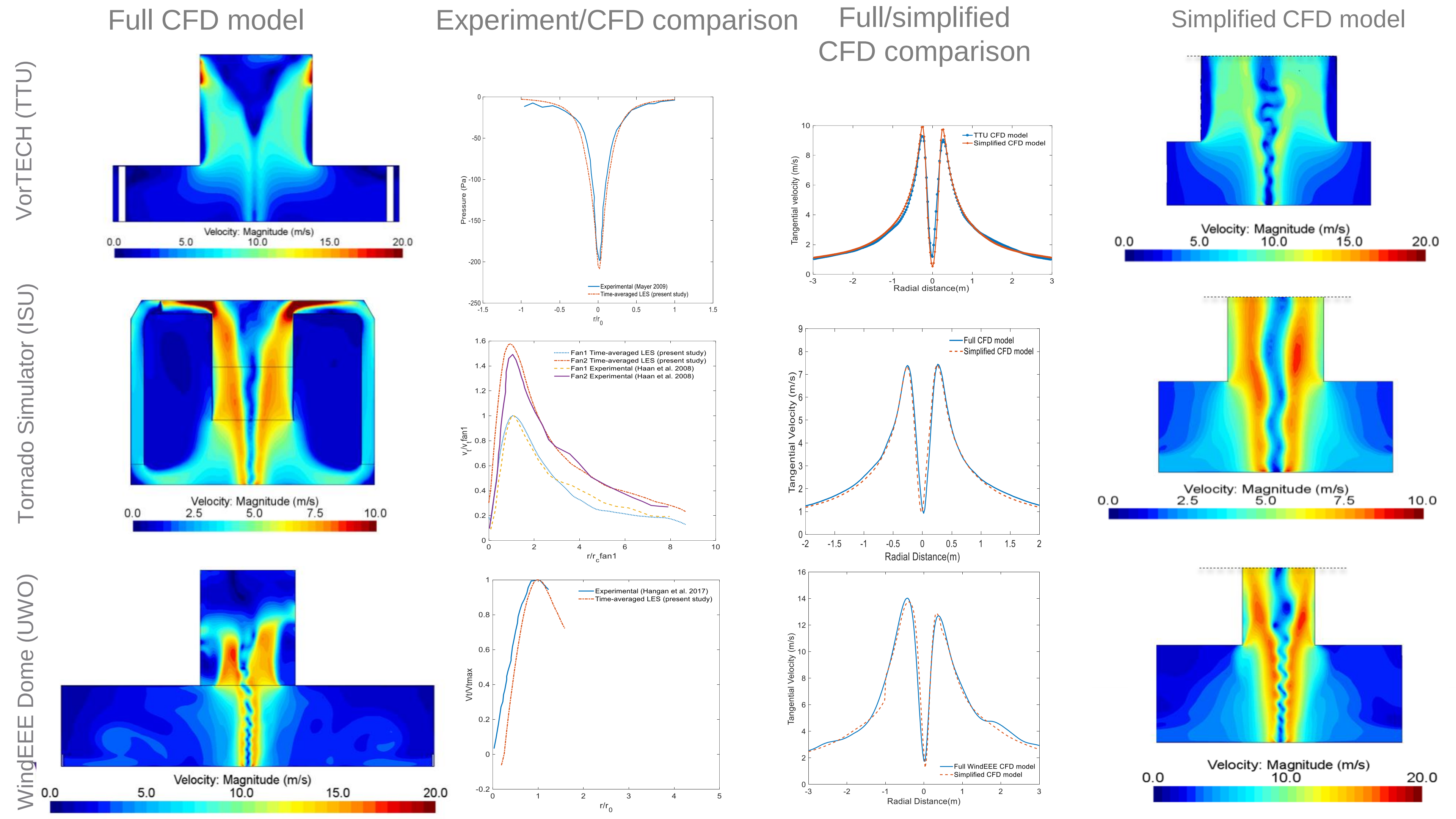




WindEEE Dome (UWO)



Gairola, A., & Bitsuamlak, G. (2019). Numerical tornado modeling for common interpretation of experimental simulators. *JWEIA*, *186*, 32-48.

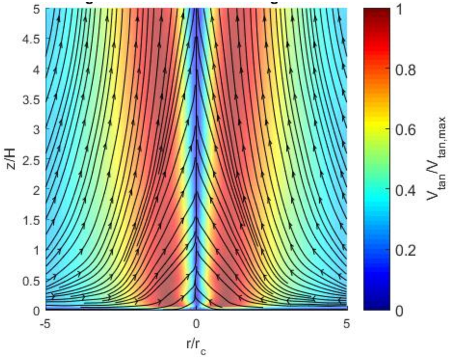


Full CFD model
Experiment/CFD comparison
Full/simplified CFD comparison
Simplified CFD model
VorTECH (TTU)
Tornado Simulator (ISU)
WindEEE Dome (UWO)
Velocity: Magnitude (m/s)
0.0 5.0 10.0 15.0 20.0
0.0 2.5 5.0 7.5 10.0
Pressure (Pa)
r/r0
Experimental (Mayer 2009)
Time-averaged LES (present study)
TTU CFD model
Simplified CFD model
Tangential velocity (m/s)
Radial distance(m)
vt/vt fan1
r/rc fan1
Fan1 Time-averaged LES (present study)
Fan2 Time-averaged LES (present study)
Fan1 Experimental (Haan et al. 2008)
Fan2 Experimental (Haan et al. 2008)
Full CFD model
Simplified CFD model
Tangential Velocity (m/s)
Radial Distance(m)
Vt/Vtmax
Experimental (Hangan et al. 2017)
Time-averaged LES (present study)
Full WindEEE CFD model
Simplified CFD model

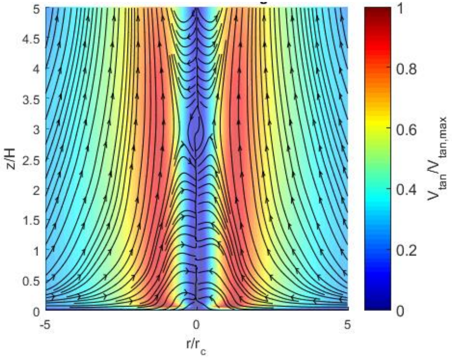
Tornado Flow Field

CFD Simulation Results:

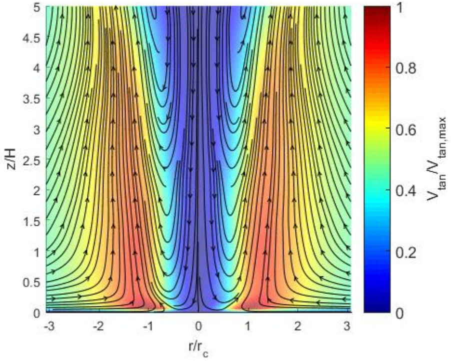
Single-celled Vortex – S=0.25



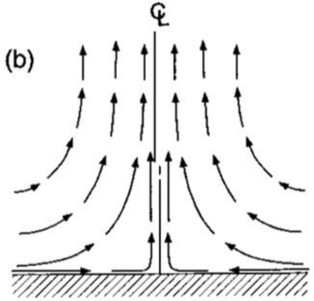
Transition Vortex – S=0.4

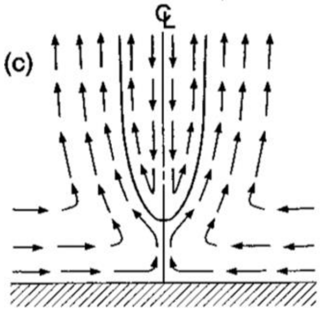


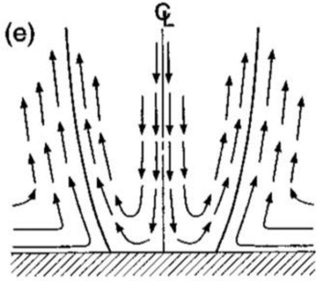
Double-celled Vortex - S=0.66

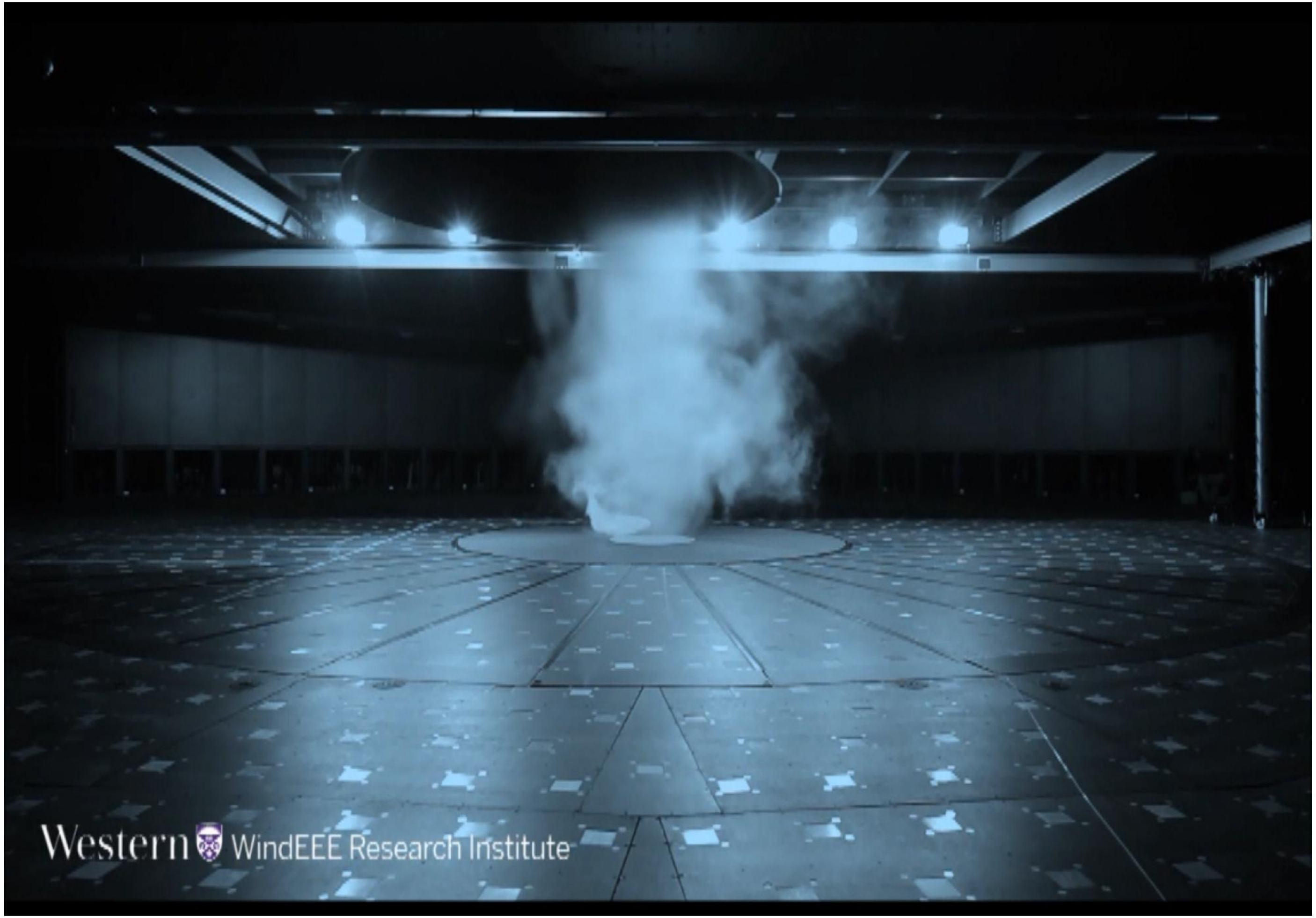


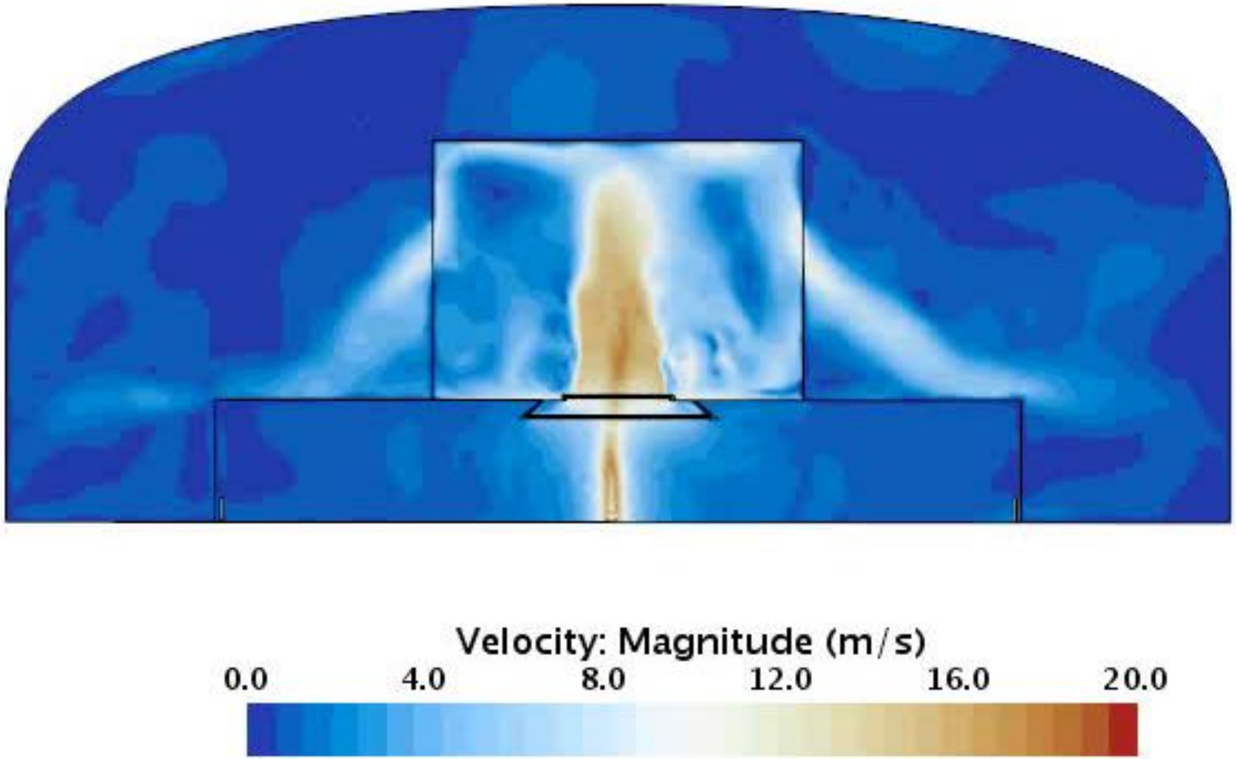
Observed Vortex Structures from Davies-Jones, 1986:

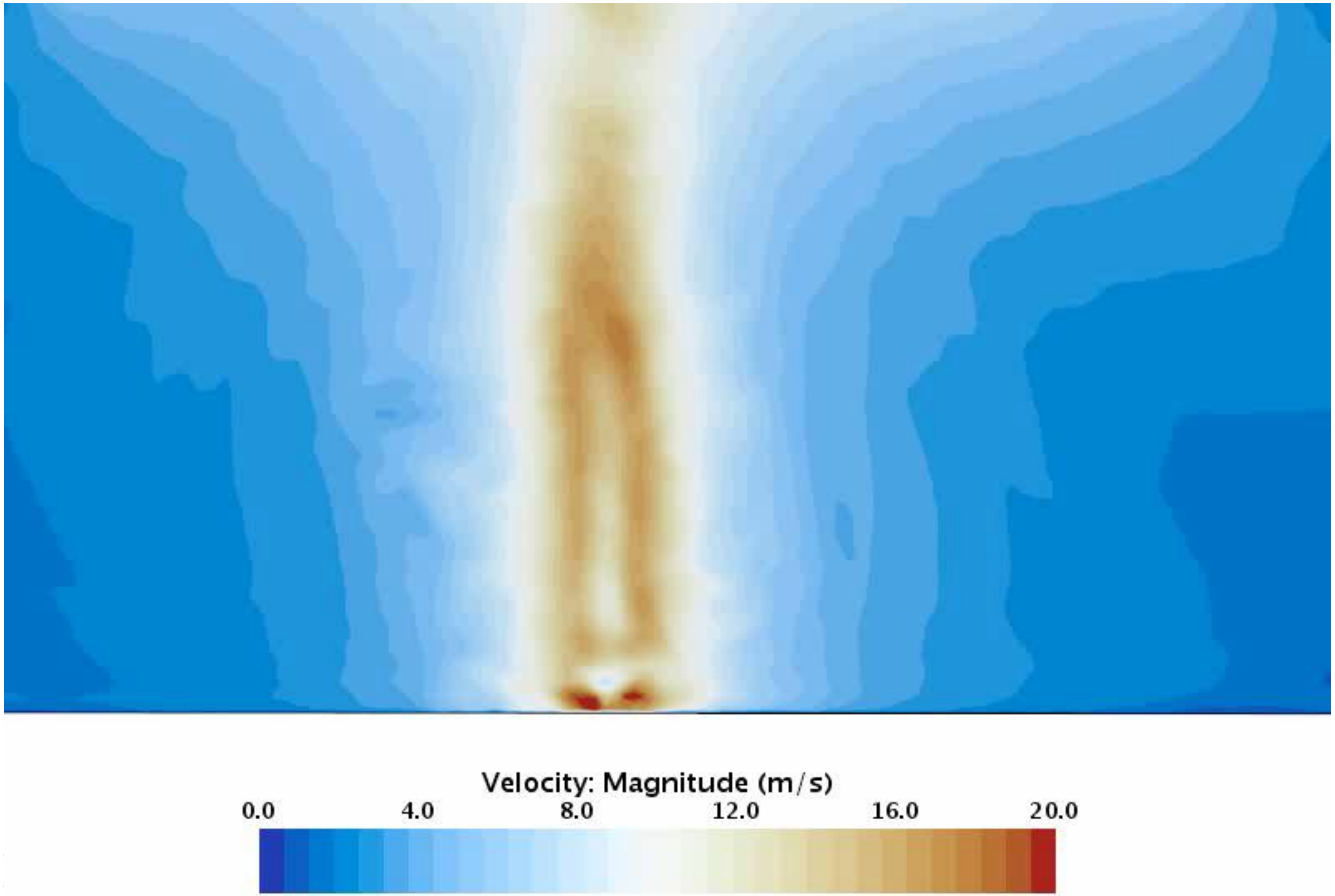






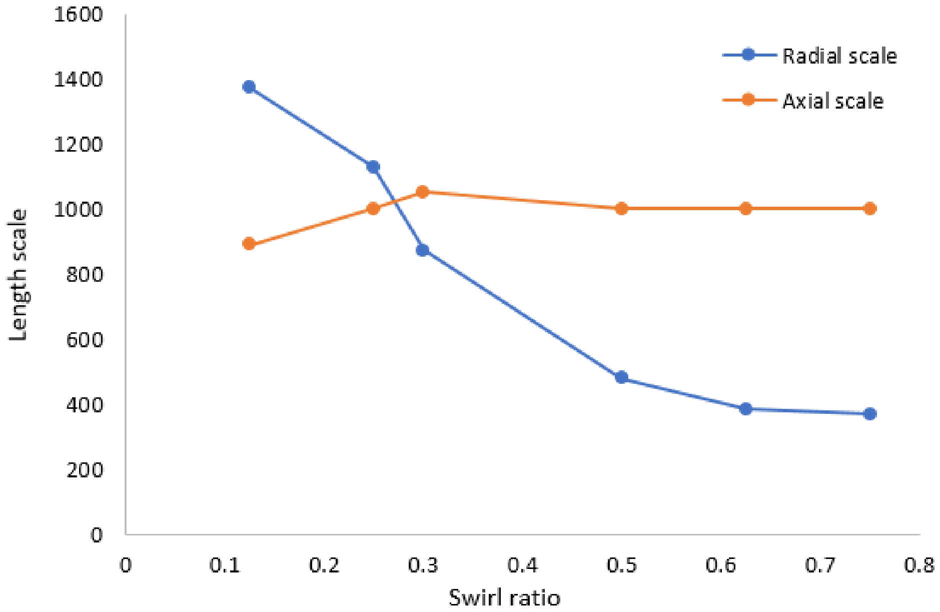

Western WindEEE Research Institute


Velocity: Magnitude (m/s)
0.0
4.0
8.0
12.0
16.0
20.0

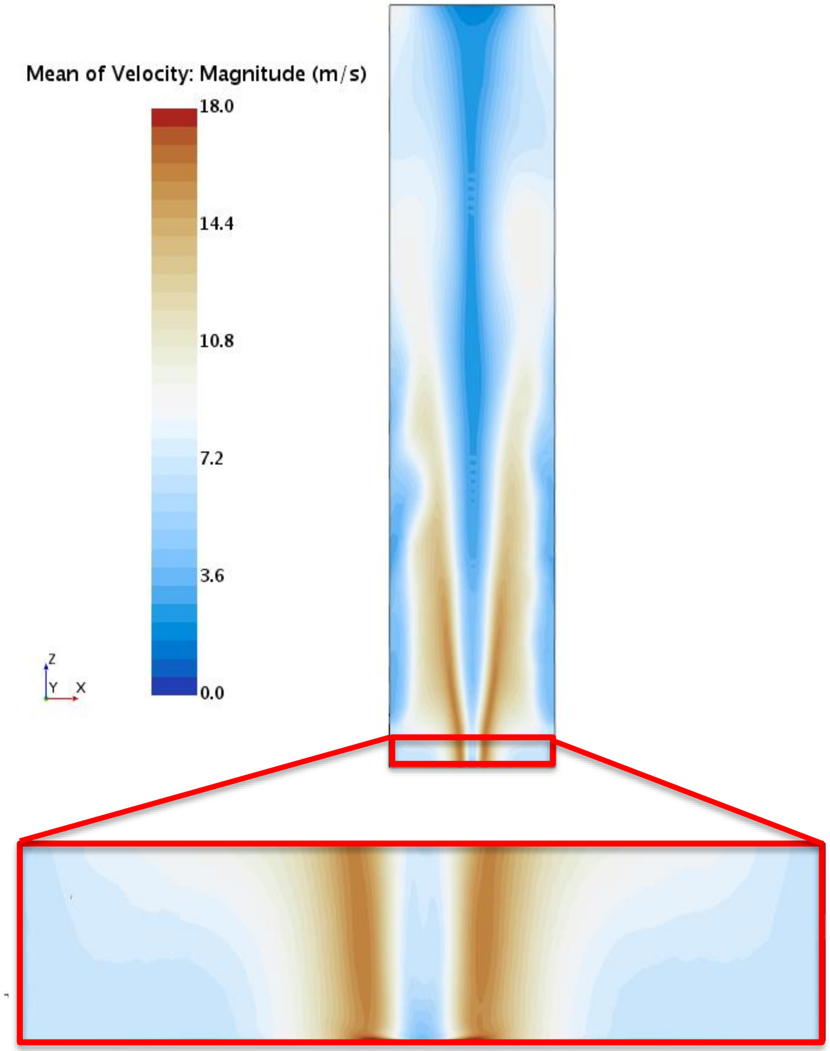


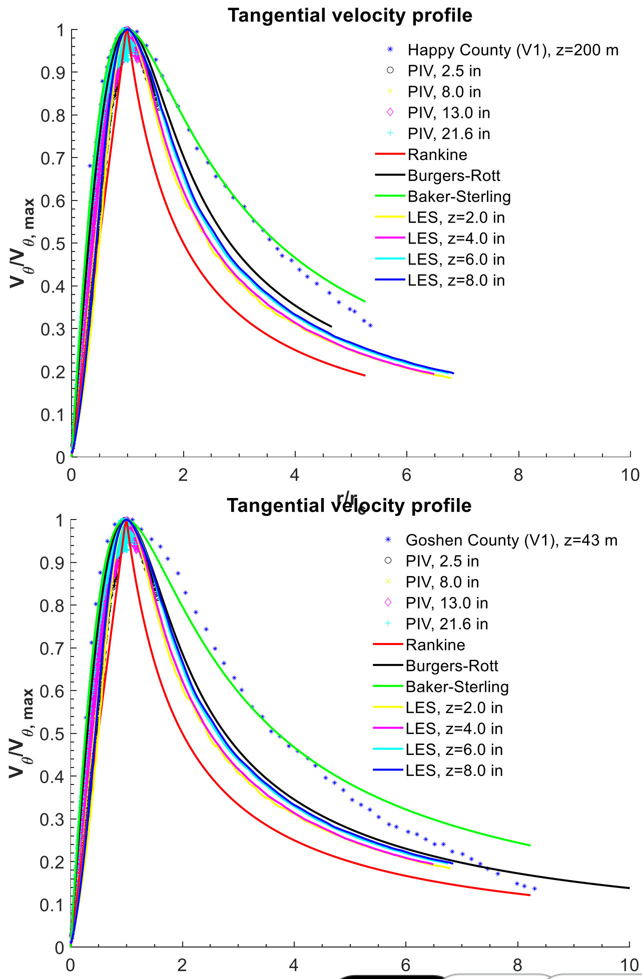
Western

How do we scale both the numerical and experimental data to full scale.



Vertical and radial location of maximum tangential velocity (Refan and Hangan)


Mean of Velocity: Magnitude (m/s)
18.0
14.4
10.8
7.2
3.6
0.0
Z
Y
X


Tangential velocity profile
Happy County (V1), z=200 m
PIV, 2.5 in
PIV, 8.0 in
PIV, 13.0 in
PIV, 21.6 in
Rankine
Burgers-Rott
Baker-Sterling
LES, z=2.0 in
LES, z=4.0 in
LES, z=6.0 in
LES, z=8.0 in
$V_\theta/V_{\theta,\,max}$
r/r_c
Tangential velocity profile
Goshen County (V1), z=43 m
PIV, 2.5 in
PIV, 8.0 in
PIV, 13.0 in
PIV, 21.6 in
Rankine
Burgers-Rott
Baker-Sterling
LES, z=2.0 in
LES, z=4.0 in
LES, z=6.0 in
LES, z=8.0 in
$V_\theta/V_{\theta,\,max}$

Dunrobin tornado aftermath

Before

After

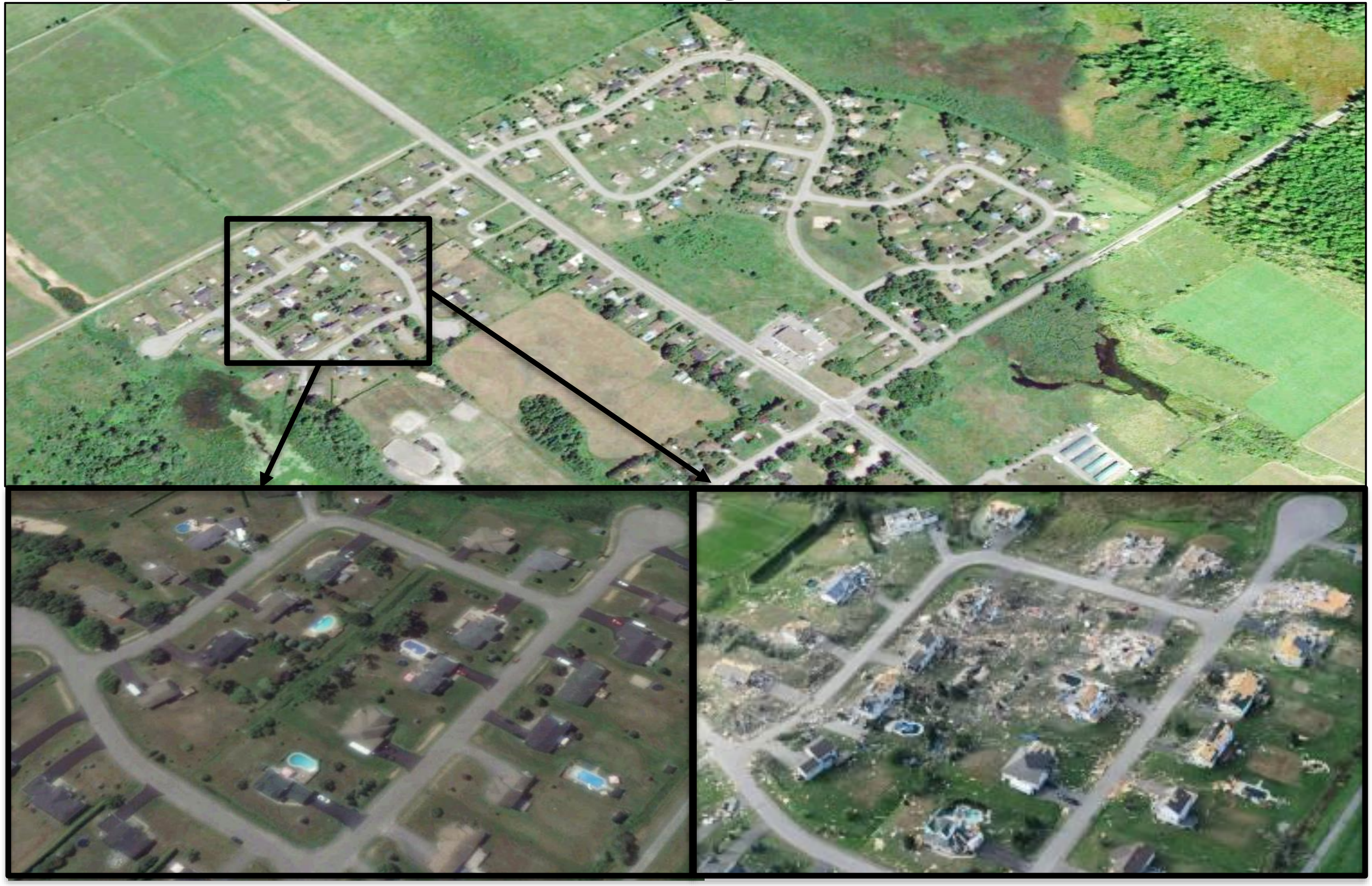
- Ottawa region (Dunrobin-Gatineau) struck by 6 tornadoes on 21st September 2018 between 3:30 PM and 6:00 PM
- Two main tornadoes that struck Dunrobin-Gatineau and Nepean area categorized as EF2 and EF3. Loss estimate $3M

Tornado impact on Dunrobin neighborhood (EF3 tornado)

Courtesy: Northern tornadoes project (NTP) at UWO

Western Engineering

Tornado impact on Dunrobin neighborhood (EF3 tornado)



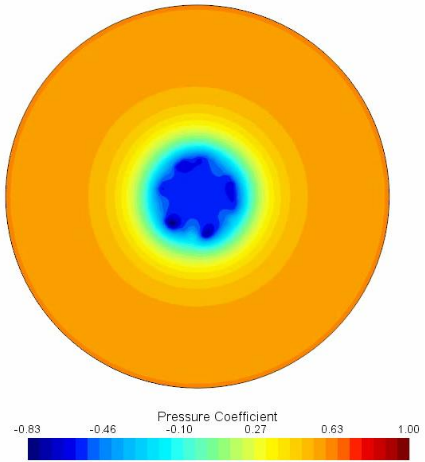
Before

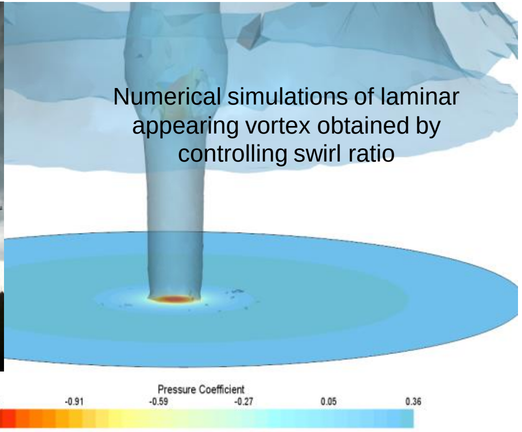
After

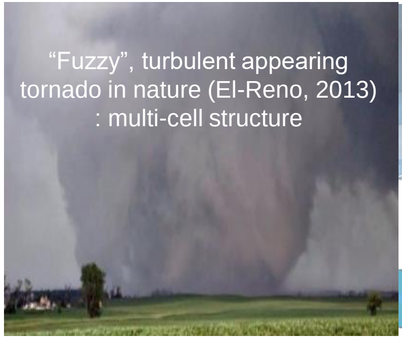
Dunrobin tornado wind field description

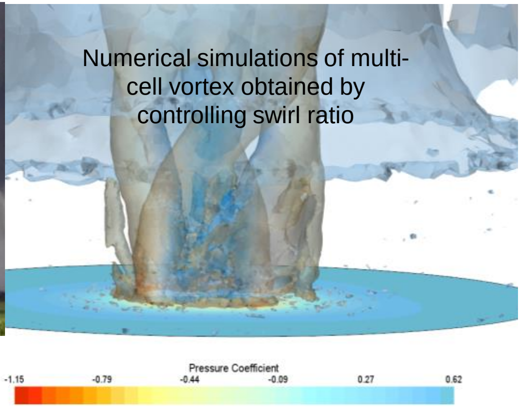
- Ideally: Doppler radar velocity measurements can be used as target to calibrate numerical simulations
- In absence of Doppler radar: qualitative estimation of vortex parameters (aspect ratio, swirl ratio)
- Aspect ratio: 0.5 (range in nature 0.1-0.9)
- Swirl ratio: 0.65-0.85 (qualitative inspection of available videos)
- Target core diameter at the ground level: ~250-300 m (same order of magnitude as the damaged neighborhood)
- EF3 rating: 62.5 m/s to 73.6 m/s (3-sec gust)
  Source: Environment Canada + NTP
- EF3 speed is set to $v_\theta + v_{translation} = v_{target}$

- Average translation speed estimated 15 m/s (based on damage length and duration)
- A representative time taken by the vortex to travel through the neighborhood ($t_s = 40s$)
- EF scale wind speed converted approximately from 3-s gust to a 40 s average to obtain target v_θ for a stationary tornado during calibration stage.

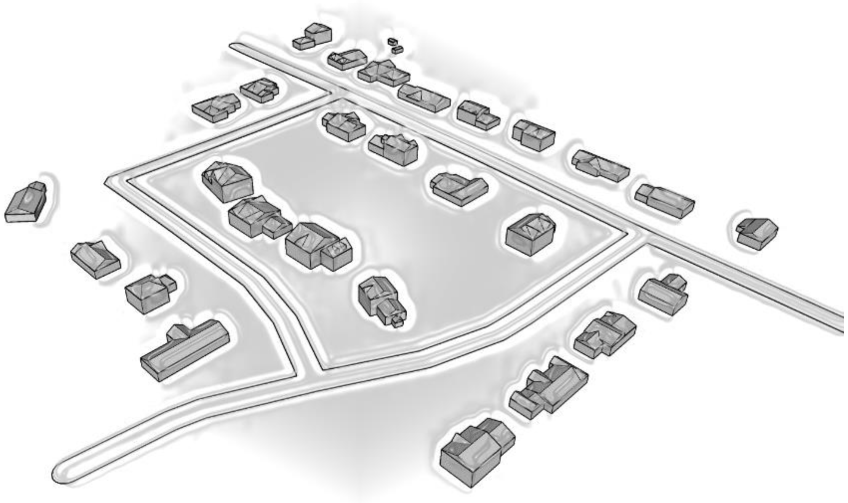






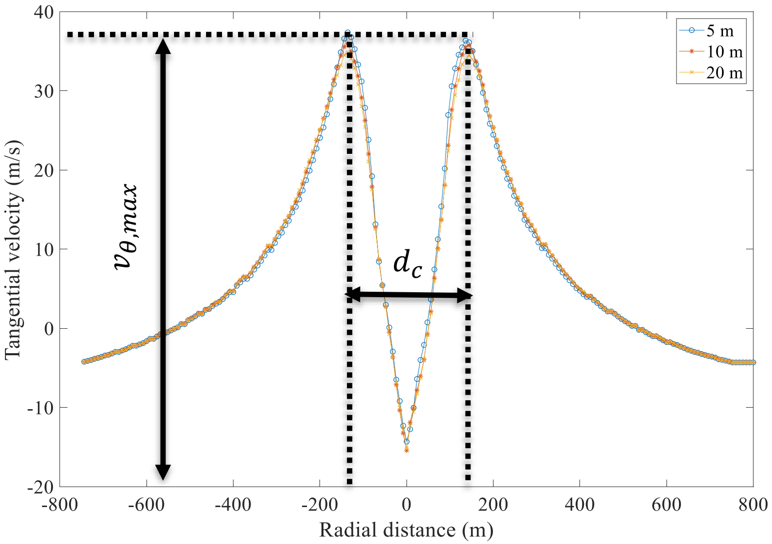


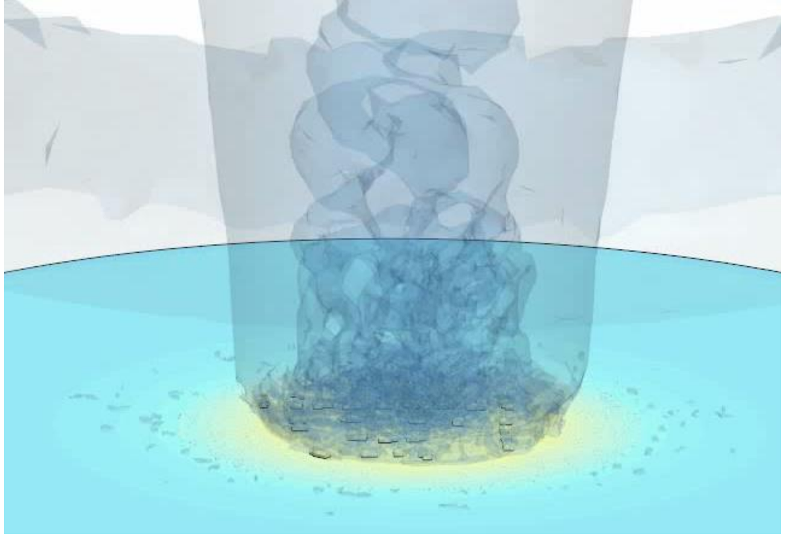
Donrobin model/physics setup

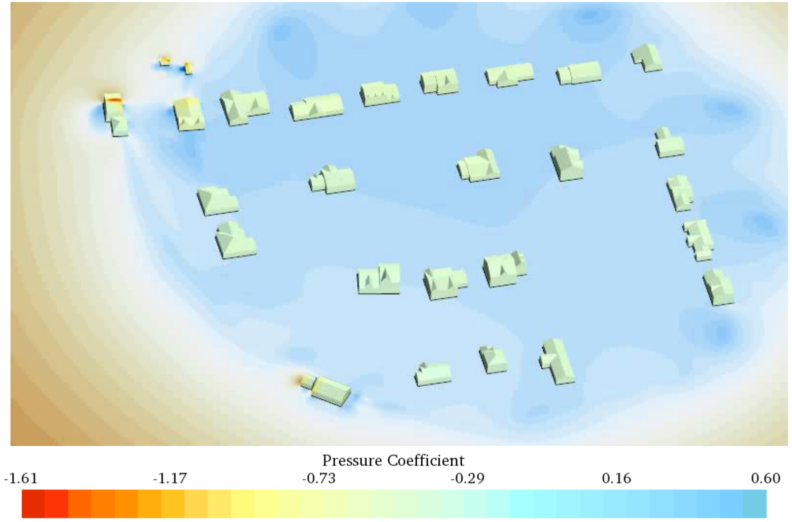


Stationary tornado wind field calibration

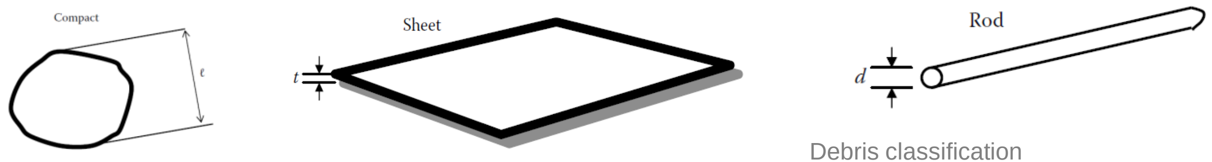
- EF-3 wind speed target (40-s average):53 m/s-62.5 m/s
- $v_\theta + v_{translation} = v_{target}$
- Average near ground tangential velocity: 38m/s -47.5 m/s
- Maximum near ground tangential velocity achieved ($v_{\theta,max}$) ~38m/s
- Near ground core diameter (d_c)~ 300 m (engulfing the neighborhood)







Wind field generation for wind borne debris analysis



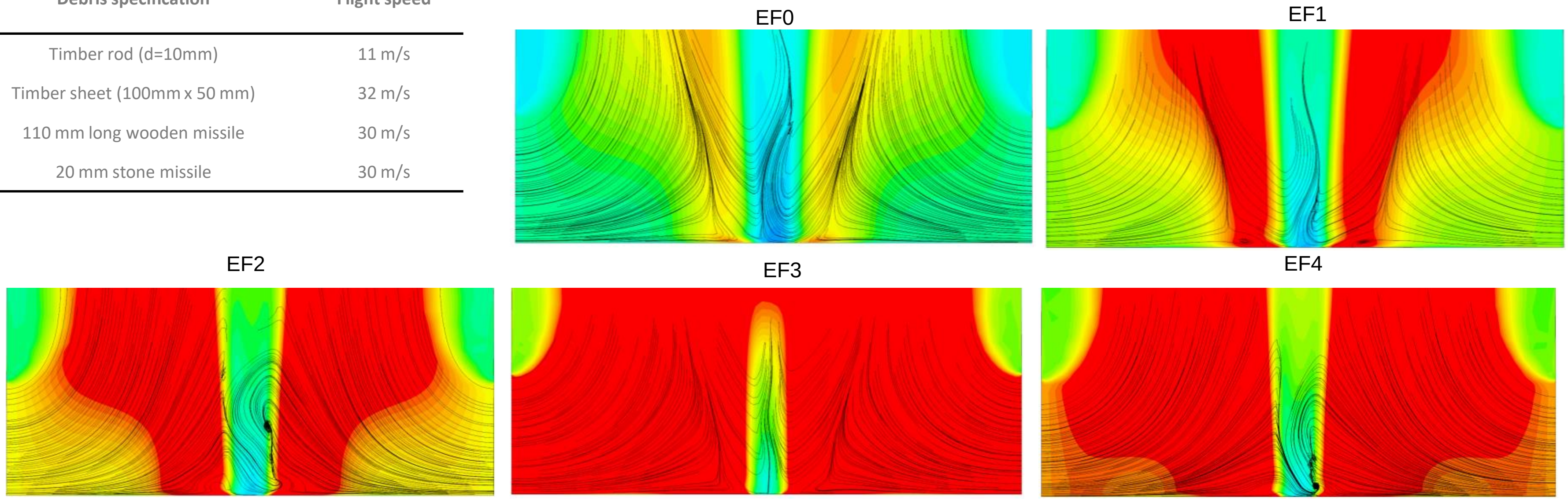
Debris classification

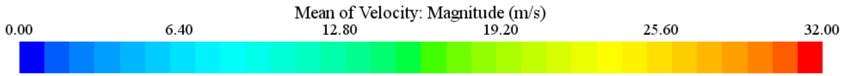
$$U_f = \sqrt{\frac{\rho_m t I g}{0.5 \rho_{a C_F}}}$$

Debris flight speed estimation (Wills et al.)

Tornado size picked based on U.S. Nuclear Regulatory Commission, *Regulatory Guide 1.76, Design-Basis Tornado and Tornado Missiles for Nuclear Power Plants,* Revision 1, 2007.

Debris specification	Flight speed
Timber rod (d=10mm)	11 m/s
Timber sheet (100mm x 50 mm)	32 m/s
110 mm long wooden missile	30 m/s
20 mm stone missile	30 m/s





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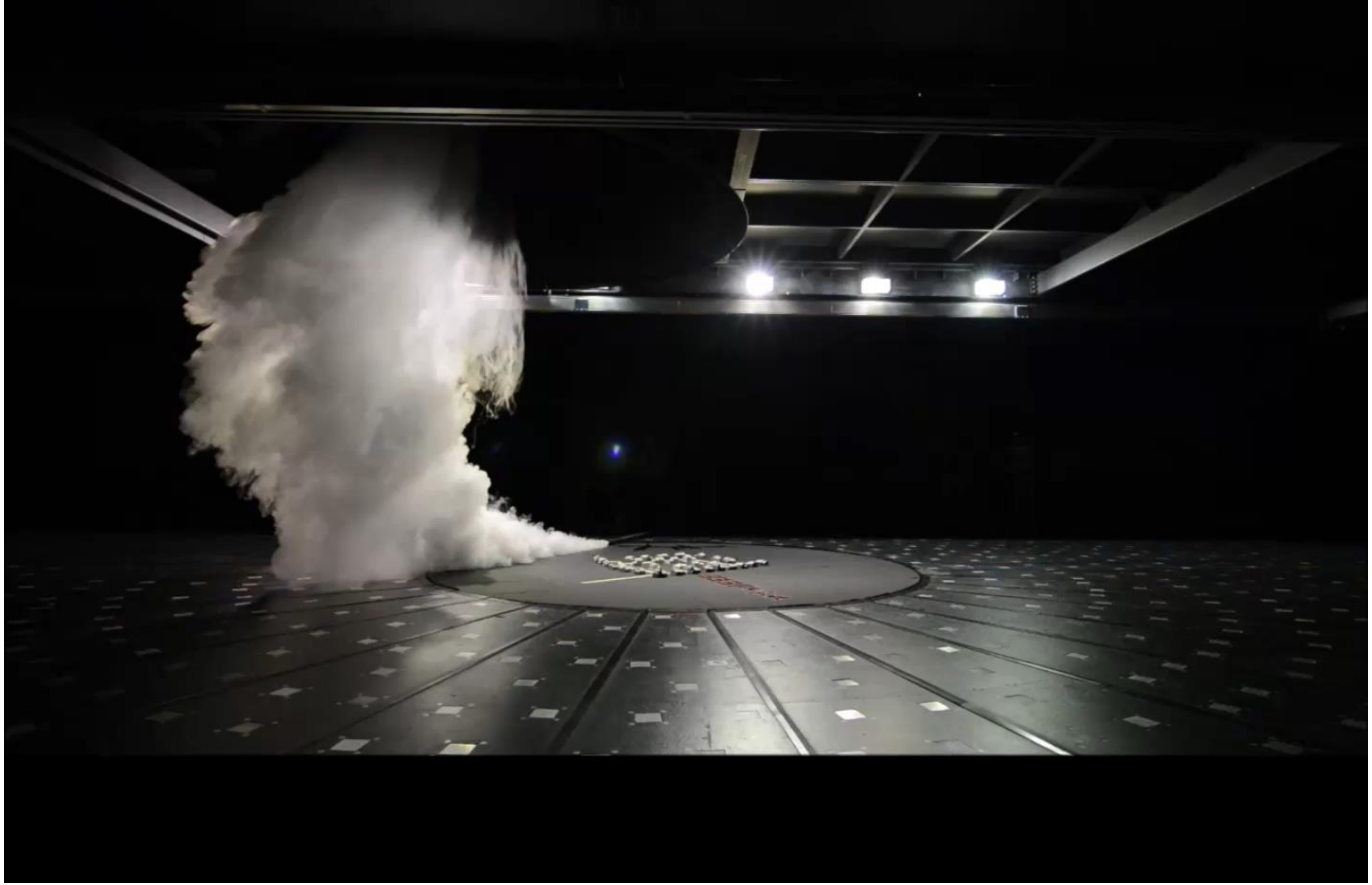
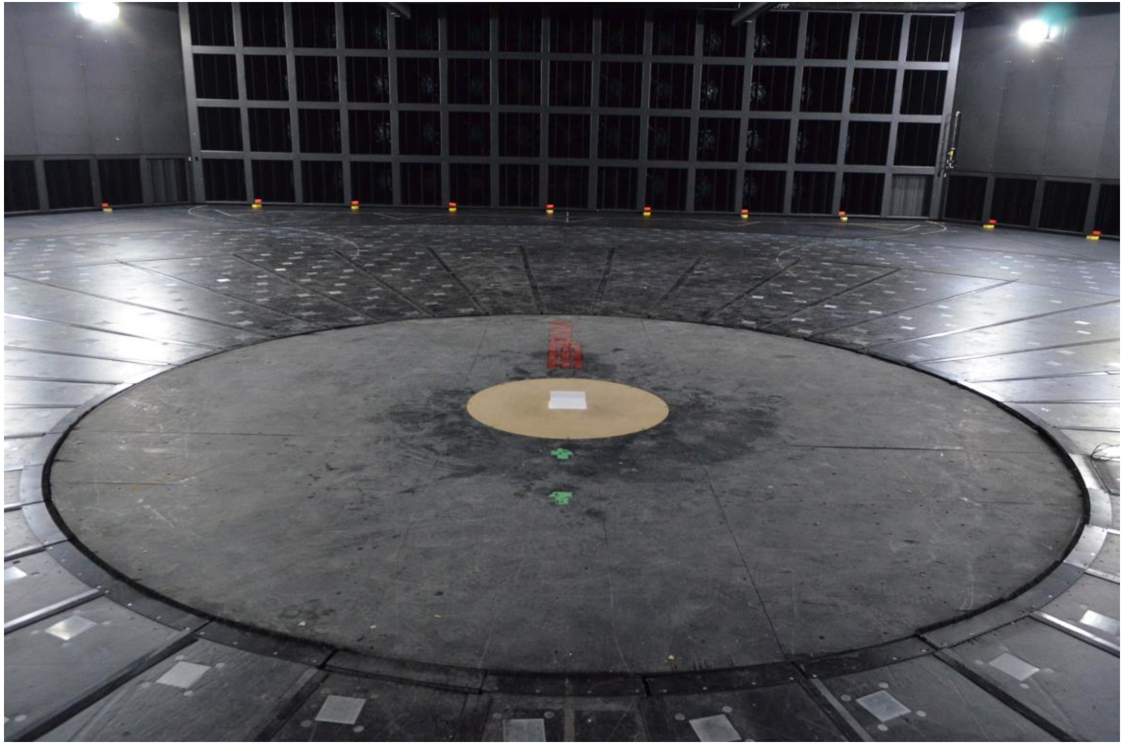
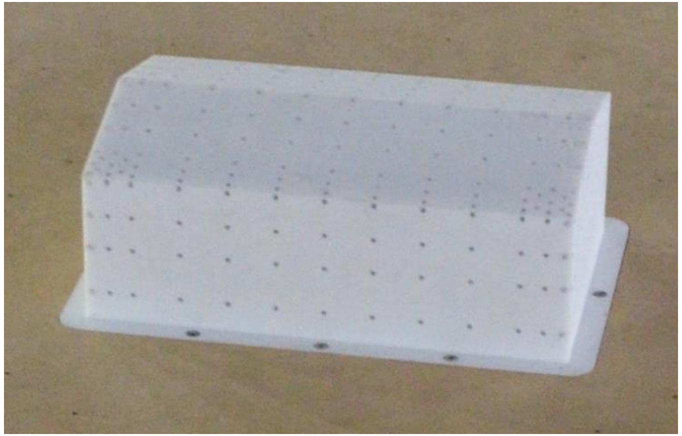
Current testing at WindEEE

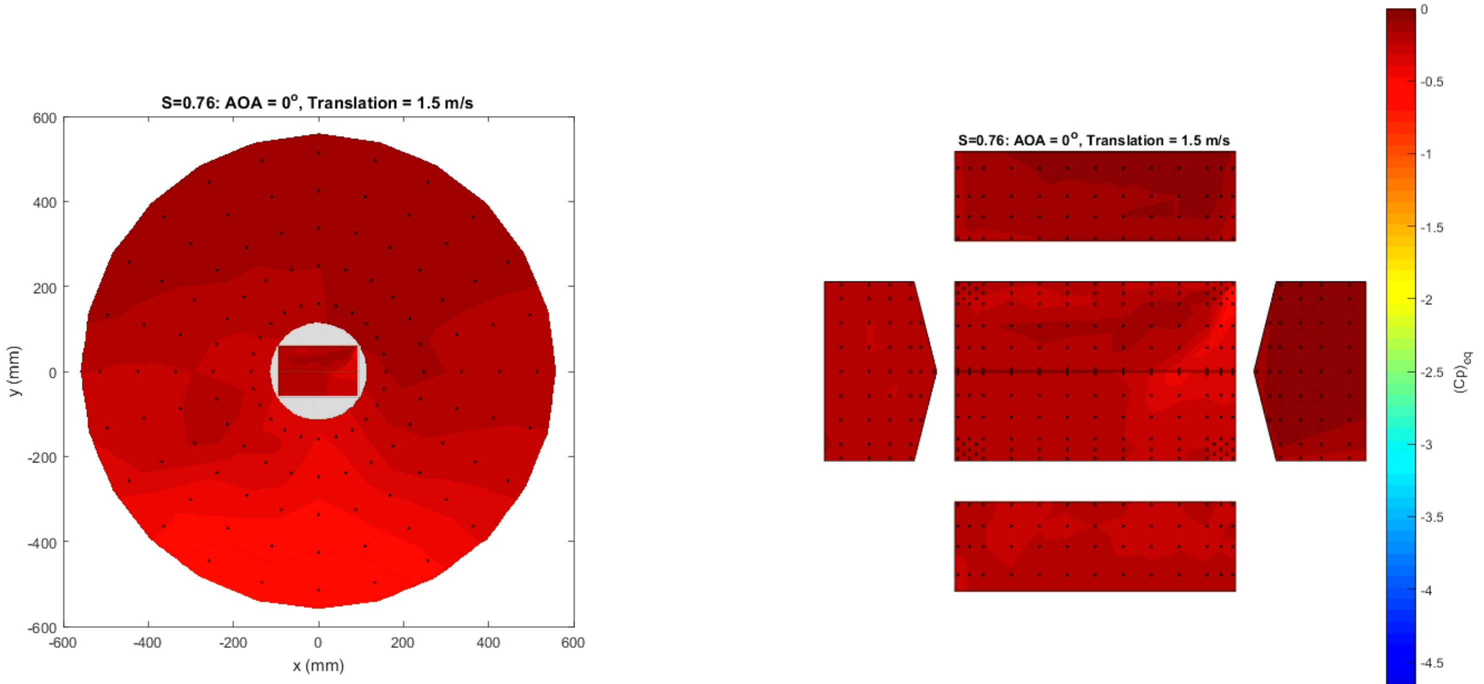


Current testing at WindEEE

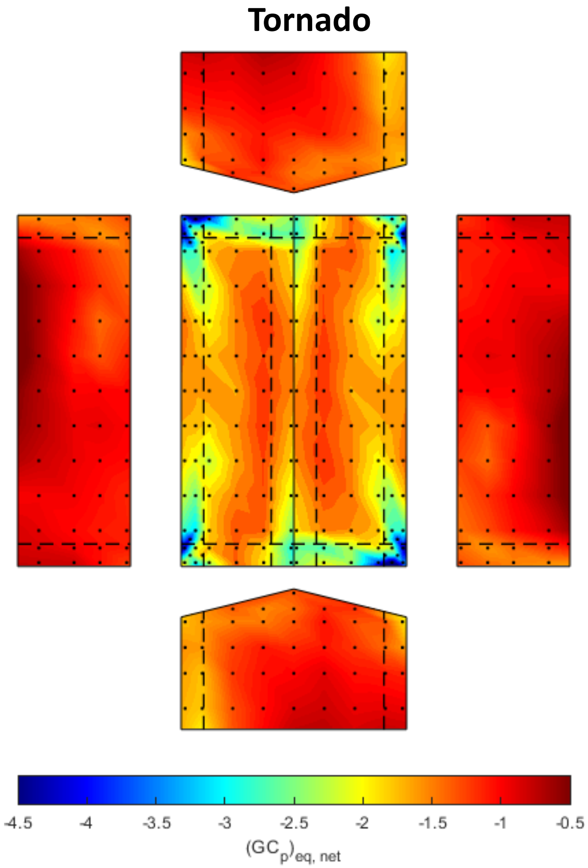


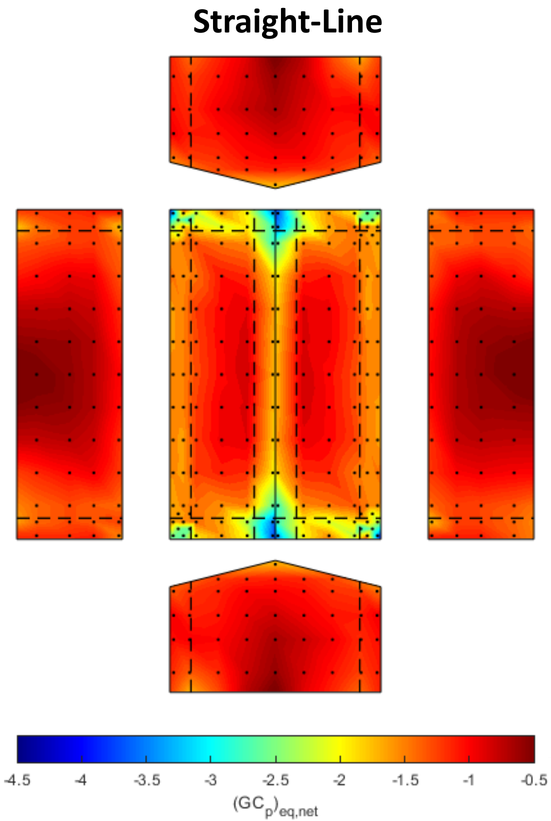


Animation: S = 0.76, V_T = 1.5 m/s, θ = 0º (0.25x Full-Speed)



Enveloped GCp_{net} (Distributed Leakage)





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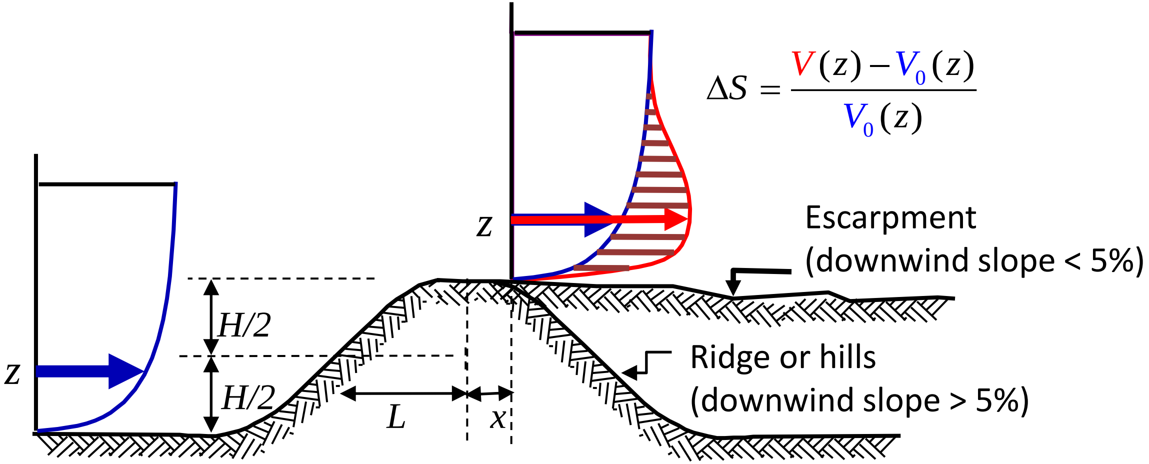
Wind-speed up due to topography

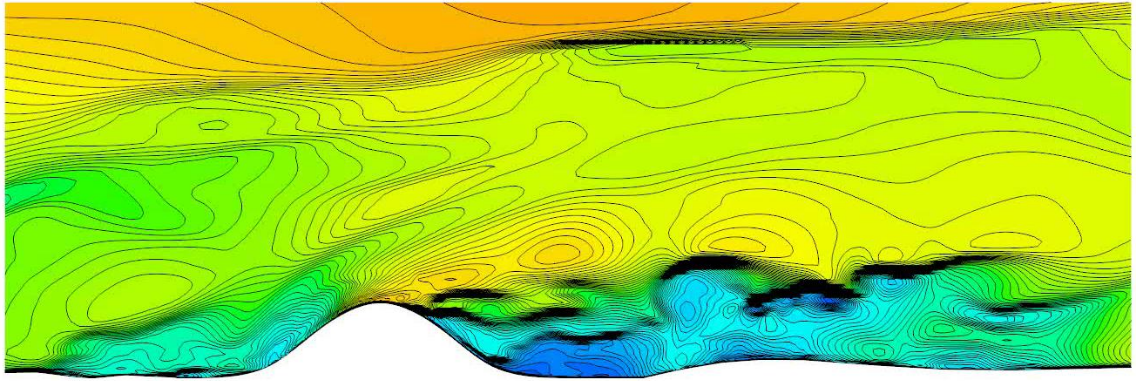


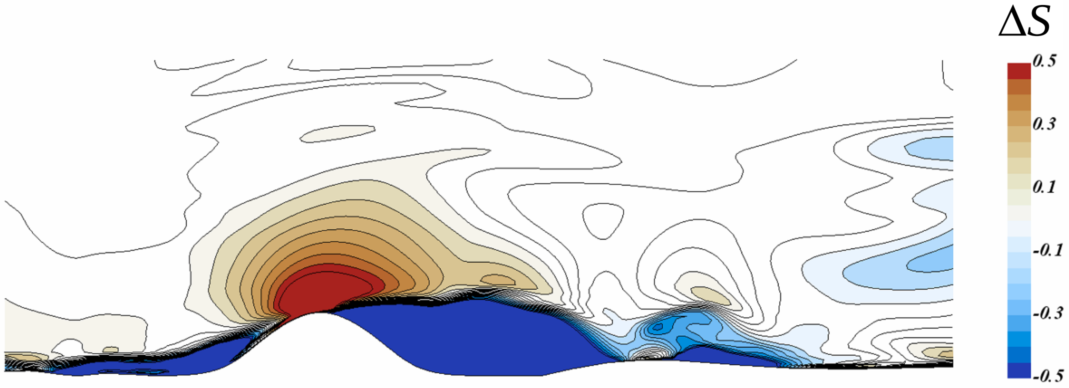
$$\Delta S = \frac{V(z) - V_0(z)}{V_0(z)}$$

ΔS

Fractional speed-up ratio: $$FSUR = \frac{V(z)}{V_0(z)} = 1 + \Delta S$$

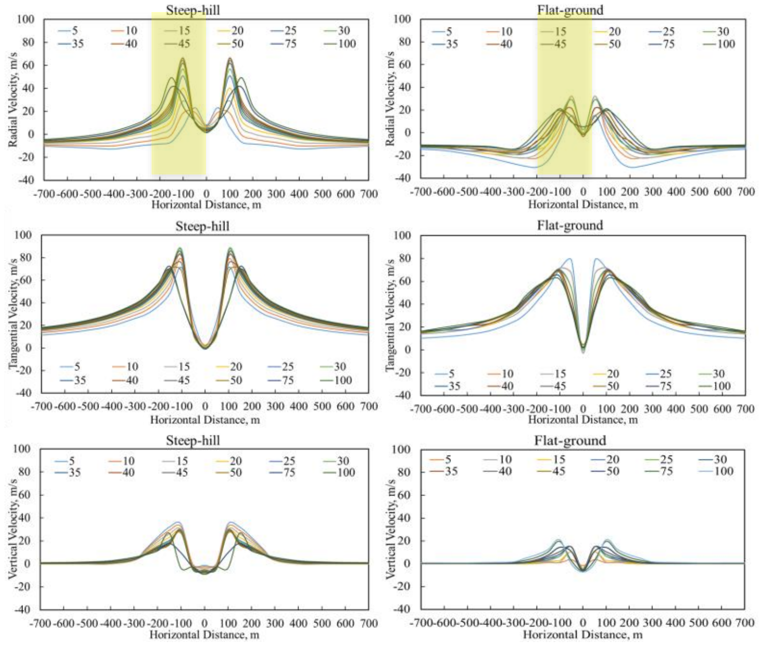
Wind speed-up due to topography

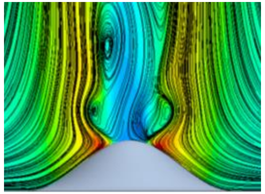




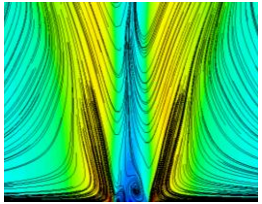
Effect of topography on tornado flow-field

- Applicable for relatively small topographic features

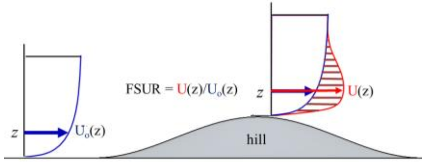




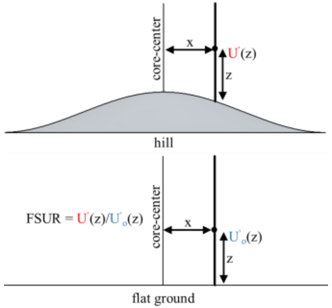
Steep-Hill



Flat ground



Synoptic flow



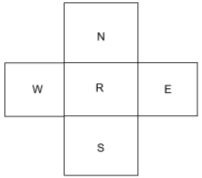
Tornadic flow

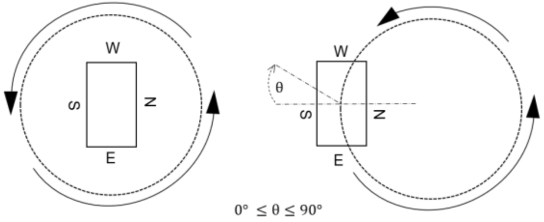
Western Engineering

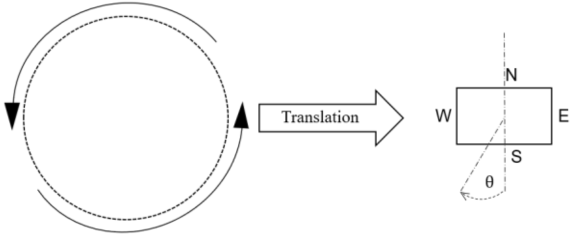
Nasir Z., and Bitsuamlak, G.T. (2018). Topographic effect on a tornado like vortex. *Wind and Structures,* 27(2), 123-136.

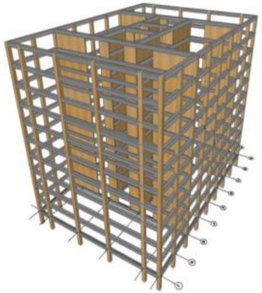
Test setups at the WindEEE Dome

Bezabeh, M. A., Gairola, A., Bitsuamlak, G. T., Popovski, M., & Tesfamariam, S. (2018). Structural performance of multi-story mass-timber buildings under tornado-like wind field. *Engineering Structures*, *177*, 519-539.

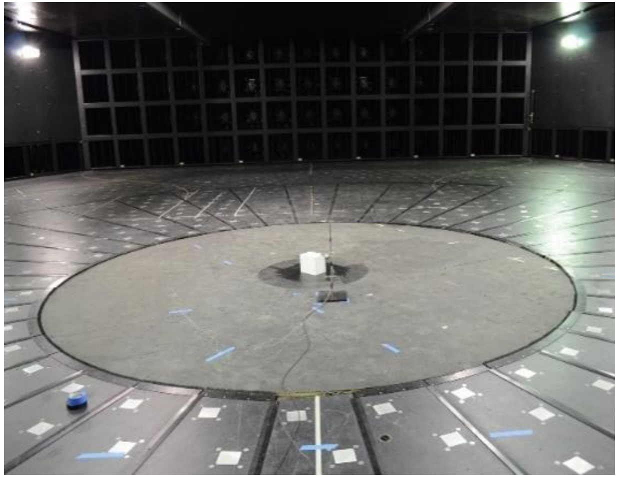








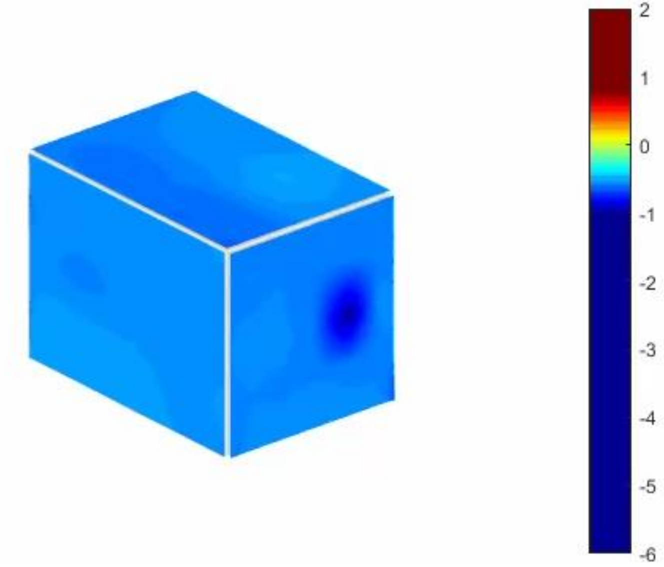
LLRS of studied building



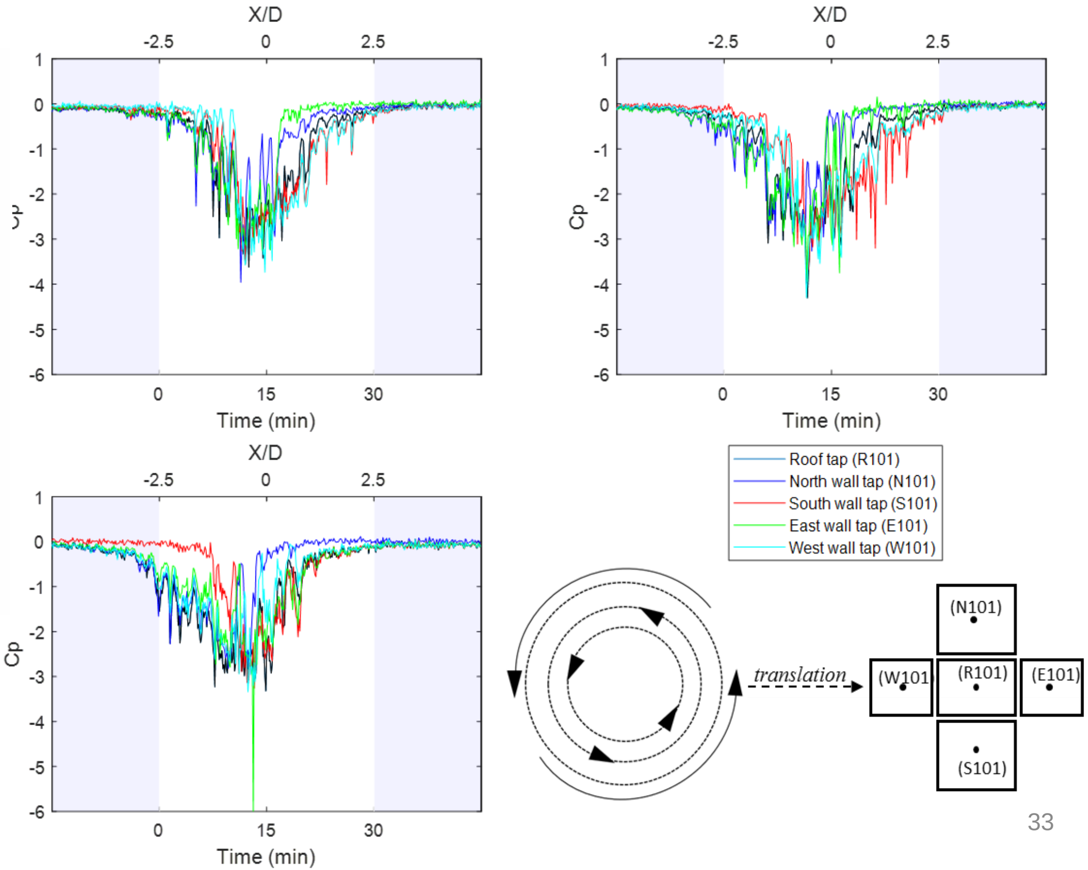
Varied variables for parametric study

Parameter	Values
Maximum mean tangential velocity (3-sec gust)	EF0 (36.1 m/s) EF1 (48.6 m/s) EF2 (61.1m/s) EF3 (73.6 m/s) EF4 (86.1 m/s) EF5 (112 m/s)
Nature of tornado-like vortex	Stationary and Translating
Critical damping ratio	1%, 2%, 3%, 5%
Building orientation with respect to the tornado axis	0^o, 30^o, 60^o, 90^o

Stationary and translating tornadic pressure coefficients

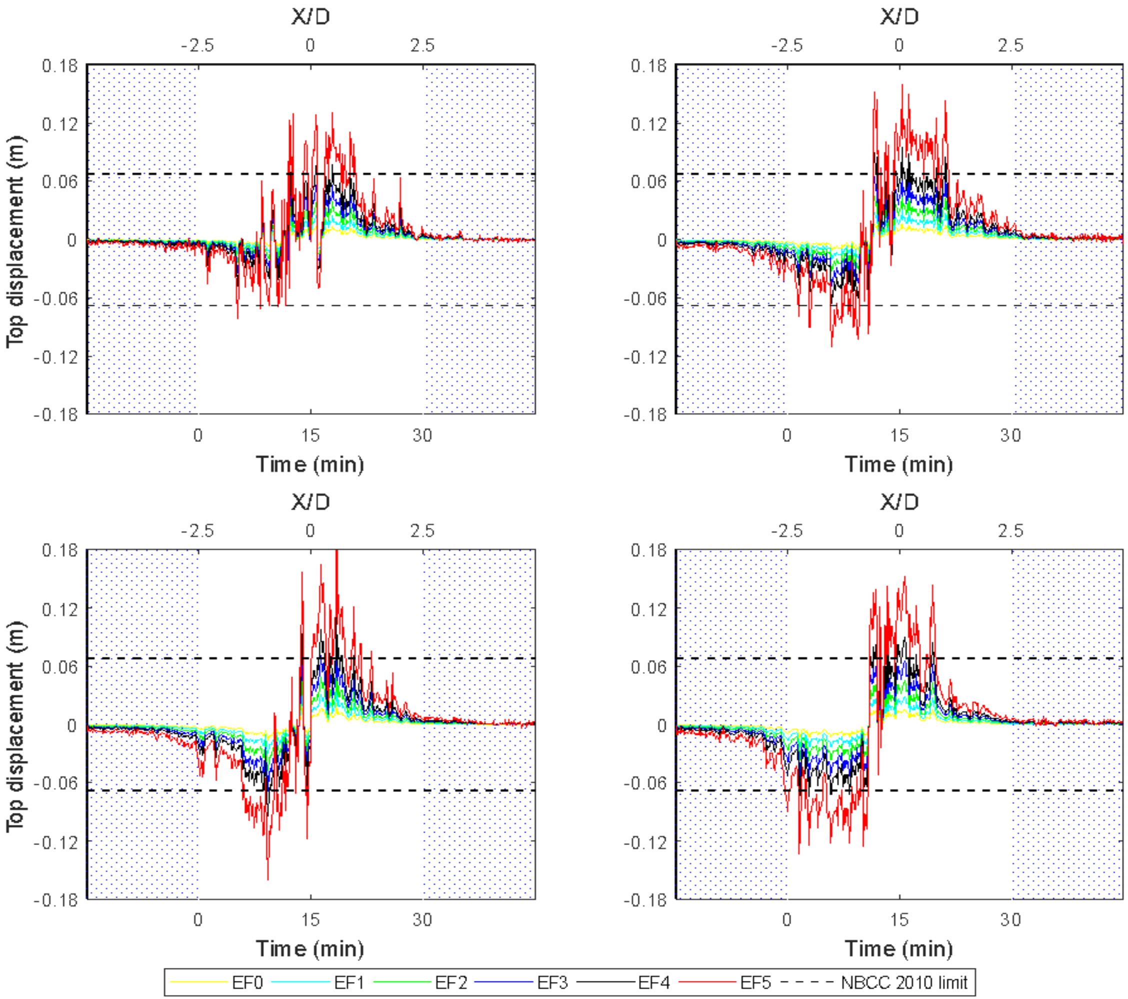


Time histories of pressure coefficients for translation tornadoes



Time histories of top floor displacement

a) Building orientation = 0º ,
b) Building orientation = 30º,
c) Building orientation = 60º,
d) Building orientation = 90º



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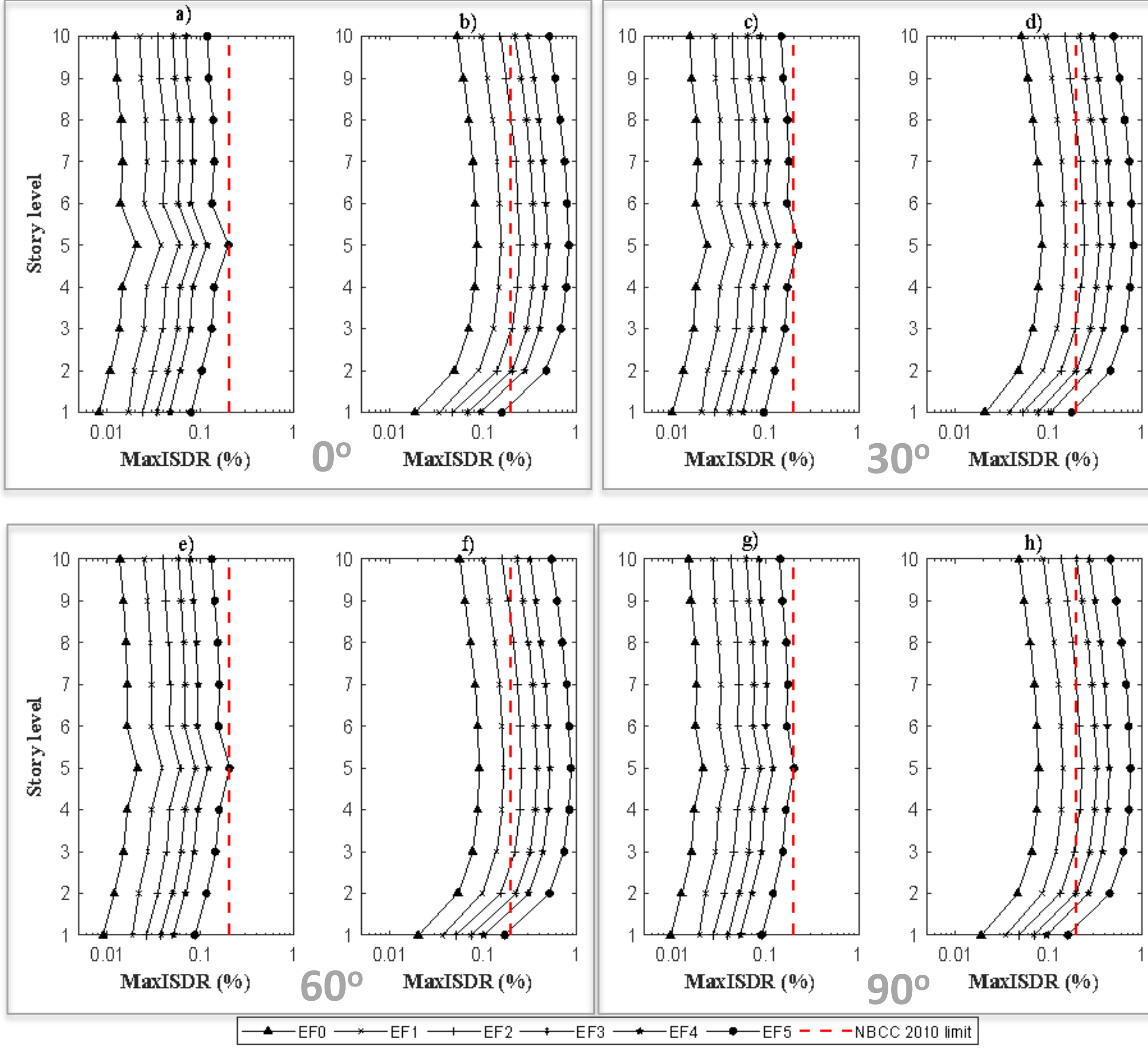
MaxISDR responses under translating tornadoes

Building orientation = 0º
a) X-direction,
b) Y-direction;
Building orientation = 30º
c) X-direction,
d) Y-direction;
Building orientation = 60º
e) X-direction,
f) Y-direction;
Building orientation = 90º :
g) X-direction,
h) Y-direction



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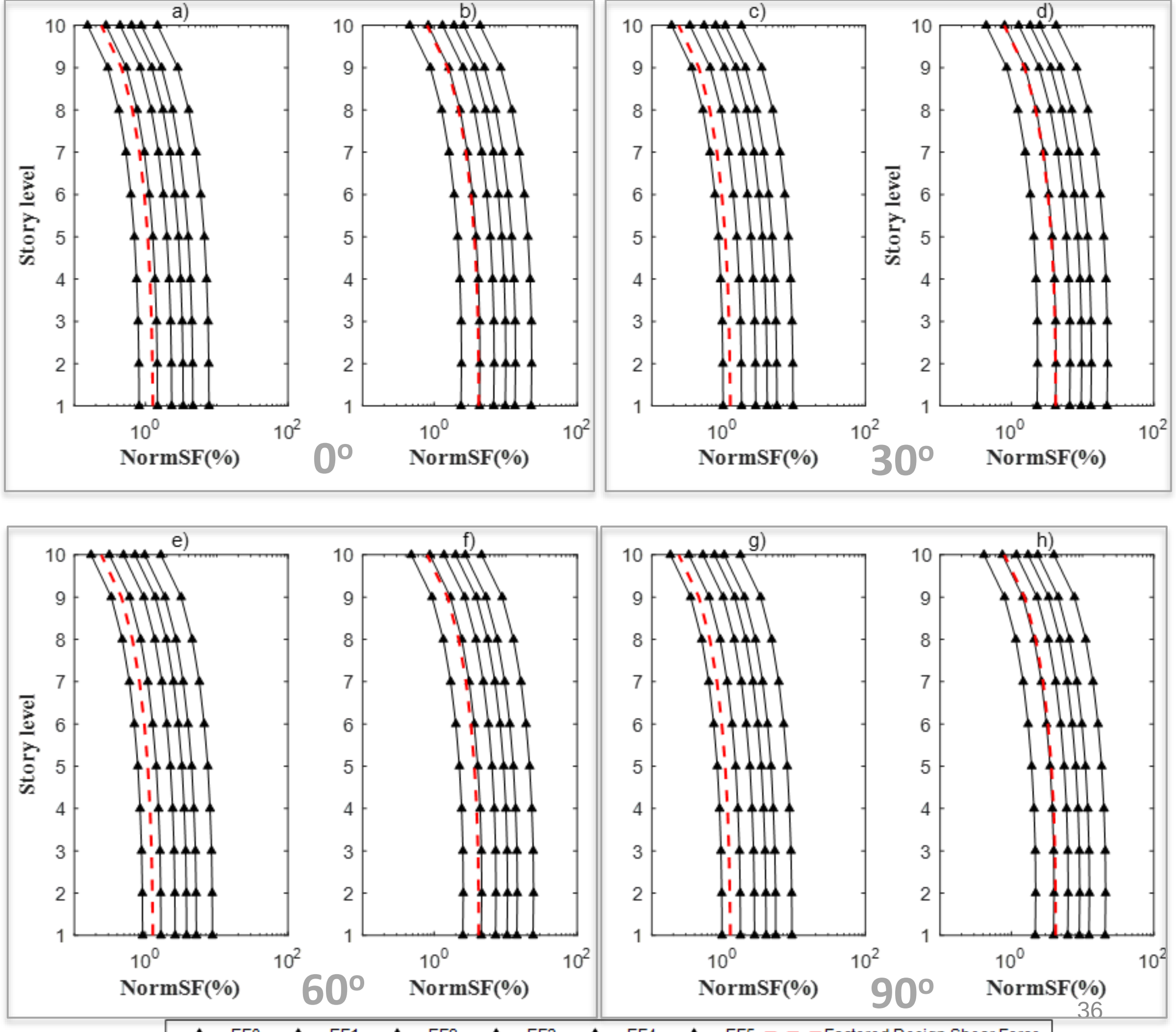
NormSF responses under translating tornado-like vortex

Building orientation = 0º
a) X-direction,
b) Y-direction;
Building orientation = 30º
c) X-direction,
d) Y-direction;
Building orientation = 60º
e) X-direction,
f) Y-direction;
Building orientation = 90º :
g) X-direction,
h) Y-direction

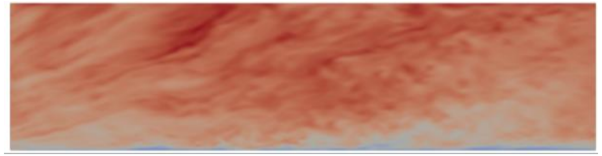


Synoptic wind remarks

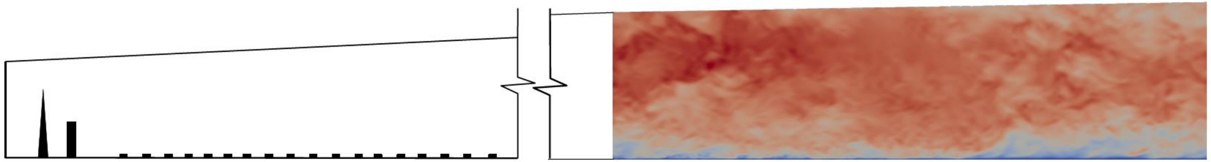
Inflow turbulence generation

Aboshosha, H., Elshaer, A., Bitsuamlak, G. T., & El Damatty, A. (2015). Consistent inflow turbulence generator for LES evaluation of wind-induced responses for tall buildings. JWEIA, 142, 198-216.

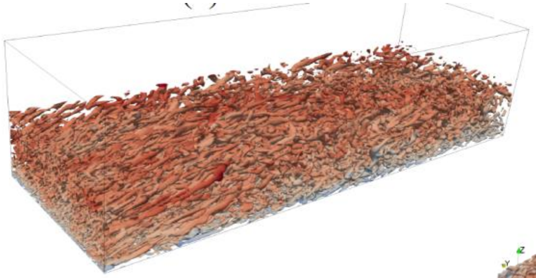
CDRFG

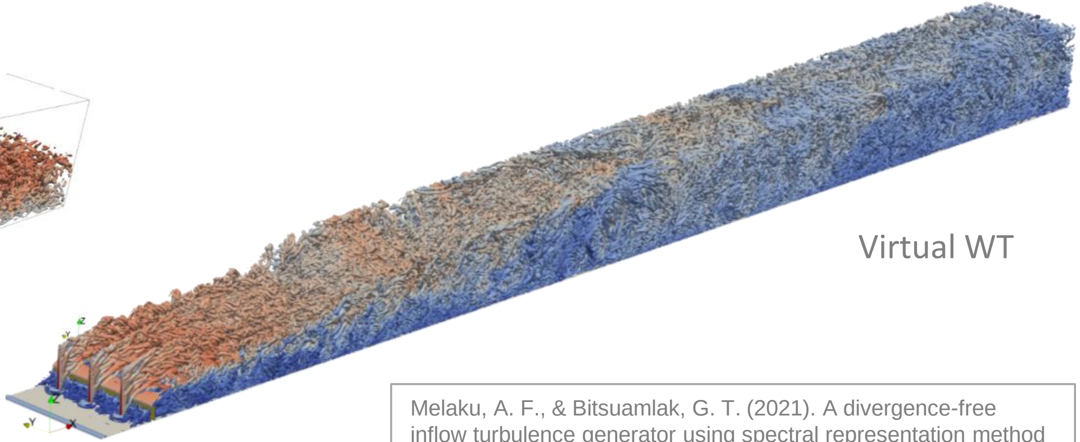


Virtual WT



CDRFG

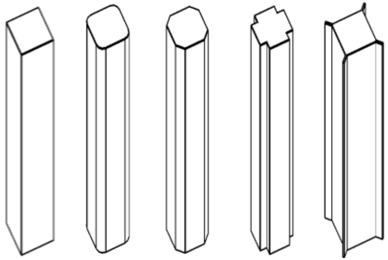




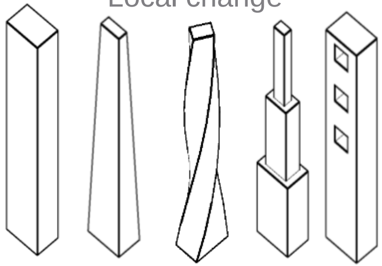
Virtual WT

Melaku, A. F., & Bitsuamlak, G. T. (2021). A divergence-free inflow turbulence generator using spectral representation method for large-eddy simulation of ABL flows. *JWEIA*, *212*, 104580.

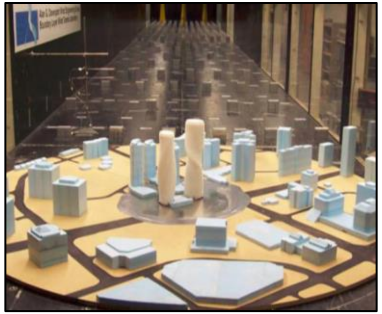
Aerodynamic optimization

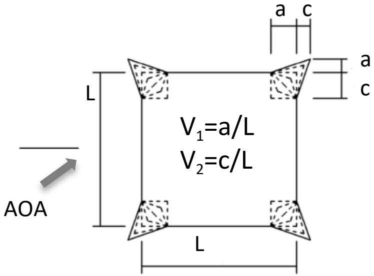


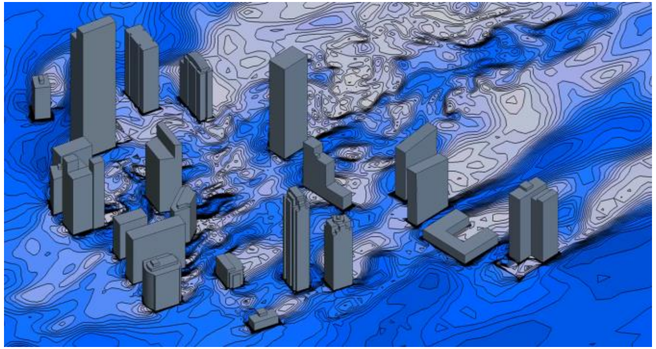
Local change

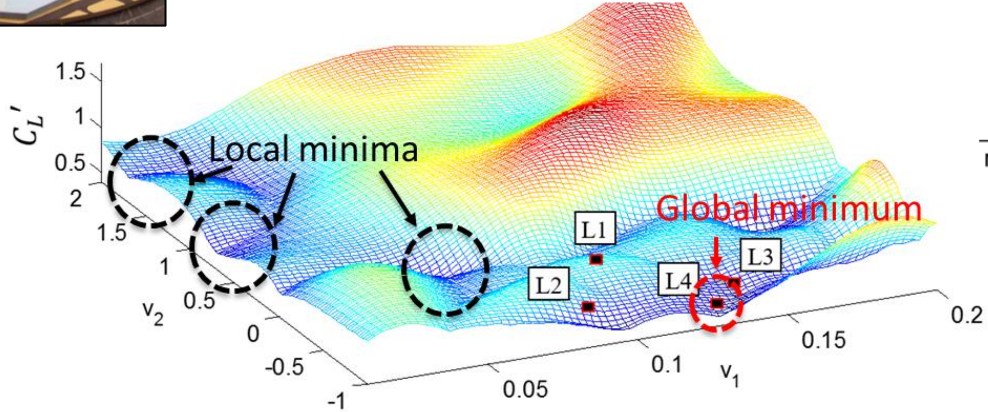


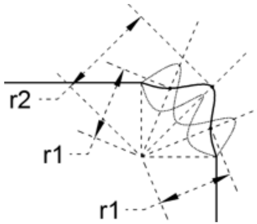
Global change

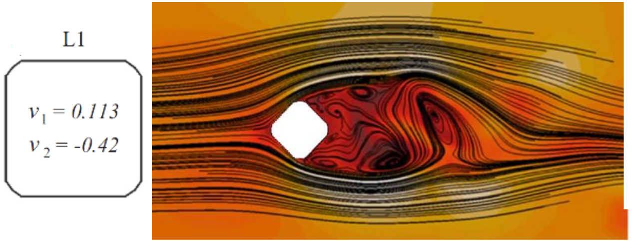


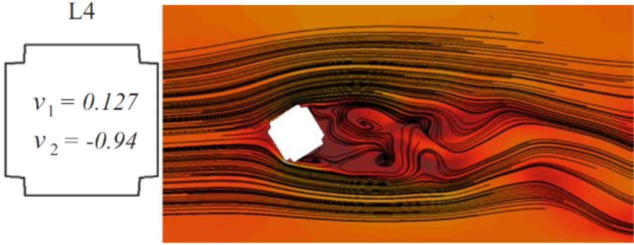












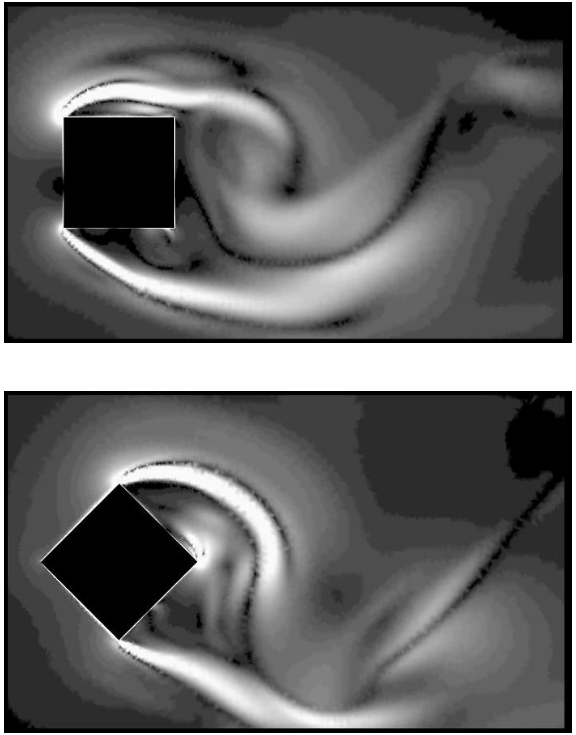
Taipei 101
2004

Burj Khalifa
2009

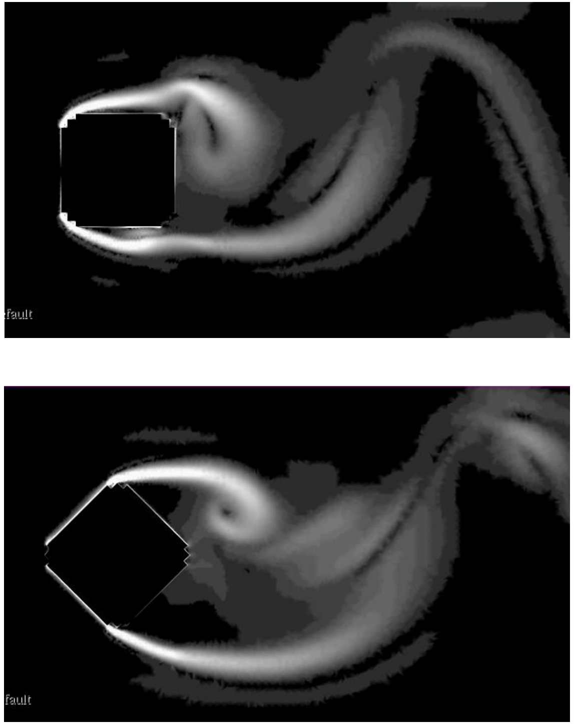
Turning Torso
2005

432 Park Avenue
2015

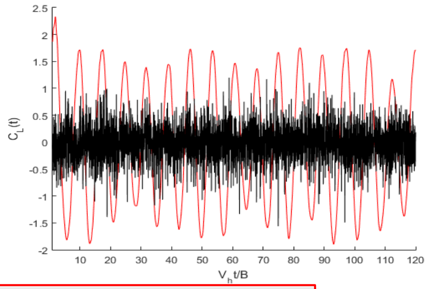
Flow structure (original and modified cross-section): *total pressure gradient*

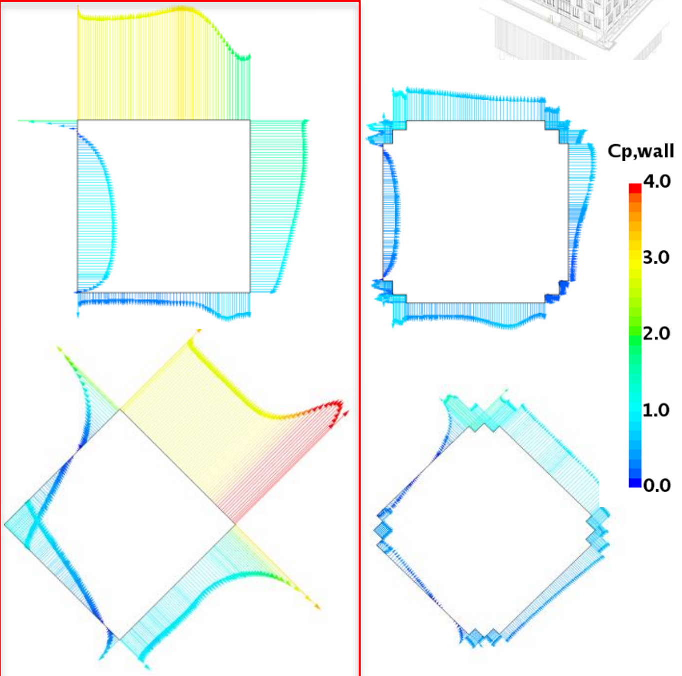


Square planform; side width = 1



Double setback: step size= 2x1/16





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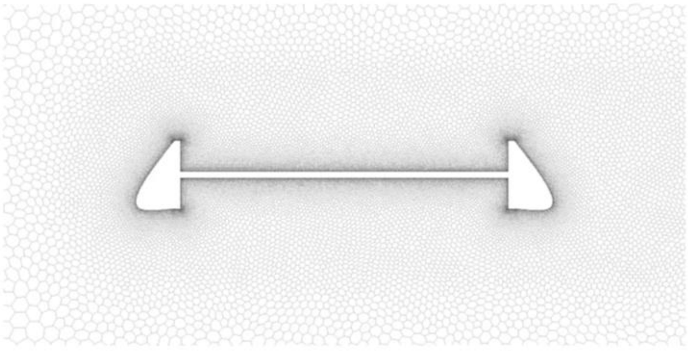
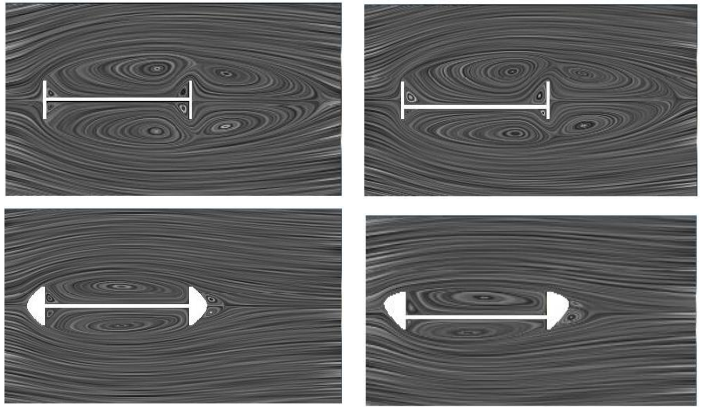
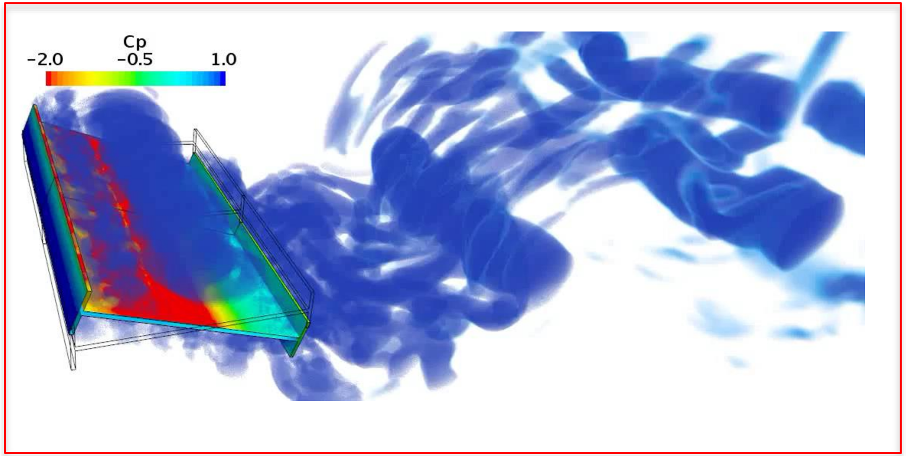
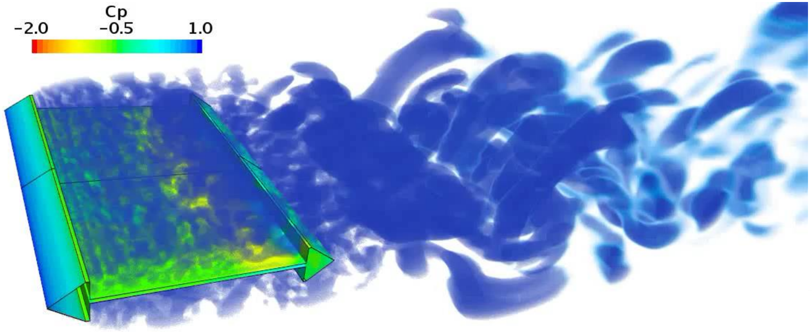
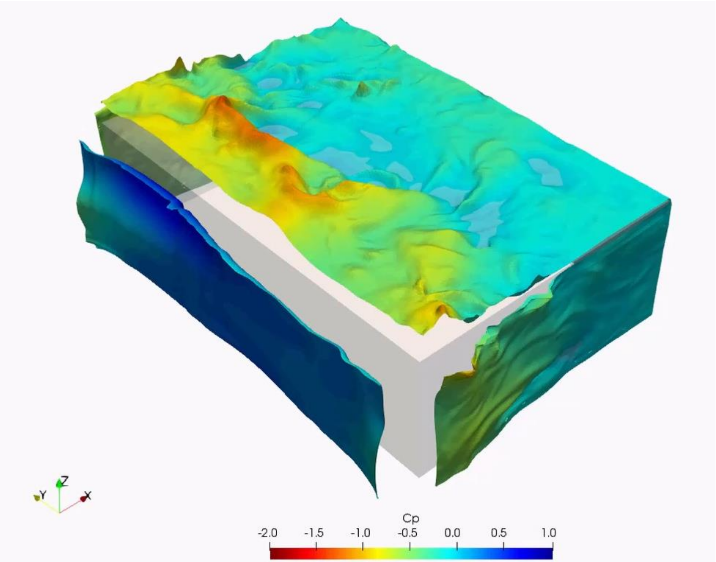
Optimal aerodynamic shapes for long-span bridges



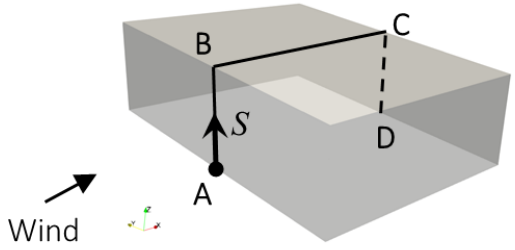






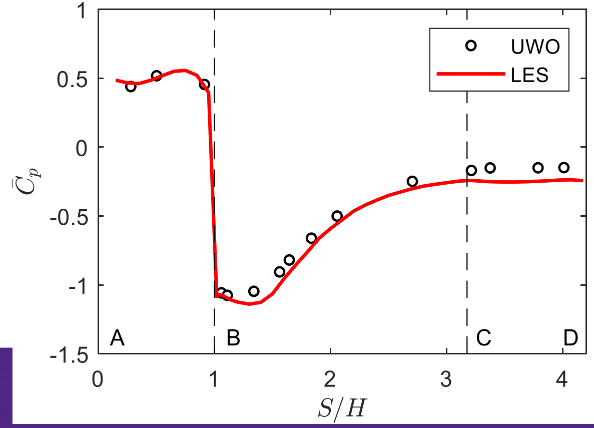


Statistics of extreme surface pressure coefficients

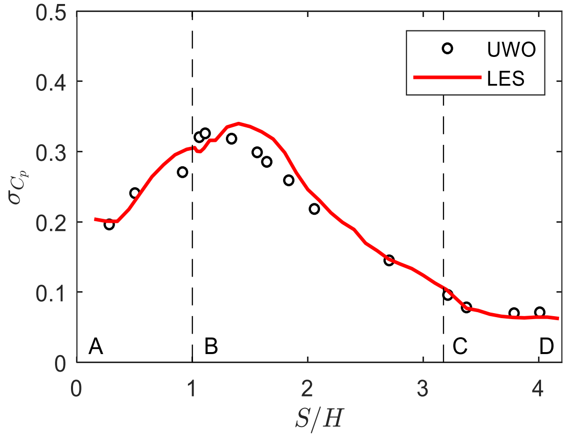


UWO : NIST database test at UWO
LES : current Large Eddy Simulation

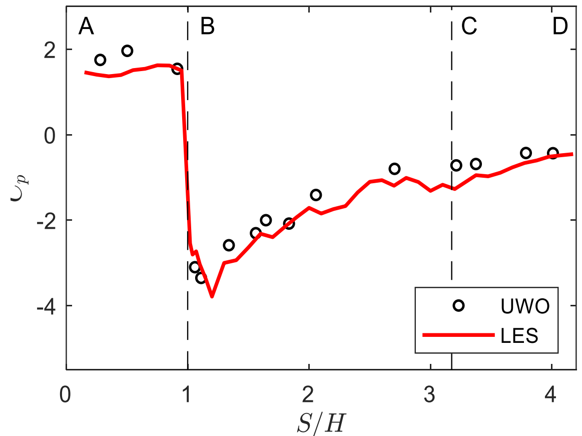
mean Cp



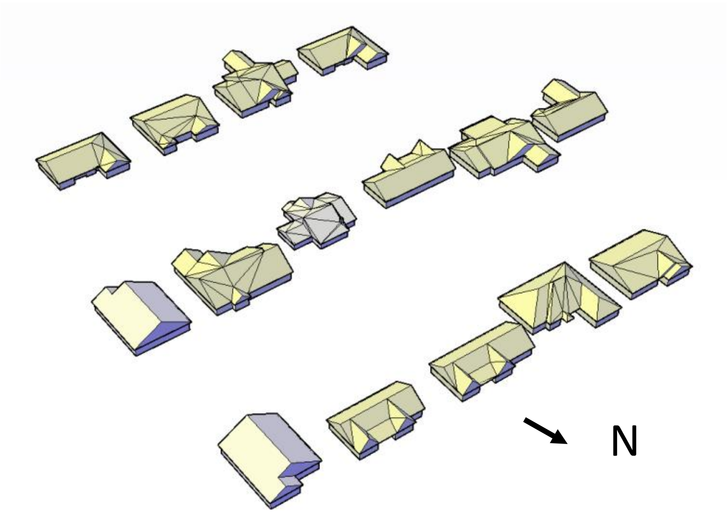
r.m.s Cp



peak Cp



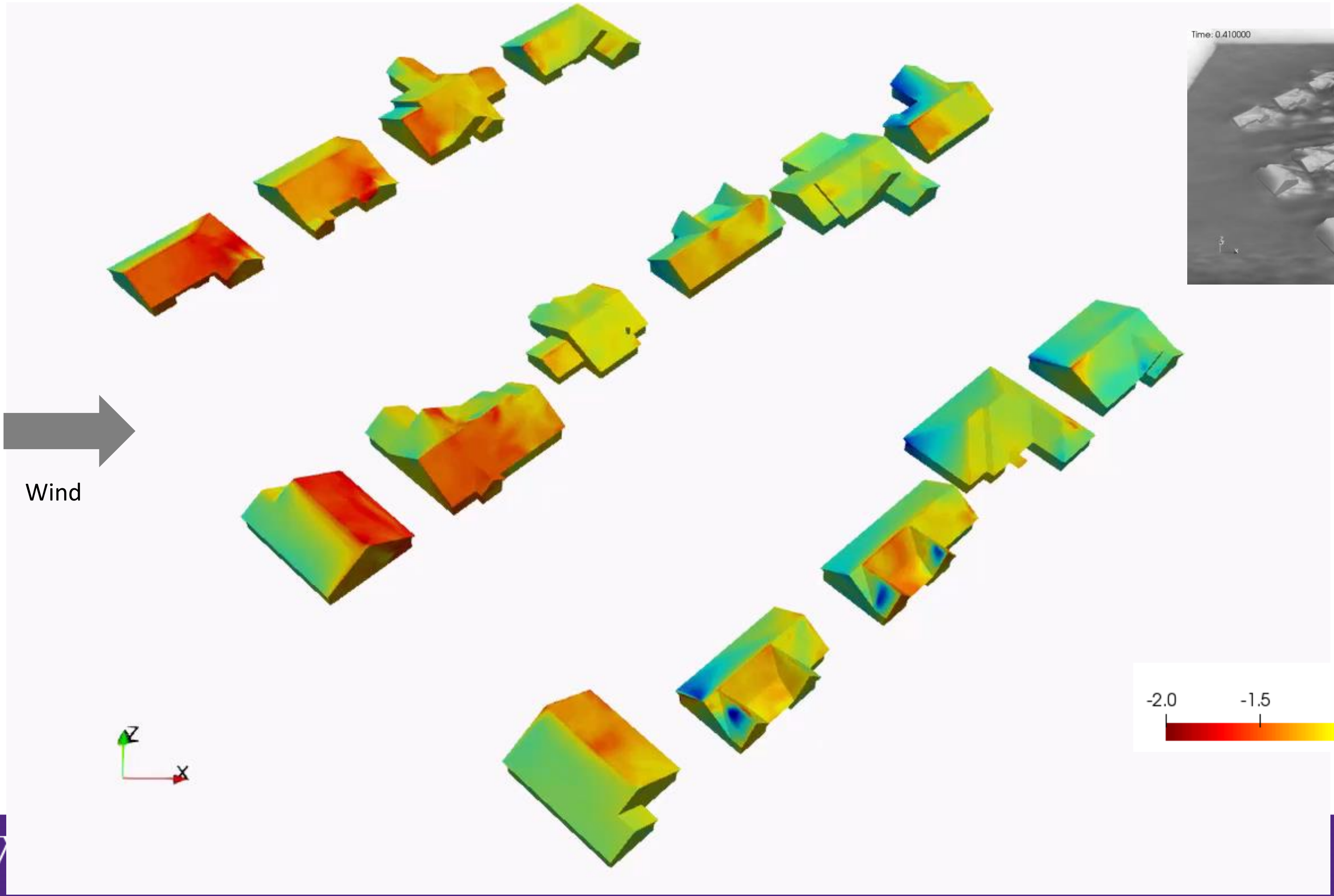
Neighbourhood scale simulations for a residential community in Florida

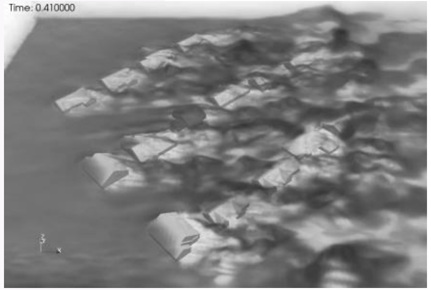


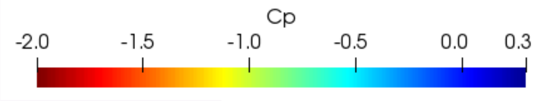
(Kopp and Gavanski 2011) and (Gurley from UF)

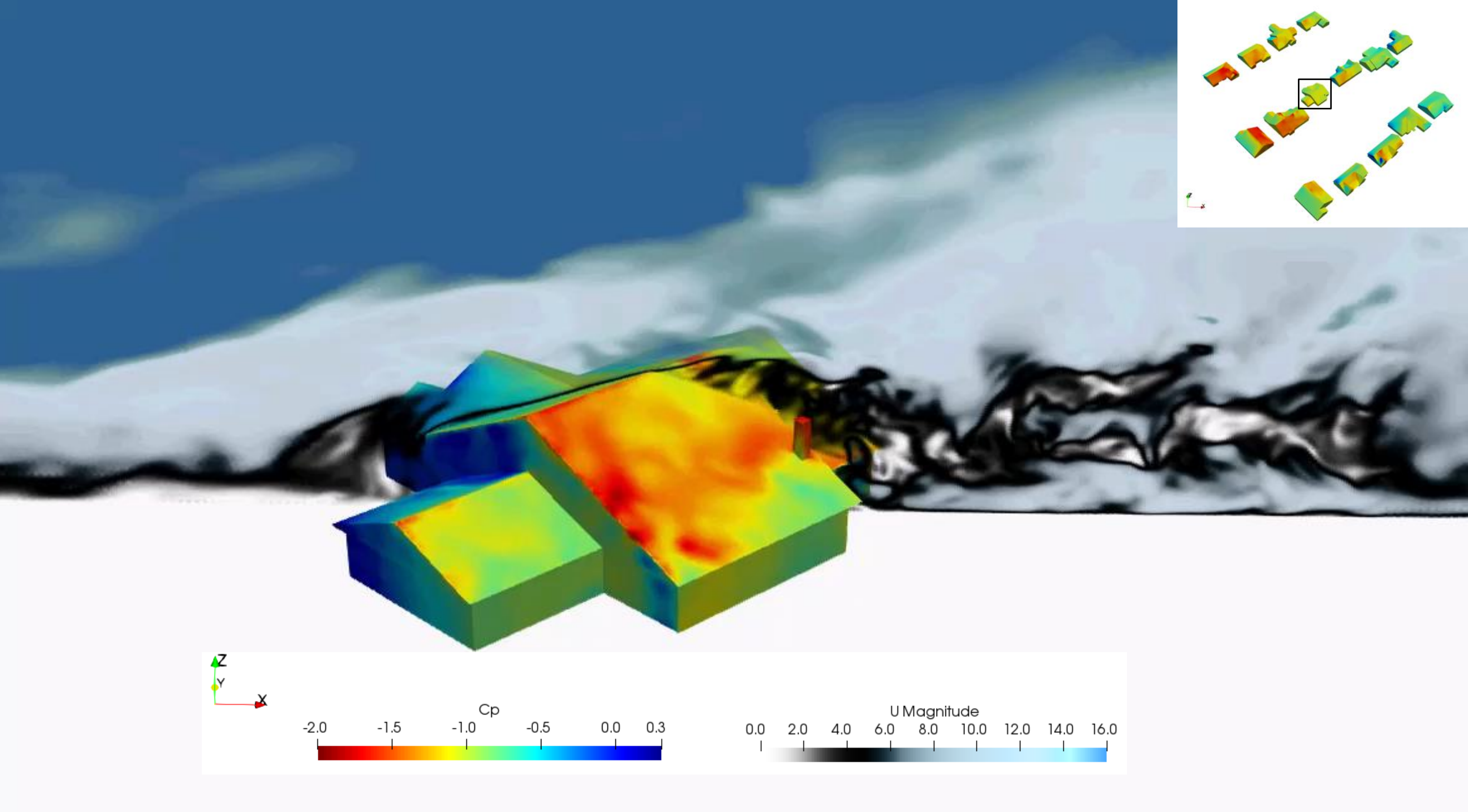
(Liu et. al 2009)

Neighbourhood scale simulations for a residential community in Florida








Z
Y
X
Cp
-2.0
-1.5
-1.0
-0.5
0.0
0.3
U Magnitude
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0

Acknowledgment

- Current research team: Tibebu, Anwar, Meseret, Matiyas, Barilelo, Abiy, Kimberly, Anant, Chris, Tsinuel, Eric, Matt, Hadil, Muna, Tewodros, Kenny, Cody, Shea, Kate, Dagmawi, Tsigereda
- All former graduate students, postdocs and visiting scholars
- Research collaborators: Fitsum from BCIT, Solomon from UBC, Popovski from FPInnovations, Laxmi from McGill, Arindam from FIU, Kaoshan from Tongji, David from McMaster, Shaker from Ryerson, Miriam from UWO, Martha from UWO and CEE faculty at UWO
- Funding agencies - NSERC CRC, Discovery, CFI, CRD; OCE; and SOSCIP
- Industry collaborators - FM Global, FPInnovations, IBM, Wausau Tile Inc., Theakston Environmental Inc., Kilmaat, Side Walks Lab, Stephenson Engineering, and Thornton Thomassetti
- Western's WindEEE Research Institute, Boundary Layer Wind Tunnel Laboratory, SHARCNET, and Northern Tornadoes Project
- UWO

1878

Western

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Sensitivity of LES peak pressure load predictions to boundary layer turbulence

Catherine Gorlé, Giacomo Lamberti
Civil & Environmental Engineering Department
Stanford University

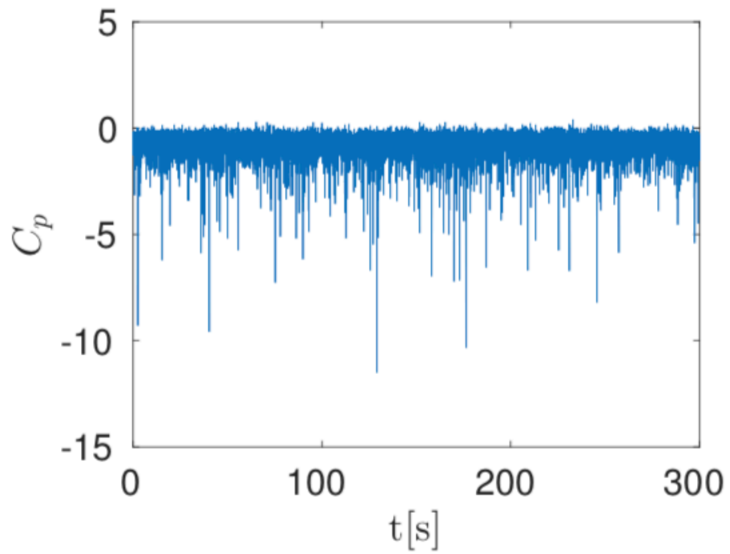
UF NHERI Virtual Workshop on *Boundary Layer Wind Tunnel Simulation of Transient and Non-synoptic Wind Events*
May 19 2021

Funding: NSF Award 1635136
Computational resources: XSEDE supported by NSF grant number CTS160009

Motivation

- Cladding design is a critical component of high-rise building design
- Suction peaks on side walls can be particularly strong

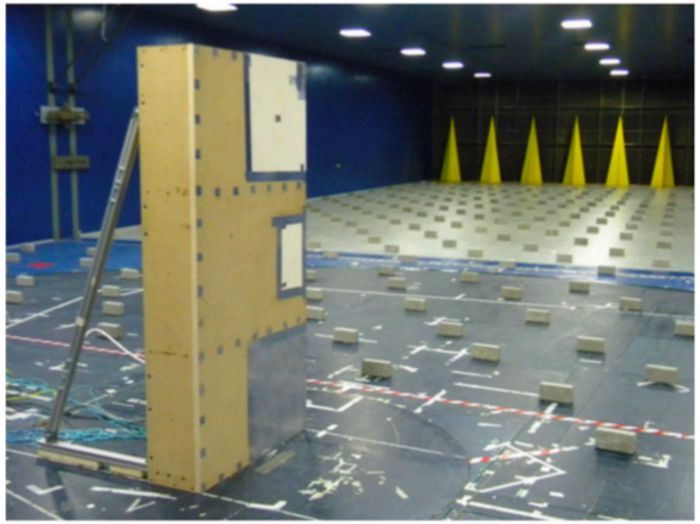
Photo courtesy of the U.S. Navy/Interior Communications Electrician 1st Class Jason Stephens



Motivation

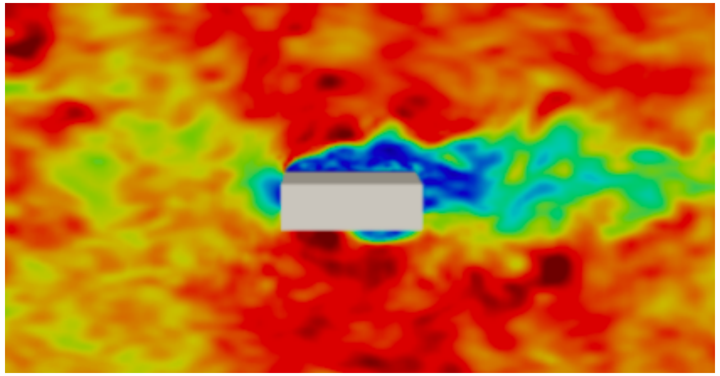
Wind tunnel testing for cladding design

- Record time series of pressures on a scaled model test
- Limitations in the number of measurement locations
  - Limited resolution - often only 1 pressure tap/panel
  - Requires assumptions to calculate the area-averaged load on the panel



CFD could provide a valuable alternative

- Provide a complete 3D solution for the flow field
- Number of pressure taps = number of cells on building façade
  - Direct calculation of area-average is possible
- Availability of simultaneous velocity and pressure fields supports detailed investigation of flow physics

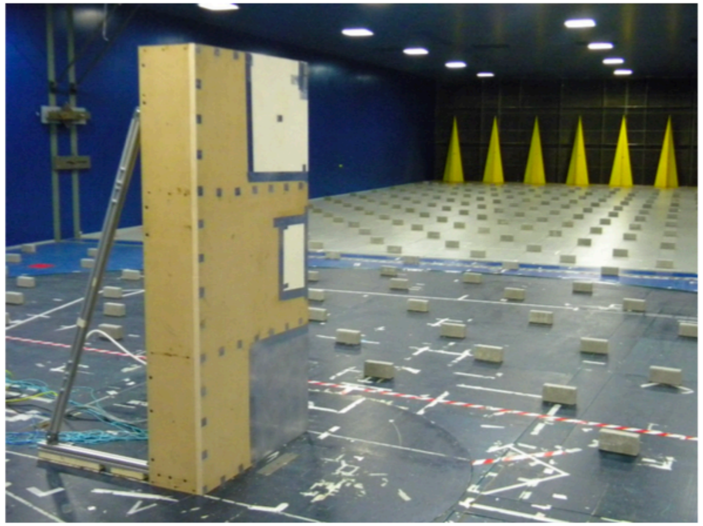


Objectives

1. Validate LES predictions of peak pressure loads
2. Quantify sensitivity to ABL characteristics

Test case:

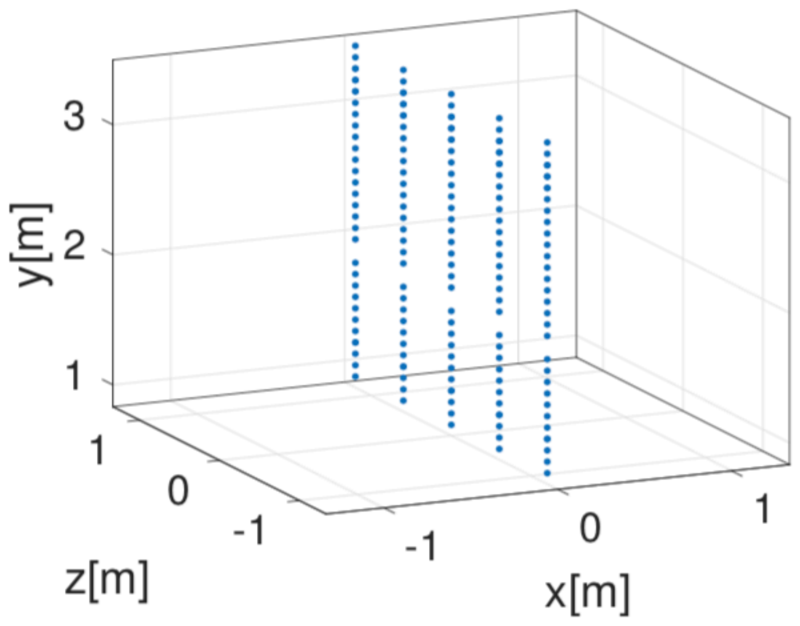
- Rectangular plan building: 2 x 1 x 0.3m
- Tested in ABL wind tunnel at Politecnico di Milano[1,3] and in Wall of Wind [2,4]

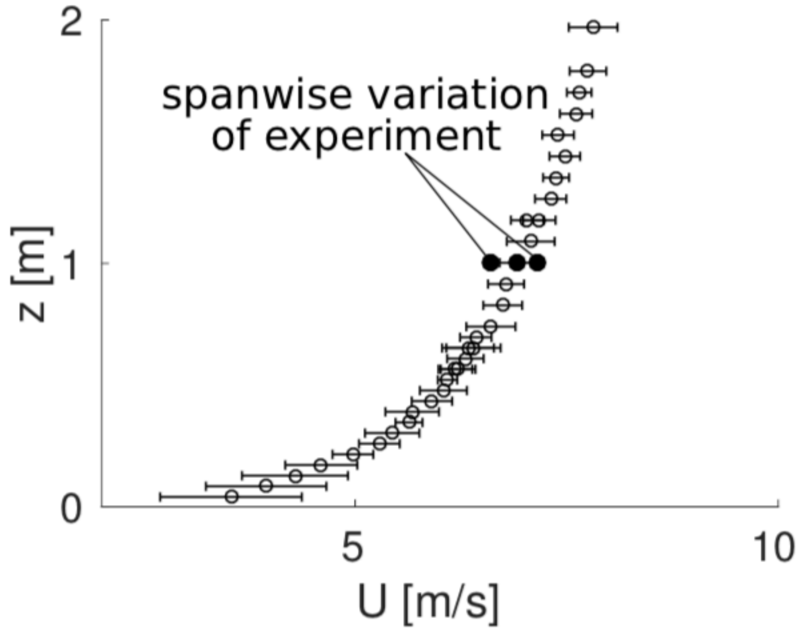


[1] L. Amerio, PhD thesis, Italy, 2018.
[2] G. Lamberti et al. J Wind Eng Ind Aerodyn, Volume 204, 2020.
[3] PoliMi data set: https://doi.org/10.5281/zenodo.3906589#.XvOI6ZraWNM.email
[4] Wall of Wind data set : https://purl.stanford.edu/nf676fm4685

Characterization of incoming ABL

- 3D hotwire measurements[1]
- 5 spanwise and 52 vertical locations
- 20s time series, sampling frequency 2000Hz

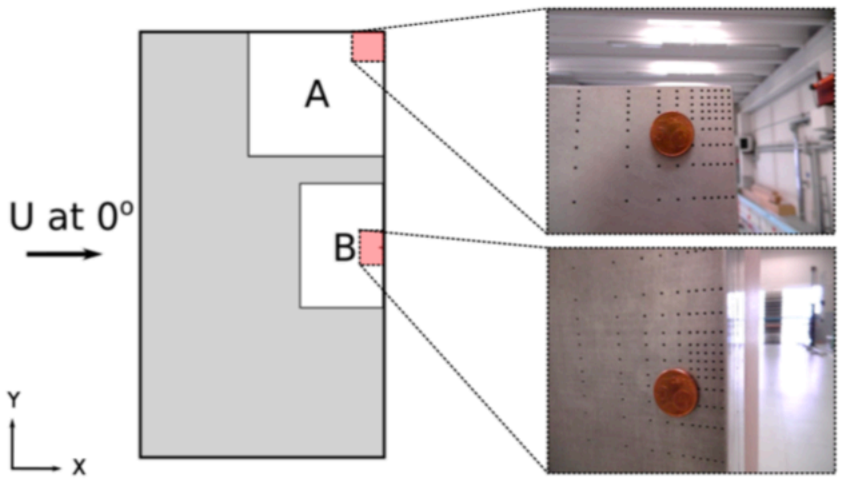




[1]Amerio, 2018

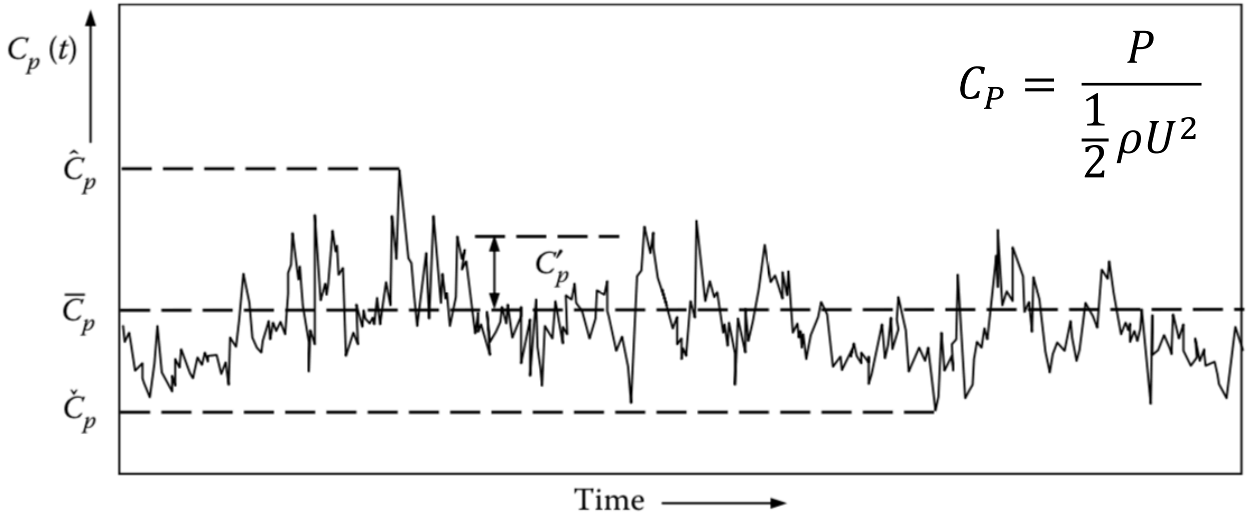
Pressure measurements

- Focus on critical locations: corners and edges[1]
- 224 pressure taps on tiles A and B, minimum tap spacing 3.4mm
- 300s time series, sampling frequency 500 Hz



Quantities of interest:

- mean pressure coefficients
- rms pressure coefficients
- peak pressure coefficients
- design pressure coefficients

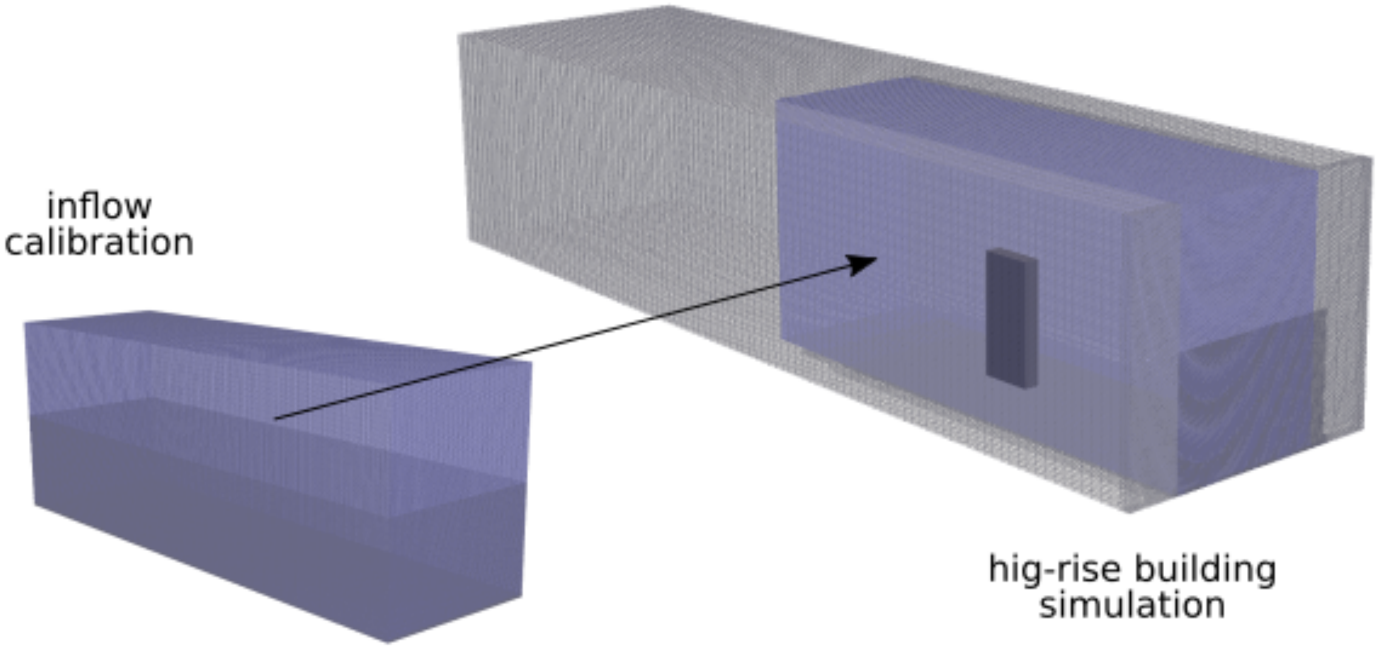


$$C_P = \frac{P}{\frac{1}{2}\rho U^2}$$

LES set-up

Computational domain and mesh:

- 20 x 4 x 5 m
- 7.5M cells; grid sensitivity tested using 5.5M cells
- Ground wall resolution: $y^+ \sim 300$
- Building wall resolution: $y^+ \sim 100$



Subgrid model: Smagorinsky

Boundary conditions:

- Periodic at sides
- No-slip on top
- Smooth log law wall function on building
- Divergence-free digital filter + gradient-based optimization at inflow
- Rough wall function on ground

Solver:

- pisoFOAM, 2nd order schemes
- second-order implicit time-stepping scheme; Dt = 0.0001s (CFL < 1)
- burn-in period ~10s, statistical averaging ~60s
- 80,000 CPUhrs on 64 processors, ~7 weeks on Stampede2

ABL inflow and wall function

- Divergence-free implementation of digital filter [5]

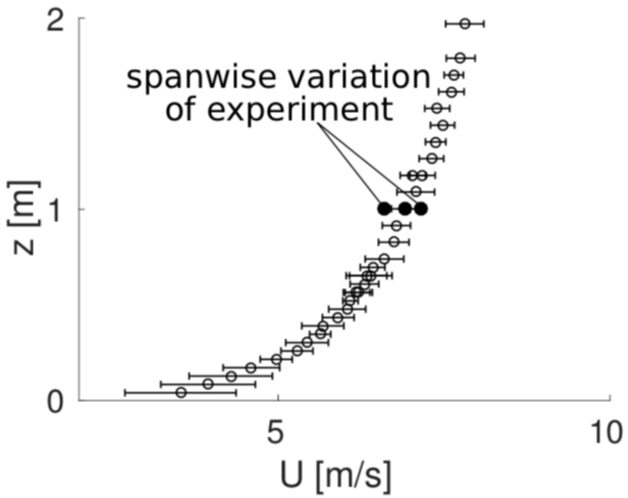
$$u_i = \overline{u_i} + a_{ij}(R_{uu}, R_{vv}, R_{ww}, R_{uv})u_{*,j}(T_u, T_v, T_w)$$

mean velocity profile

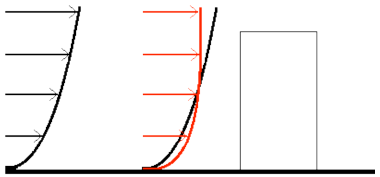
Reynolds stress component magnitudes

random field, filtered to achieve correlation with desired length/time-scales

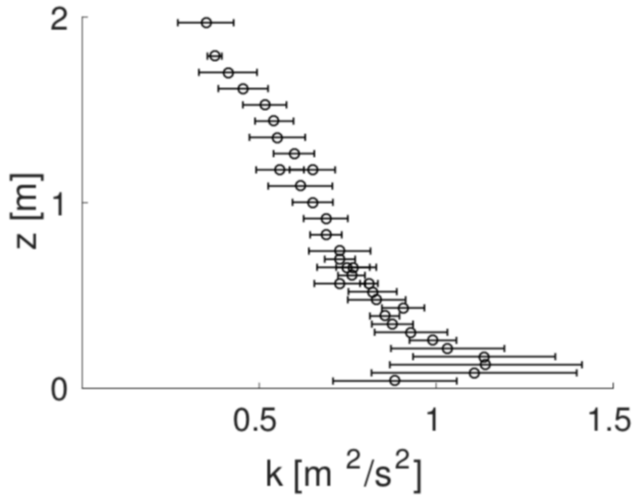
$$U = \frac{u_*}{\kappa} ln\left(\frac{z + z_0}{z_0}\right)$$



- Rough wall function to sustain the log law without resolving roughness elements:



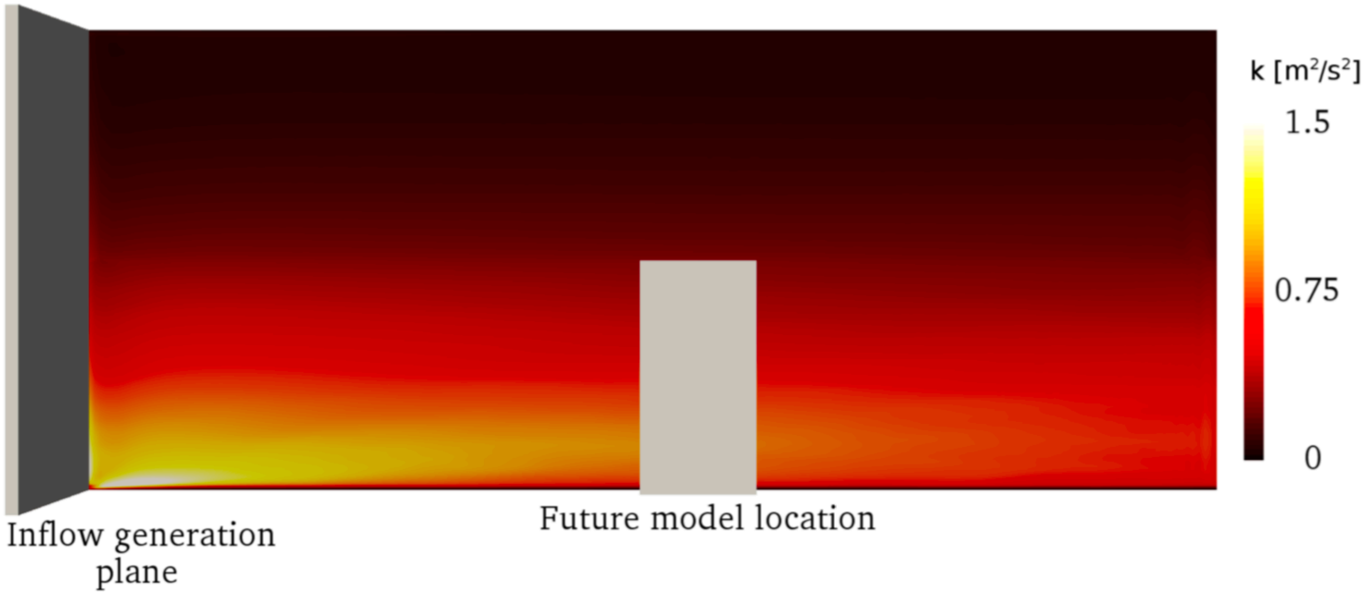
$$u_g^* = \frac{\kappa U_g}{ln\left(\frac{z_g + z_0}{z_0}\right)}$$

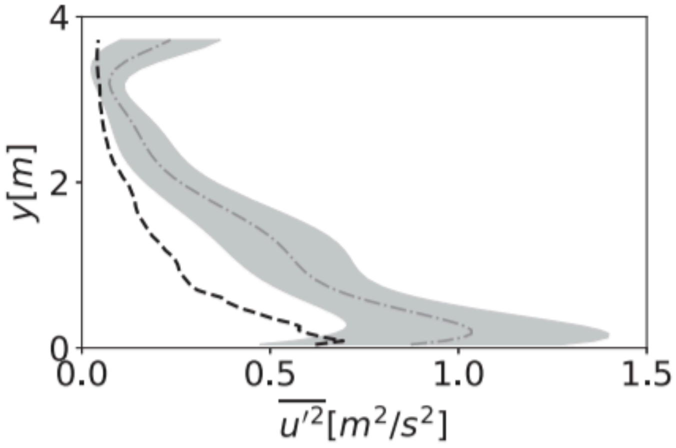


[5] Kim, Yusik, Ian P. Castro, and Zheng-Tong Xie. Computers & Fluids 84 (2013): 56-68.

ABL inflow generation

Horizontal inhomogeneity: synthetic turbulence is not a solution of the governing equations

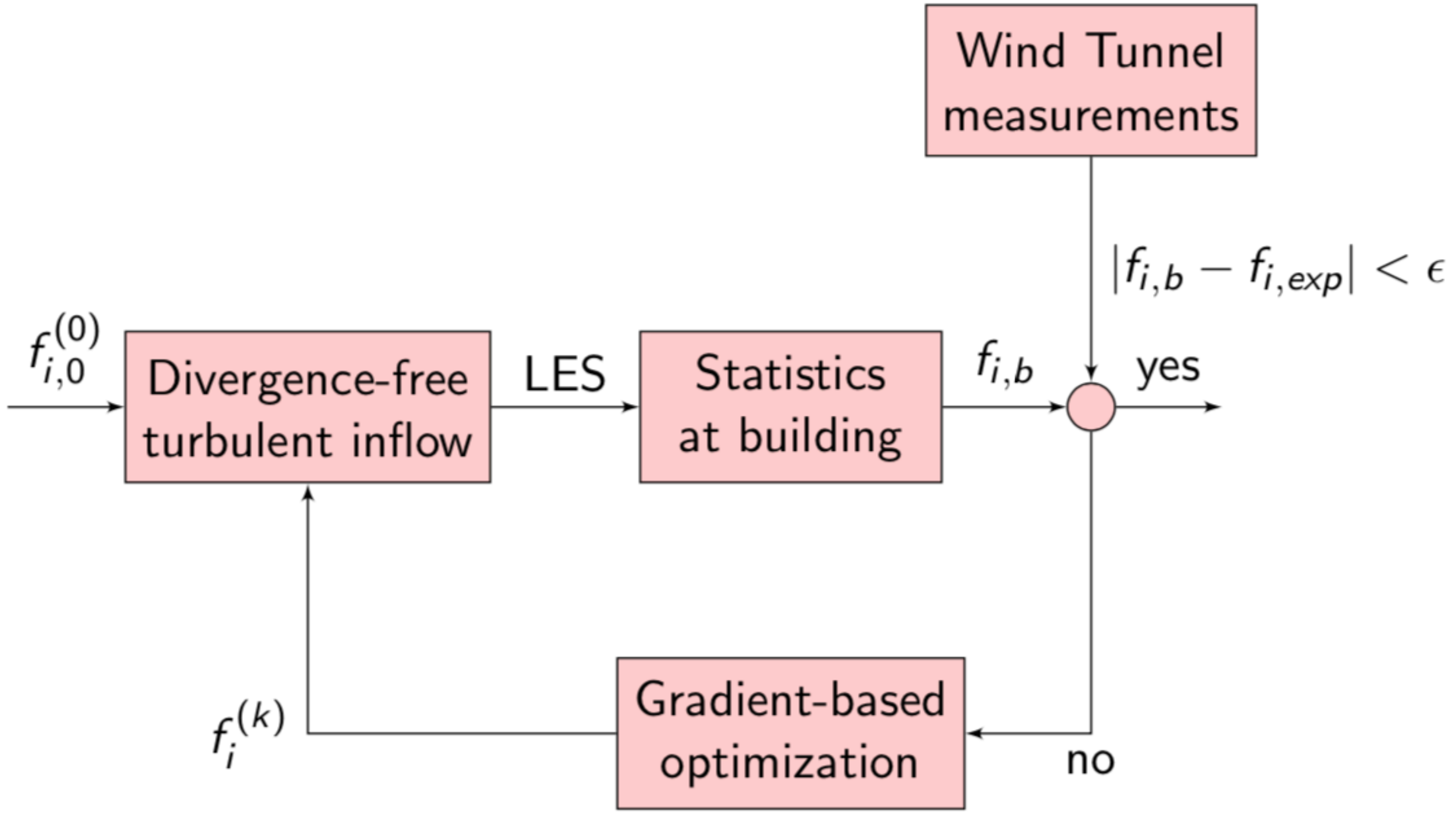




(b) streamwise velocity variance

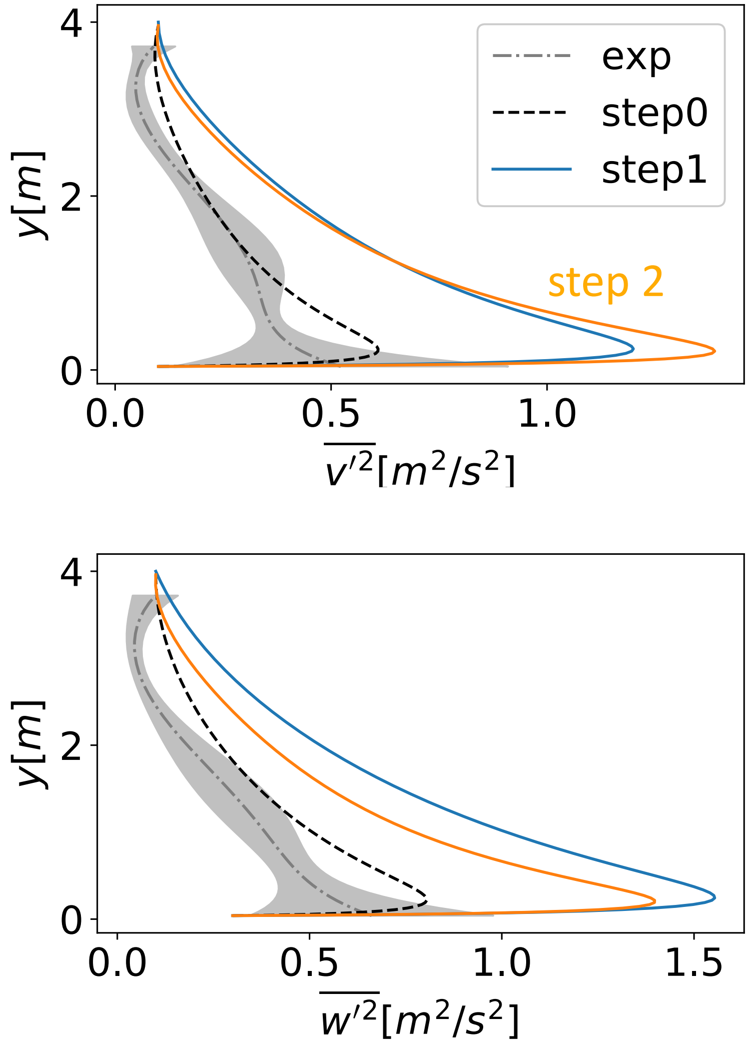
Optimization framework

Update synthetic turbulence input parameters to achieve desired ABL statistics downstream

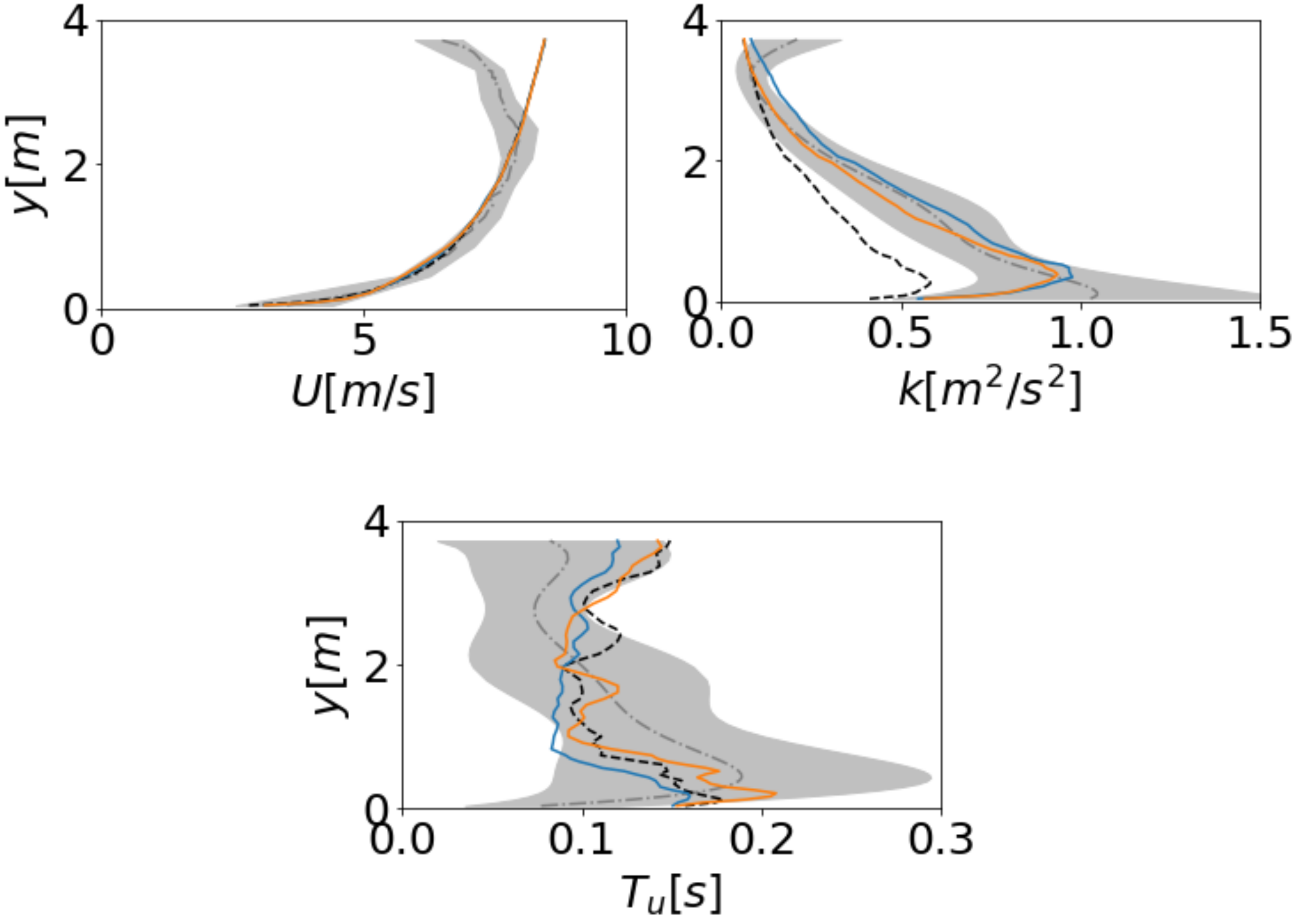


Optimization Results

Inflow generation plane



Building location

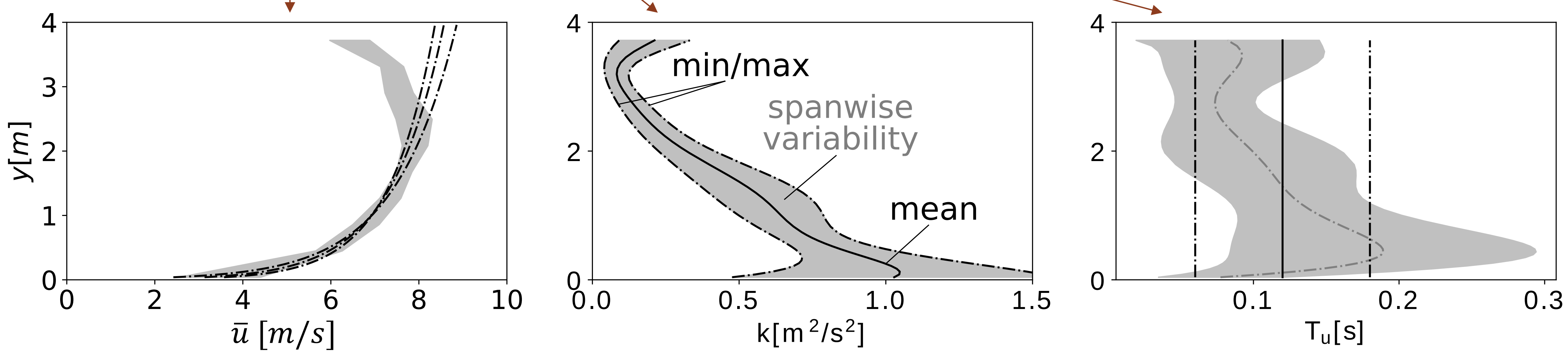


Inflow sensitivity analysis

Characterization of inflow uncertainty

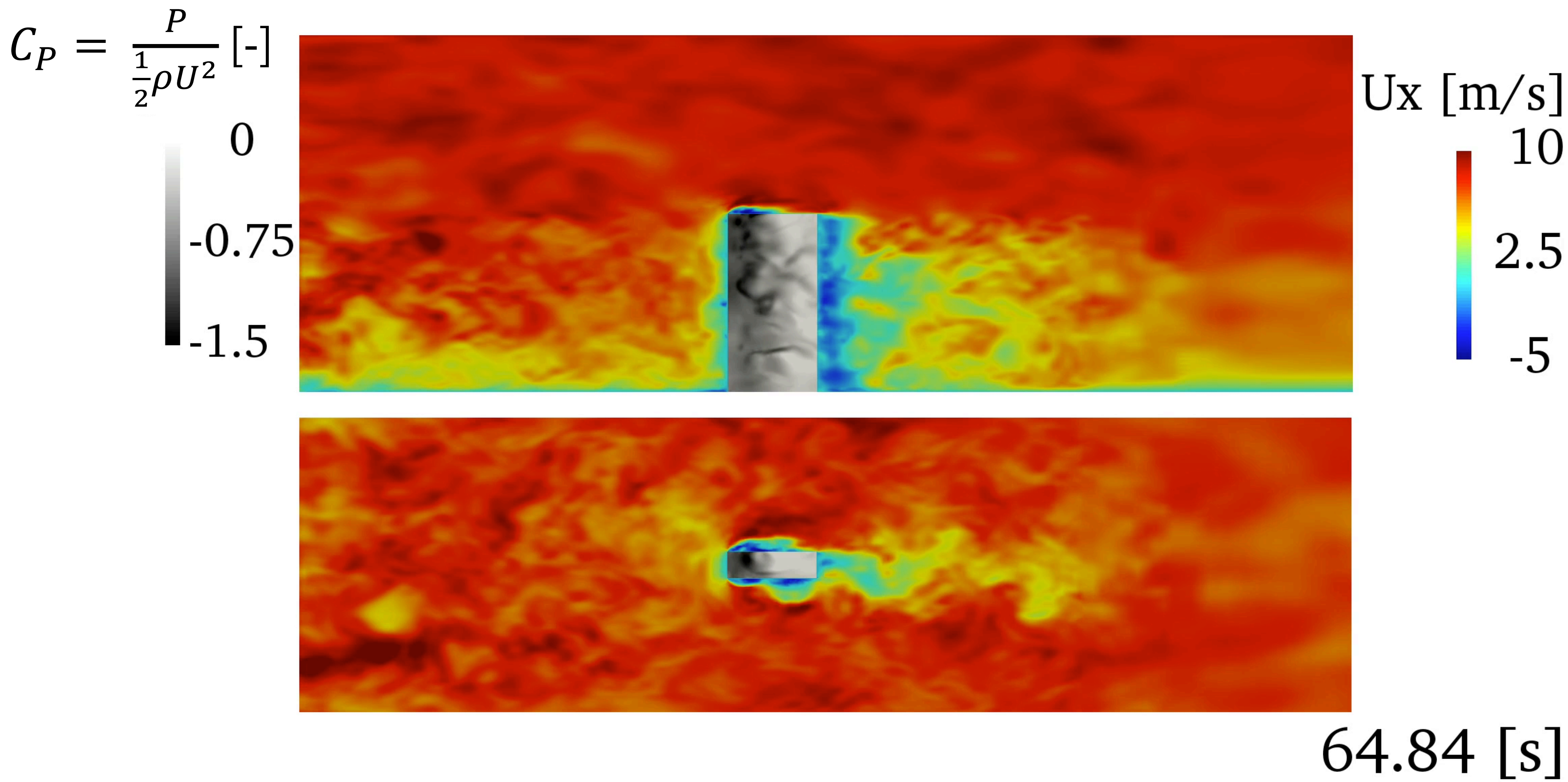
$$u_i = U_i(z_0) + a_{ij}(k)u_{*,j}(T_u)$$

Perform 27 LES simulations



G. Lamberti & C. Gorlé. J Wind Eng Ind Aerodyn, Volume 206, 104370, 2020.

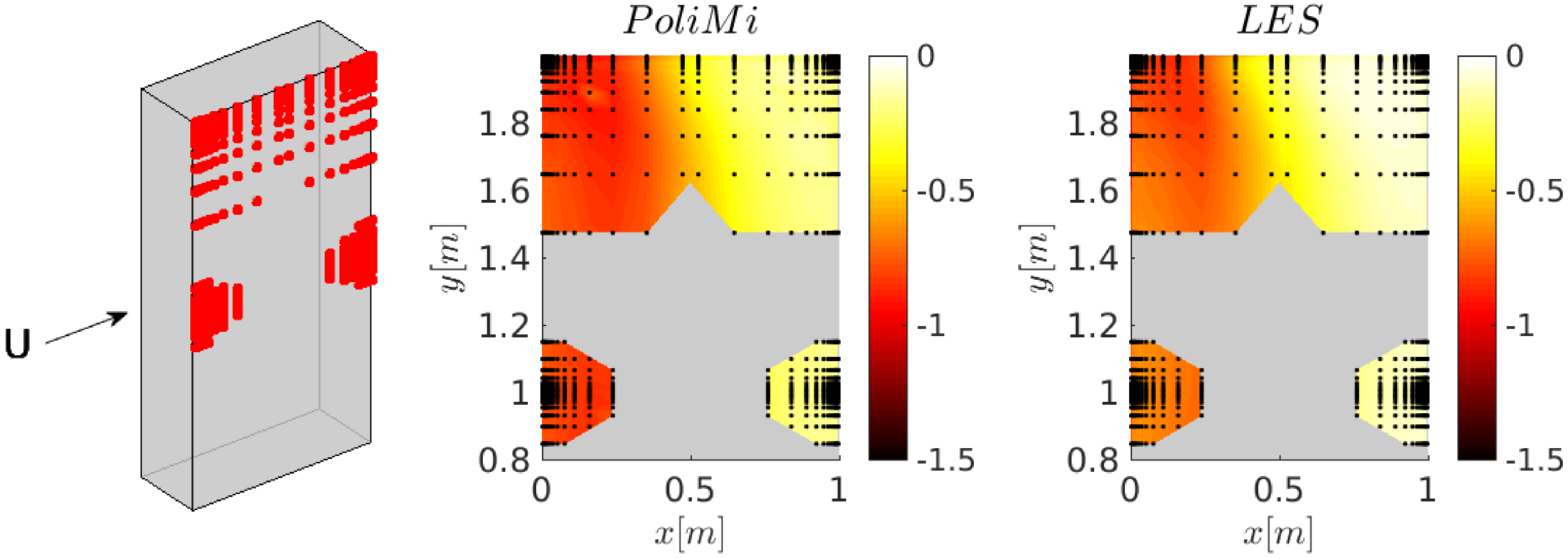
Flow topology – instantaneous velocity field and C_p distribution from LES



Stanford University

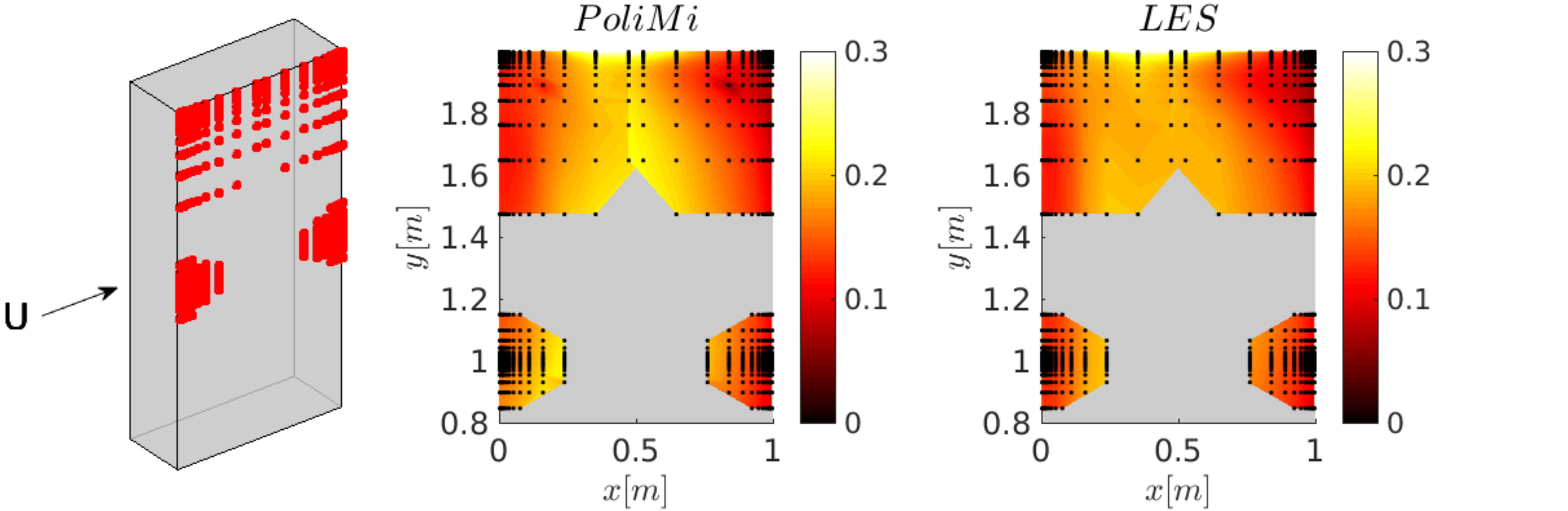
Results: baseline LES

Distribution of mean pressure coefficient: $C_P = \dfrac{P}{\frac{1}{2}\rho U^2}$

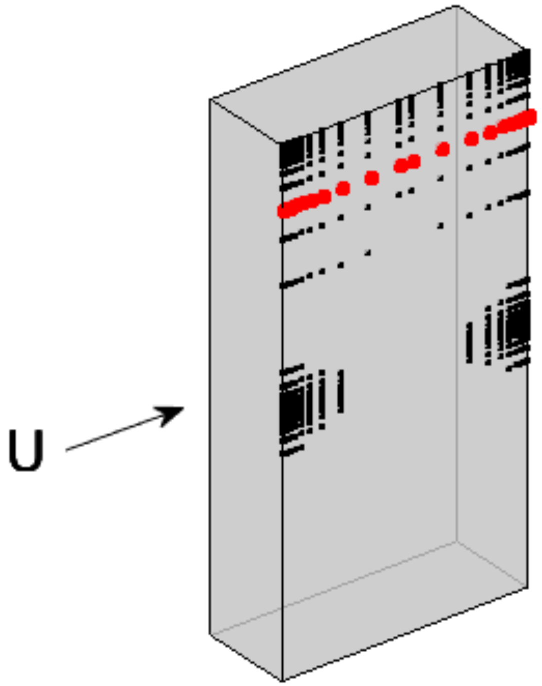


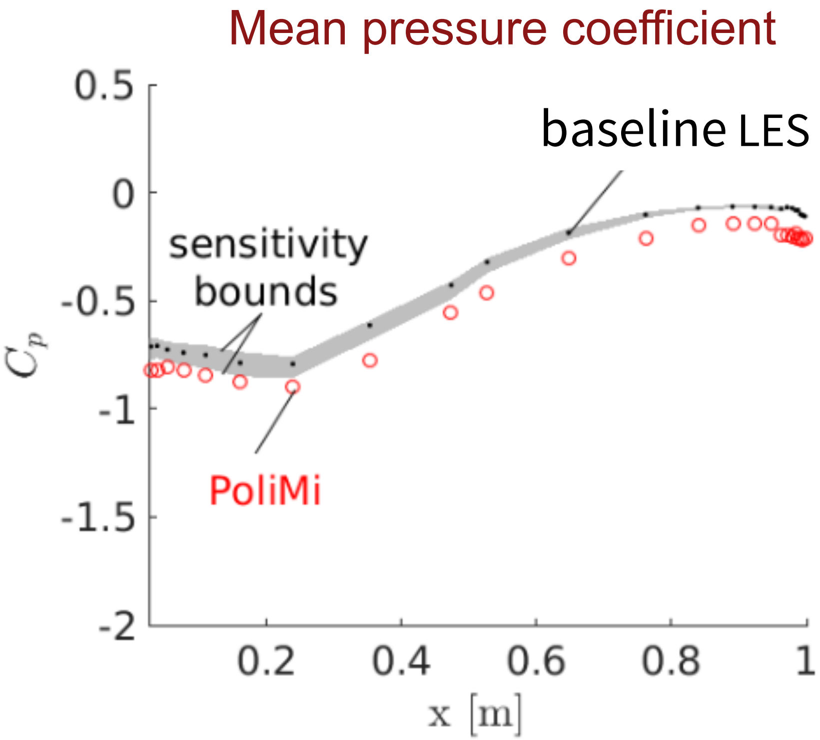
Results: baseline LES

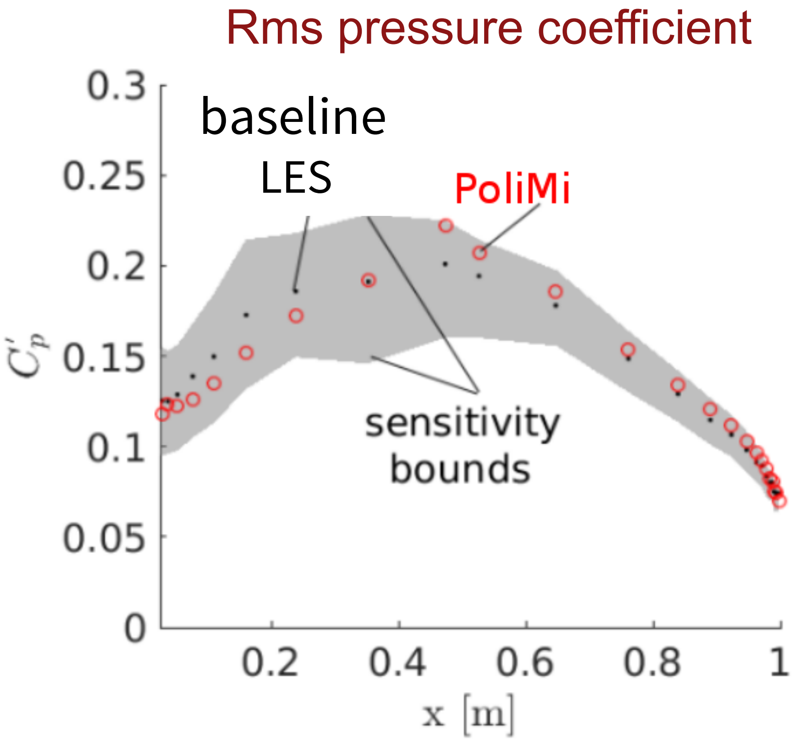
Distribution of root mean square pressure coefficient: $C'_p = \dfrac{\sqrt{\overline{p'^2}}}{\frac{1}{2}\rho U^2}$



Results: sensitivity analysis





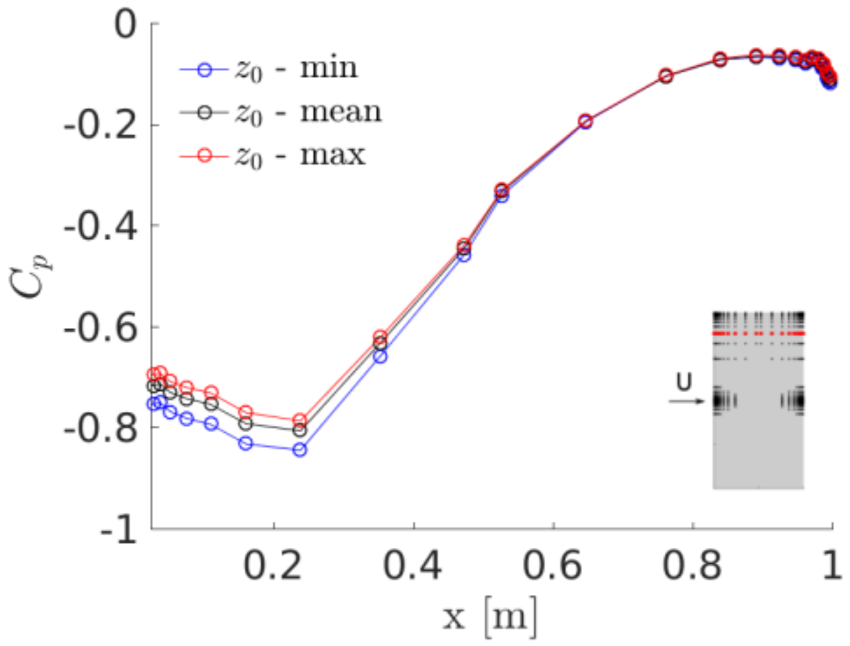


Inflow parameters have significant effect on the pressure fluctuations

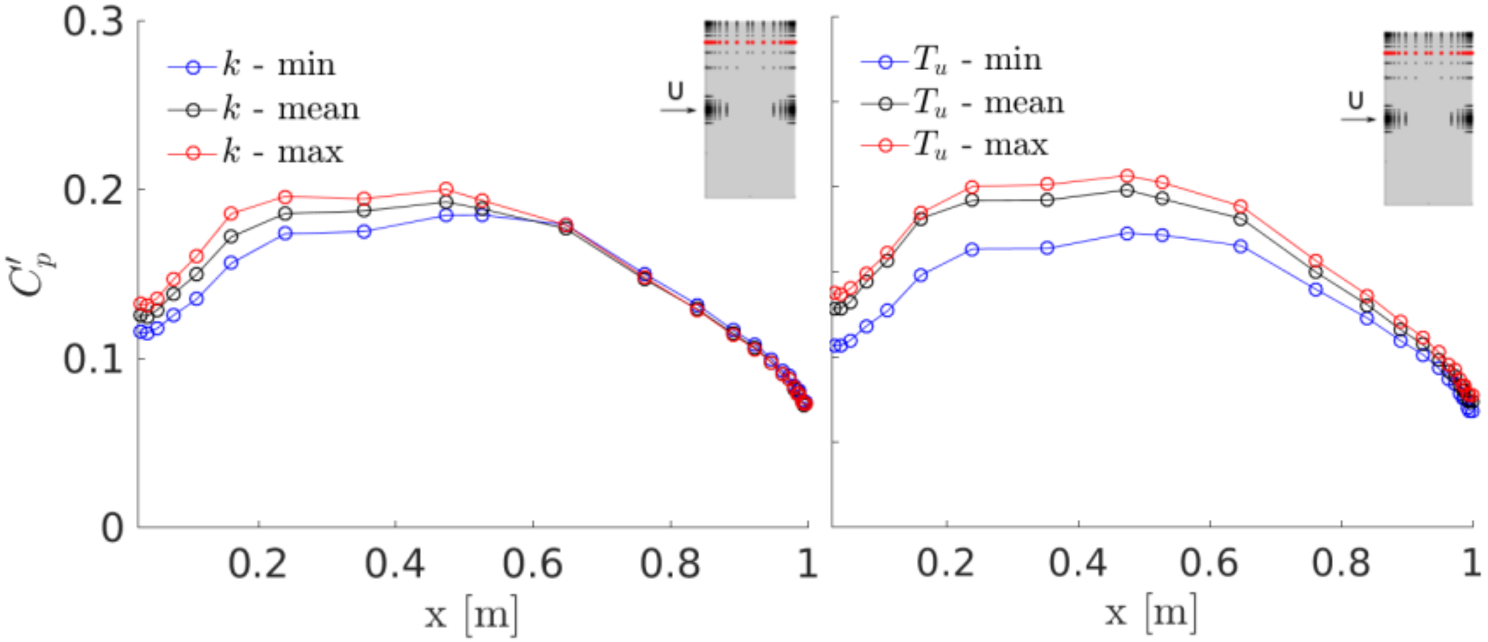
Results: sensitivity analysis

Main effect of the inflow parameters on the mean and rms pressure coefficients

Mean pressure coefficient



Rms pressure coefficient

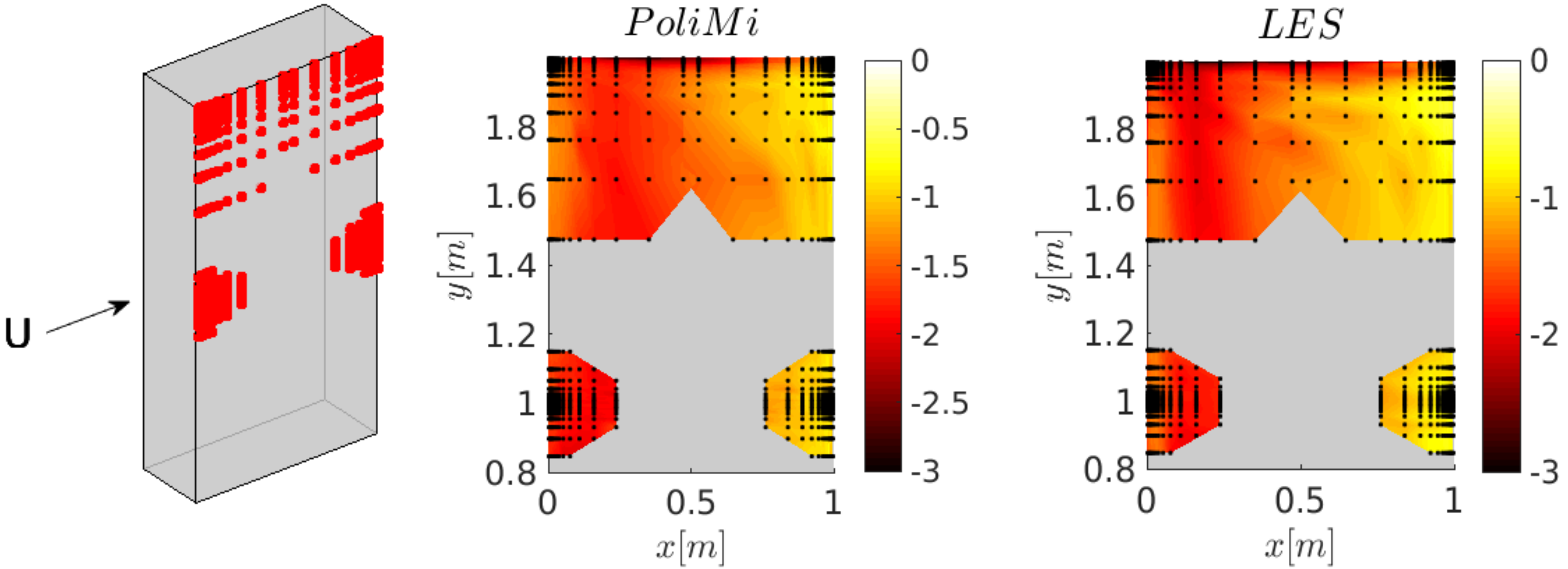


> roughness length mainly influences the mean pressure

> turbulence statistics mainly influence the pressure fluctuations

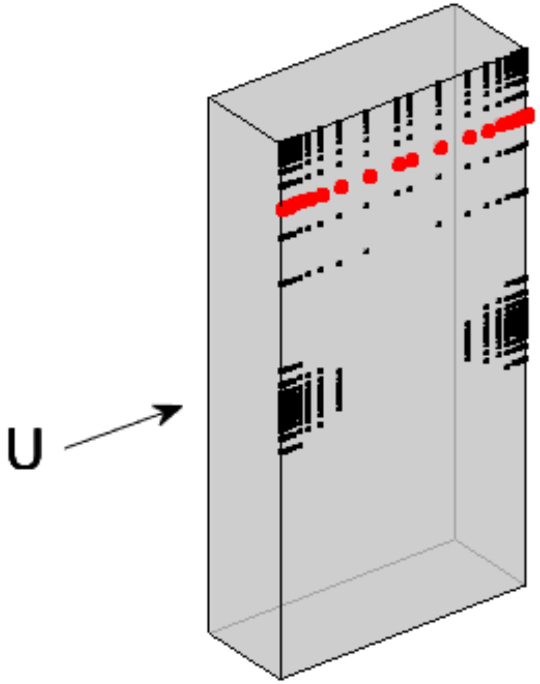
Results: sensitivity analysis

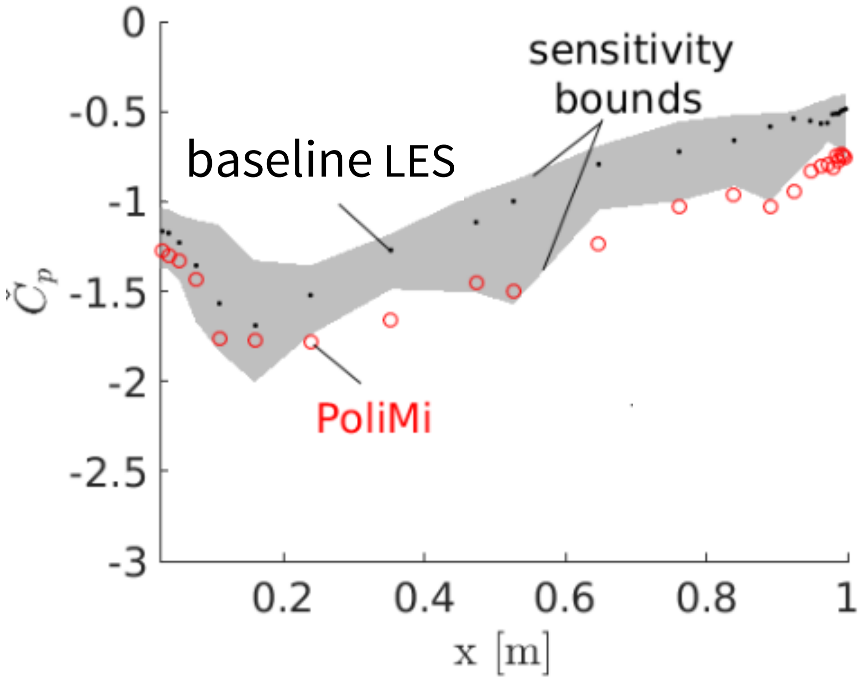
Distribution of peak pressure coefficient: $\check{C}_p = \dfrac{\check{p}}{\frac{1}{2}\rho U^2}$



Results: sensitivity analysis

Profiles of peak pressure coefficient: $\check{C}_p = \dfrac{\check{p}}{\frac{1}{2}\rho U^2}$

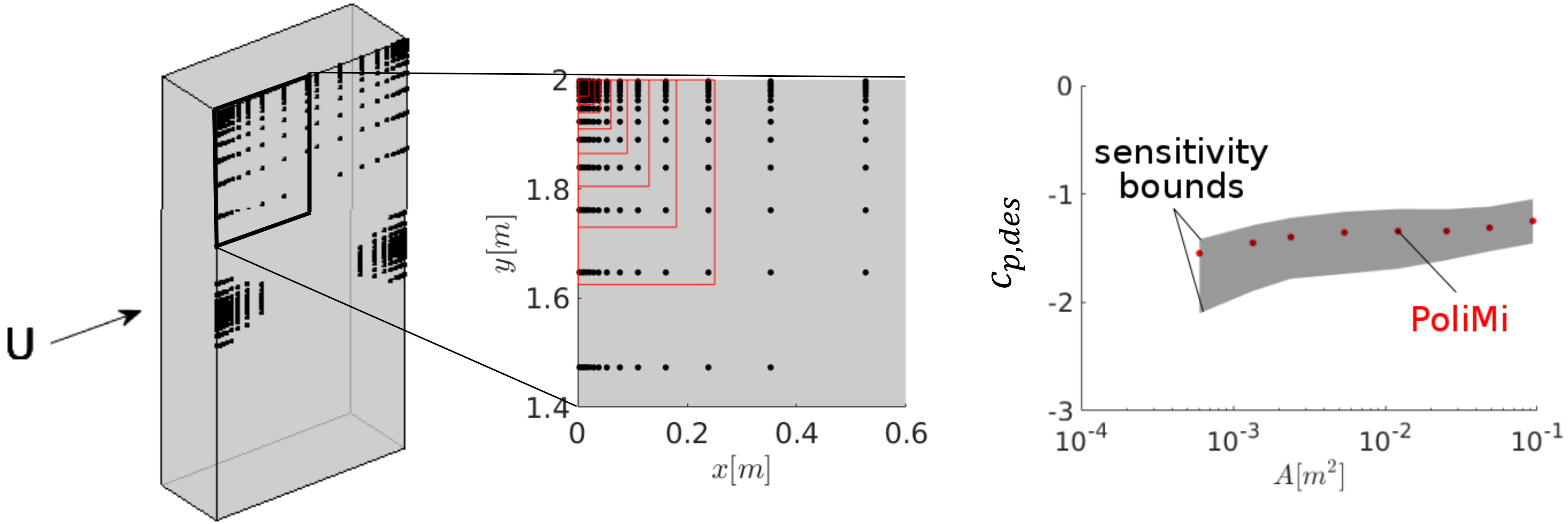




60% of the wind tunnel data are encompassed by the sensitivity bounds

Results: sensitivity analysis

Area-averaged pressure coefficient: $C_{p,AA}(t) = \dfrac{\sum_i C_{p,i}(t) A_i}{A_{tot}}$



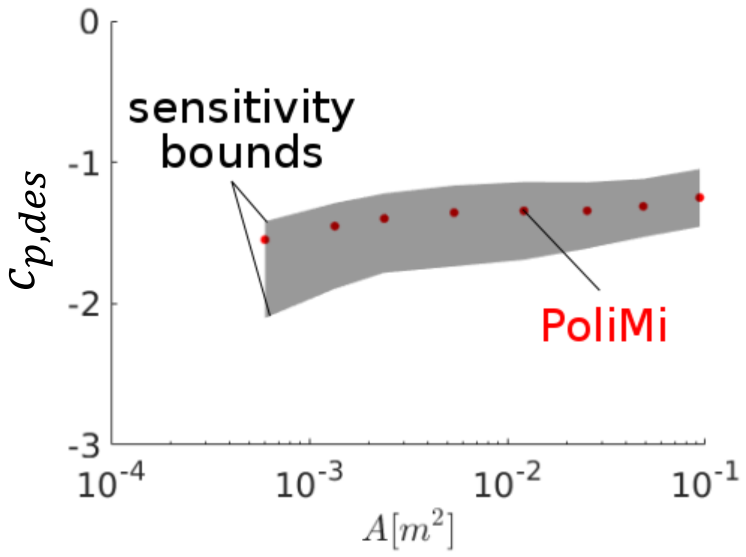
The design pressure of glazed panels of different size is well predicted

Conclusions

Carefully designed LES can reproduce C_p statistics with good accuracy

> rms and peak C_p are highly sensitive to ABL turbulence statistics at building location

> careful calibration of inflow conditions is needed

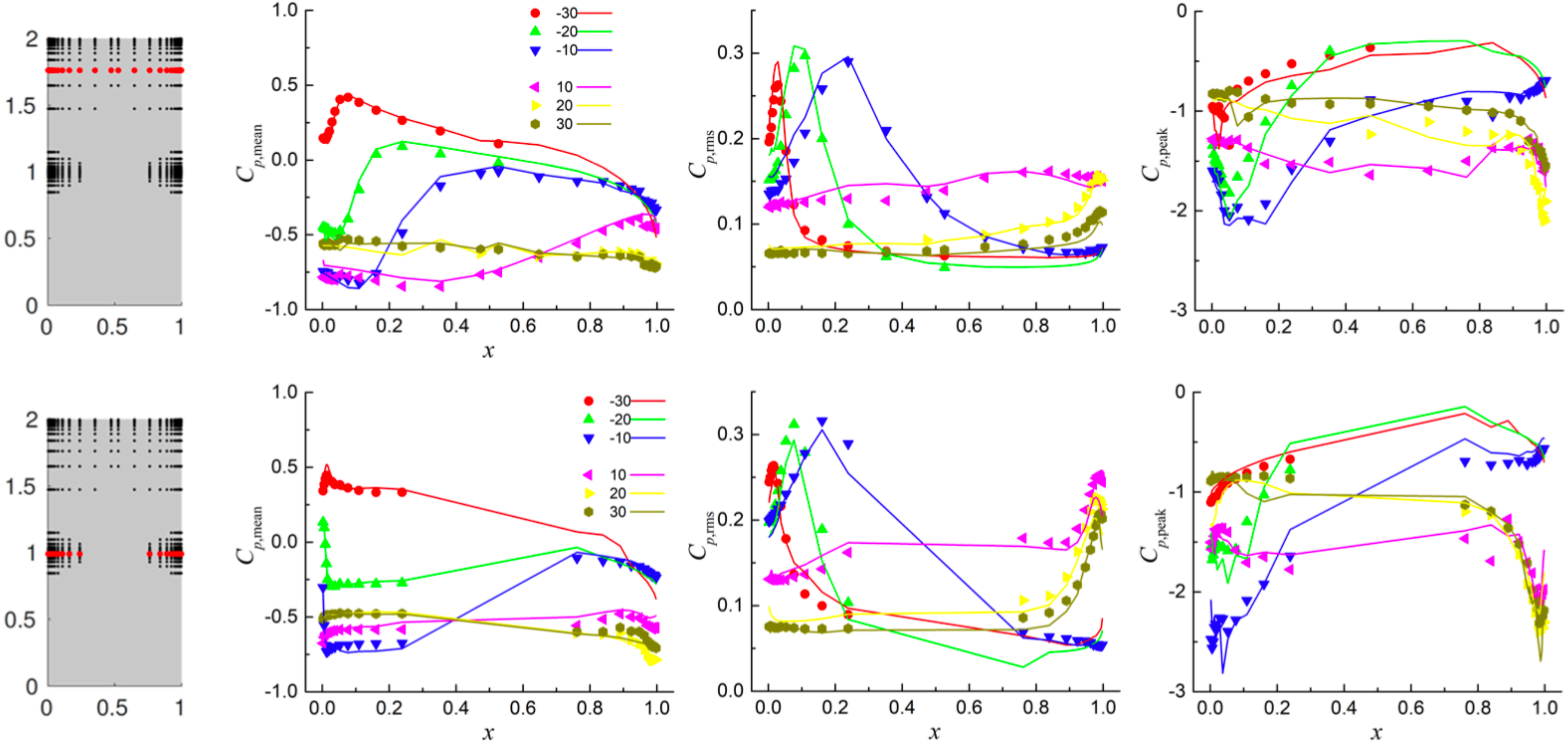


Take-aways for validation studies

> Experimental datasets used for validation should report detailed measurements of ABL turbulence characteristics at the building location, including uncertainty intervals

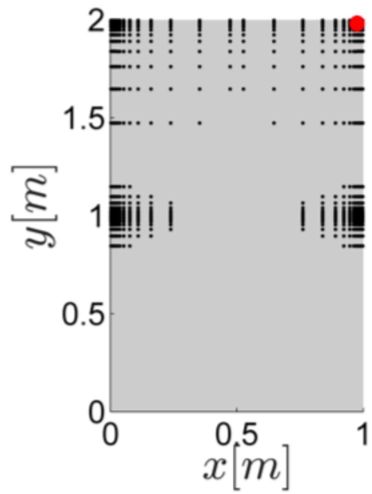
> LES should account for this uncertainty when comparing results

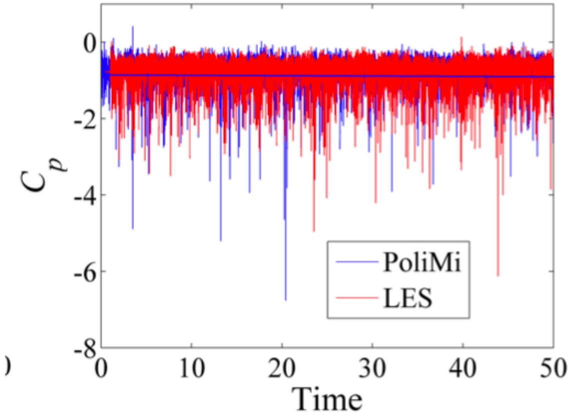
In the pipeline…



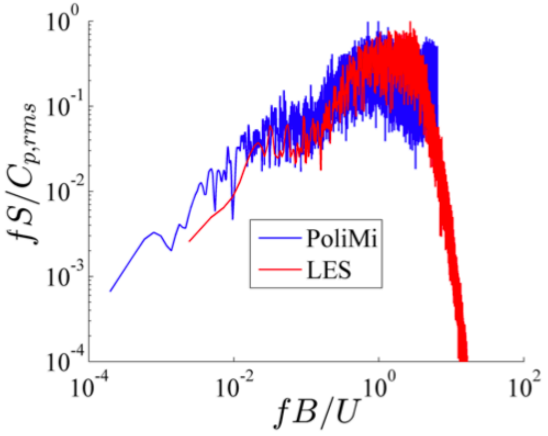
In the pipeline…

Use LES to investigate flow physics

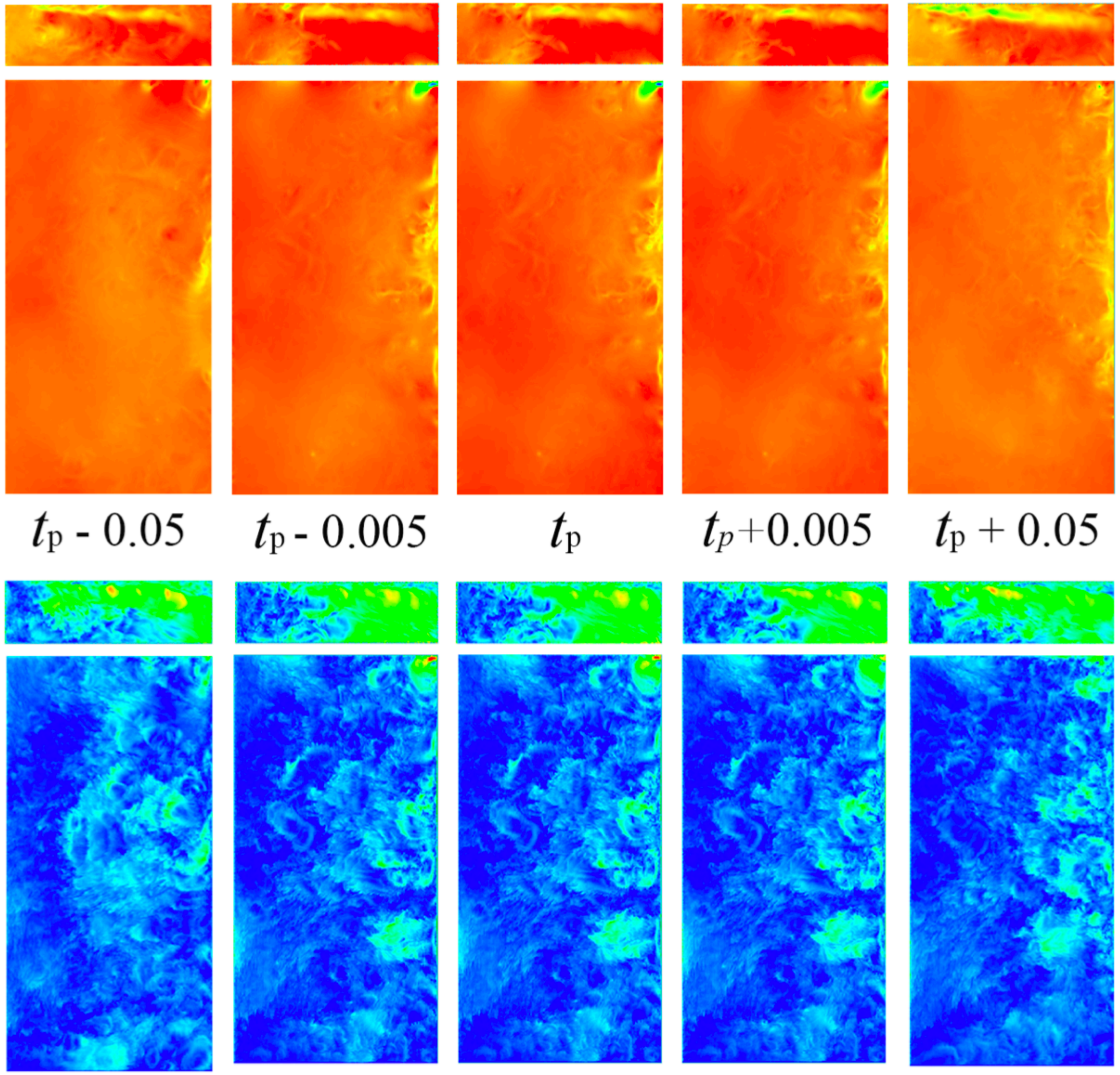




30°



pressure



velocity