Calibration and Uncertainty Quantification for Estimating Topographic Speedup Factors with CFD Models

Adam Pintar
NIST
Information Technology Laboratory

Yunjae Hwang
DongHun Yeo
NIST
Engineering Laboratory

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

October 9, 2024

FTC 2024

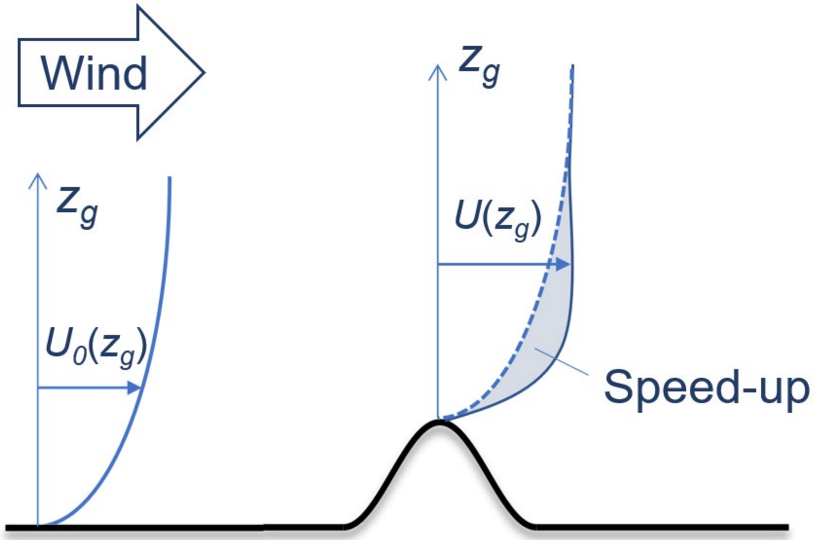
Motivation: Topographic Effects on Wind

- Mountainous topography could increase wind speeds compared to the same weather pattern over flat terrain
- Quantifying the topographic effect is crucial for accurately estimating wind loads on buildings situated in various topographical conditions

Buildings on Topographic Area in Oahu, Hawaii

Credit: Zachary Tirrell (https://openverse.org/image/fe16d0dc-5e1c-4061-b719-168d05fa6b7d?q=diamondhead, CC BY-SA 2.0)

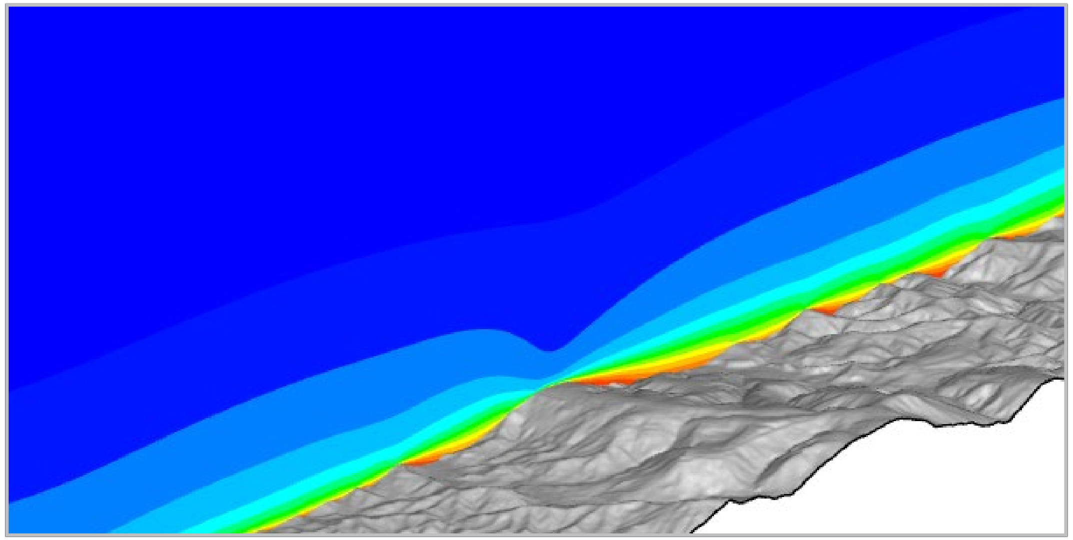
Effects of topography on wind speed



Problem: Estimating Topographic Speedup

Wind Tunnel Testing

Computational Fluid Dynamics Simulations



CFD simulation is a promising tool for investigation of topographic effects on winds, but requires comparison to wind tunnel data to ensure the quality of simulation results

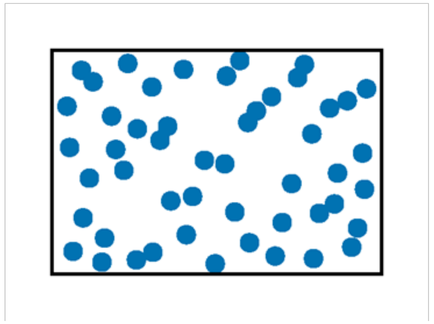
Workflow

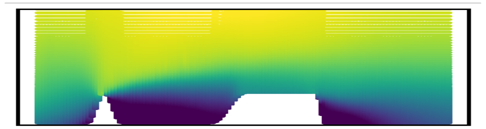
Objectives:

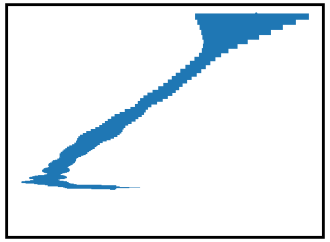
To develop a calibration and UQ framework that integrates topographic CFD simulations with wind tunnel data

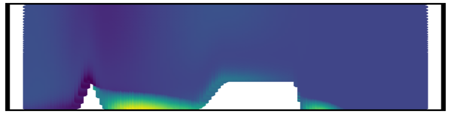
- To address various sources of uncertainties in both simulations and experiments

Choose CFD inputs → Run CFD simulations at selected input combinations → Create CFD emulator → Optimize CFD inputs to wind tunnel data → Estimate calibration correction







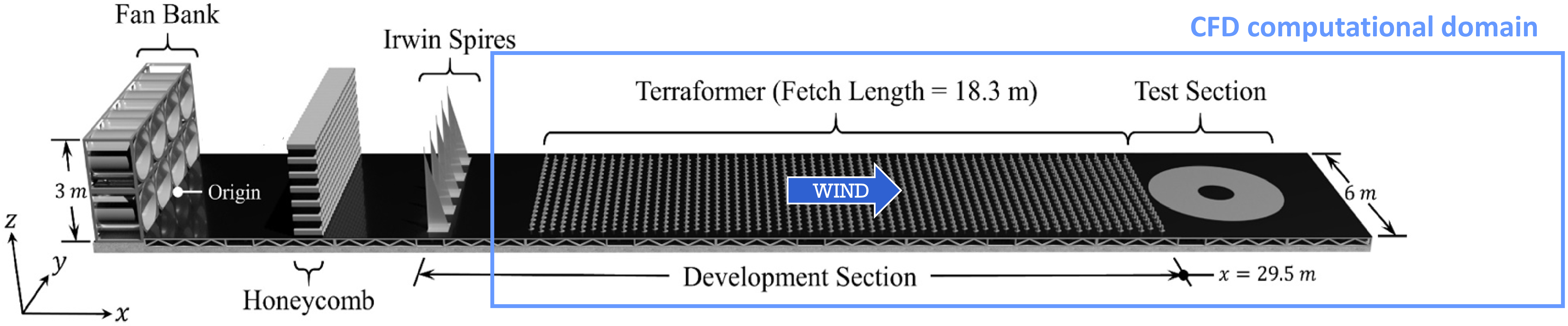


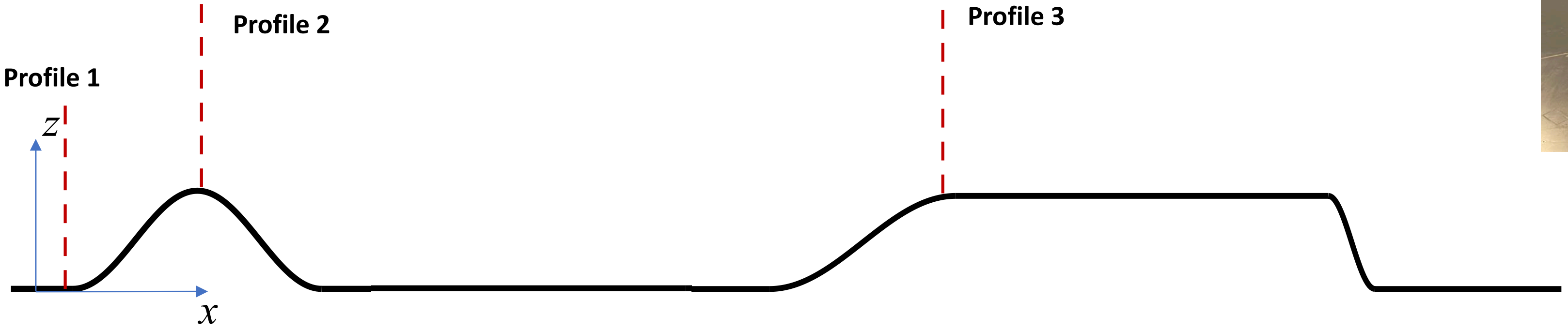
Wind Tunnel Experiments

Wind Tunnel Experiments

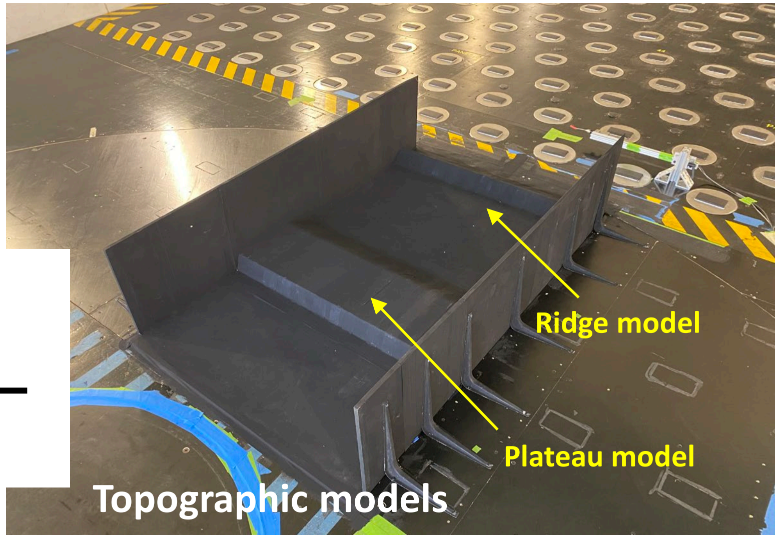
Boundary-Layer Wind Tunnel Experiments (Univ. of Florida)

NIST Contract 1333ND19PNB730233
PIs: Brian Phillips, Forrest Masters



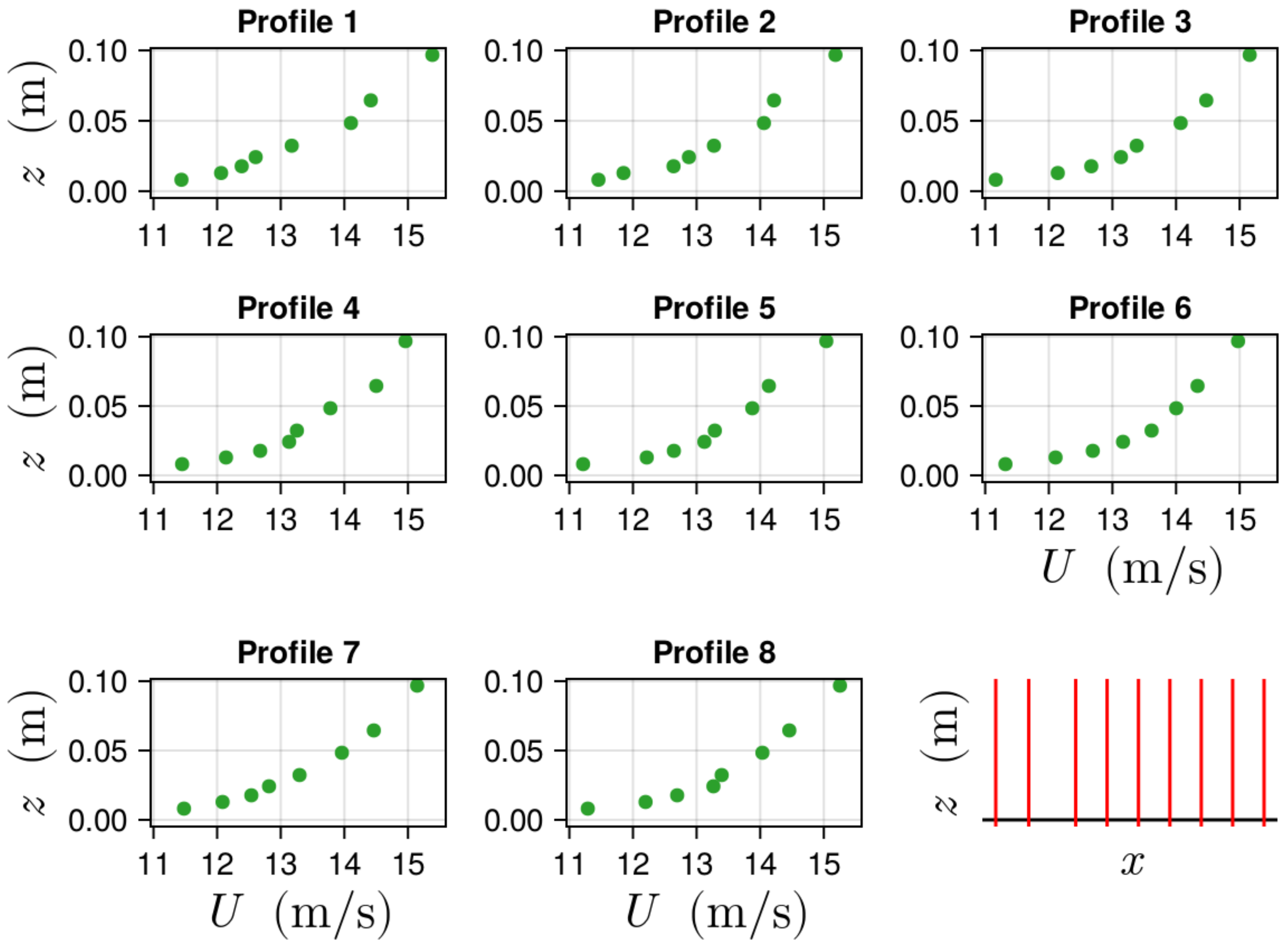


Locations for measurement of wind velocity profiles (8 heights/profile)



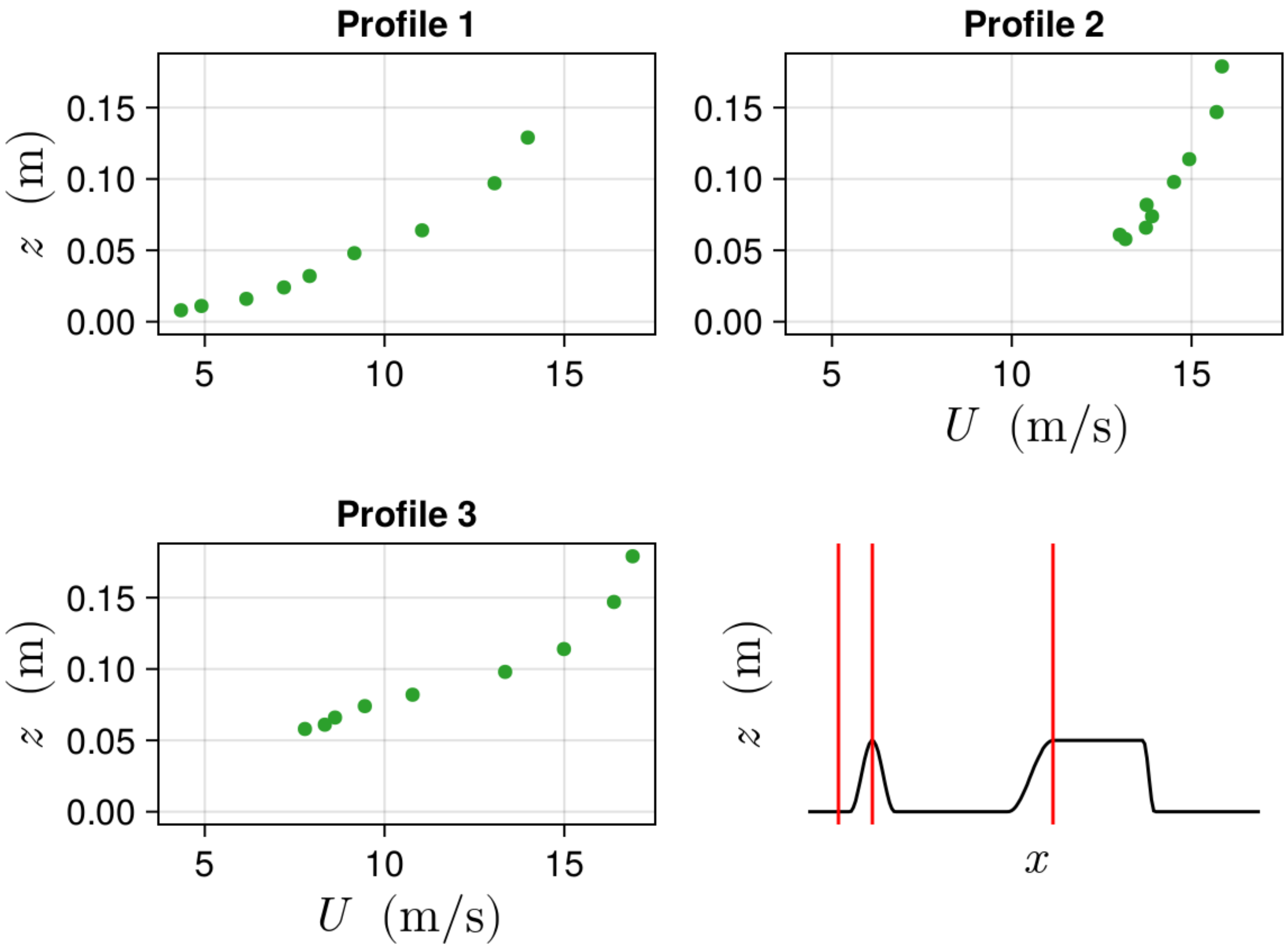
Bare Floor Wind Tunnel Data

Points are representative simulated data.



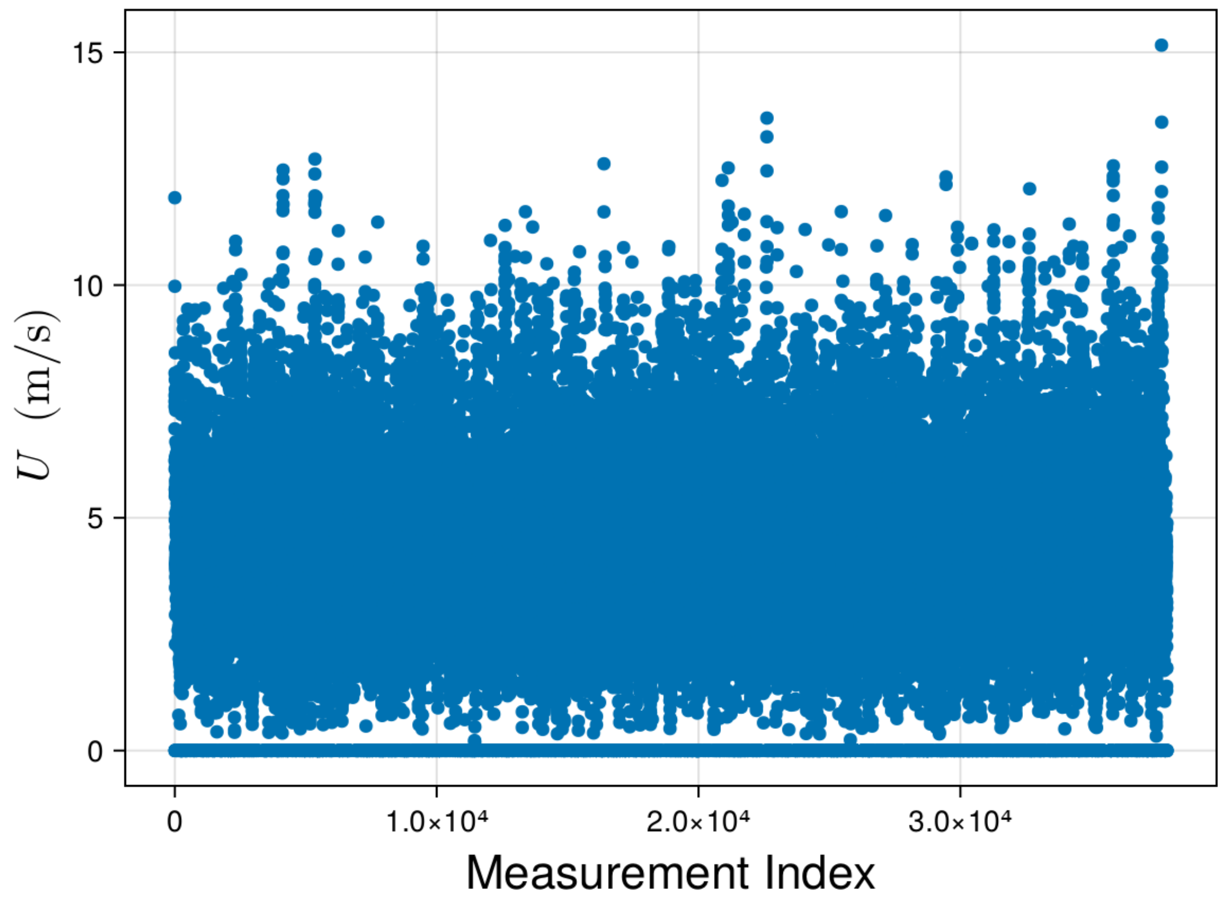
Topographic Wind Tunnel Data

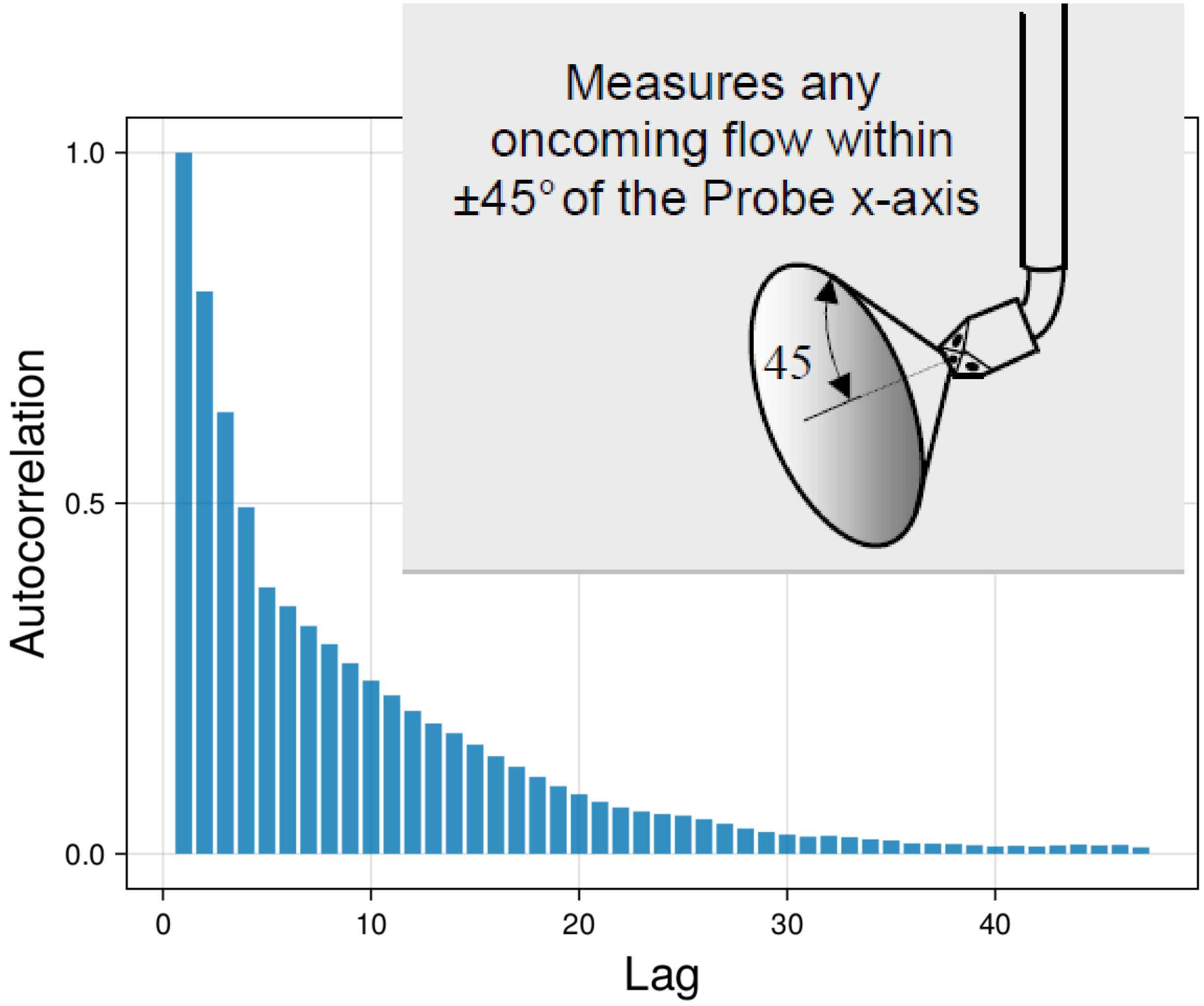
Points are representative simulated data.



Time Series and Missing Data

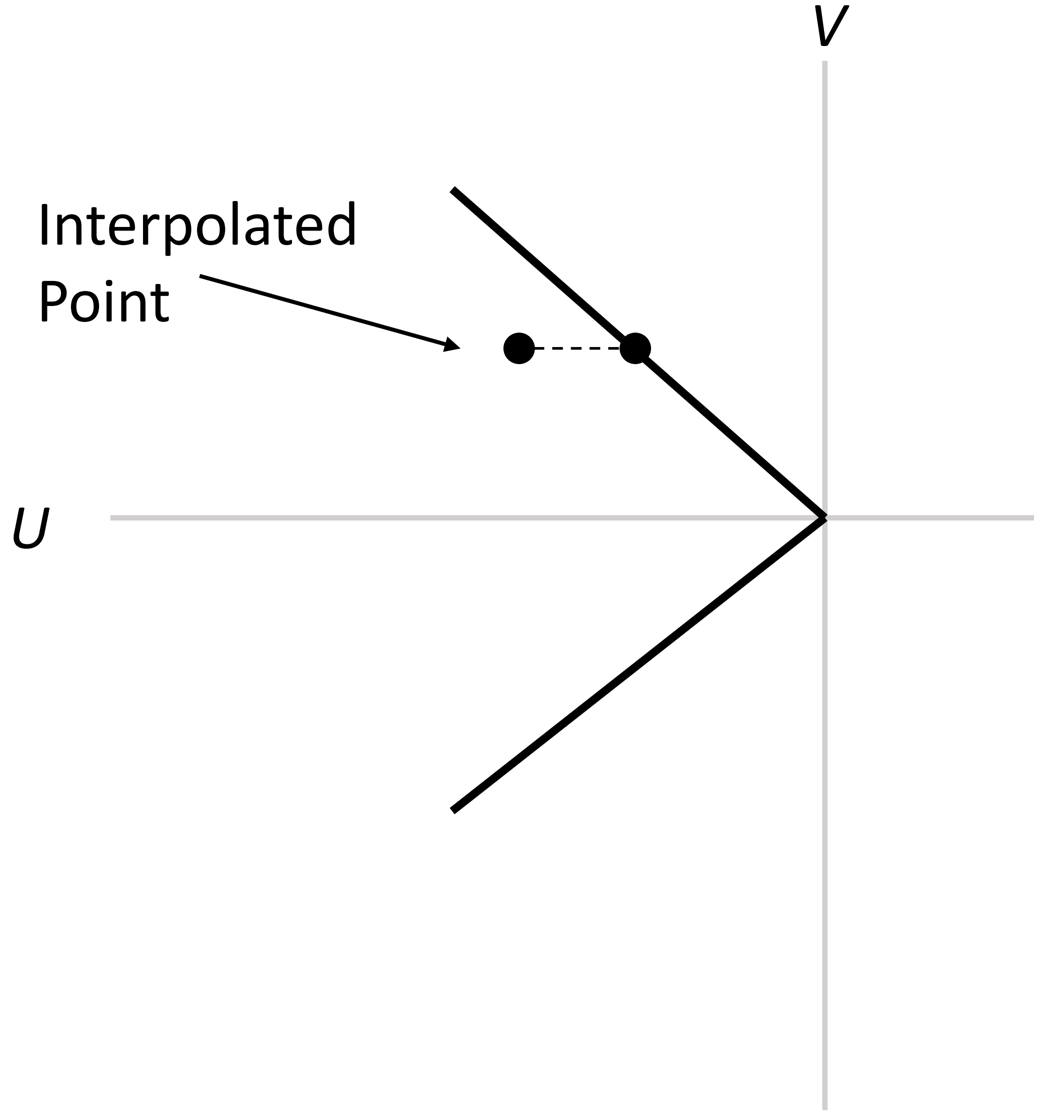
Points and bars are representative simulated data.





Interpolation Algorithm

- Assume the observation is outside of the 45° cone because *U* is small
- Interpolate three components separately
  - State space model
  - Kalman filter
- Shrink the *U* component until vector is outside of the 45° cone



CFD GP Emulator

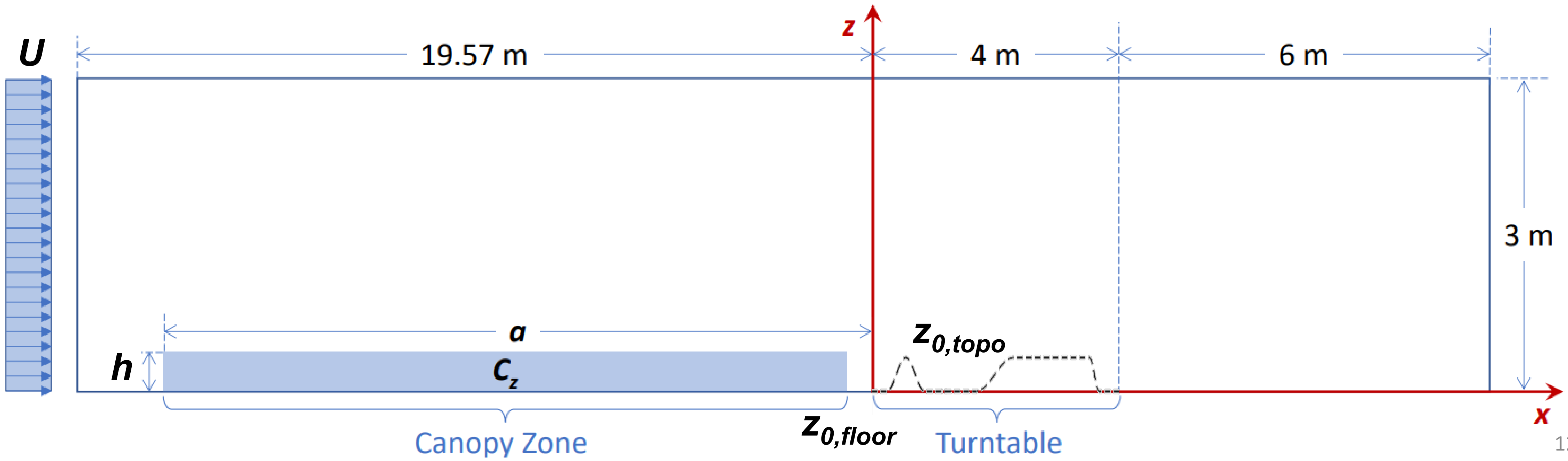
CFD Inputs

Total 6 input parameters

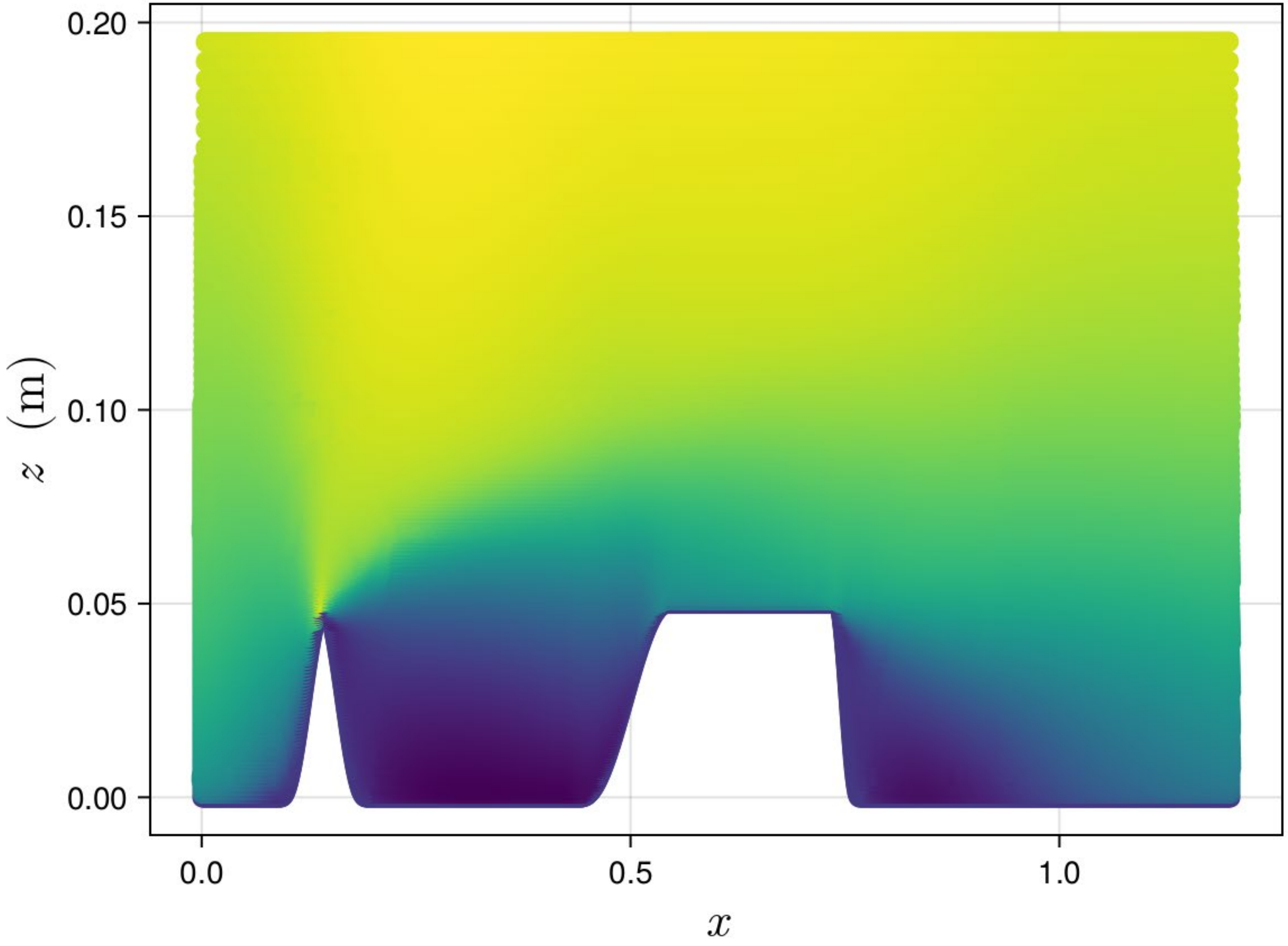
a	Canopy zone location
h	Canopy height
C_z	Canopy coefficient
$z_{0,floor}$	Roughness length of wind tunnel floor
U	Inlet velocity
$z_{0,topo}$	Roughness length of topographic models

5 input parameters for approach flow simulation (a, h, C_z, $z_{0,floor}$, U)

2 input parameters for topo. flow simulation (U, $z_{0,topo}$)



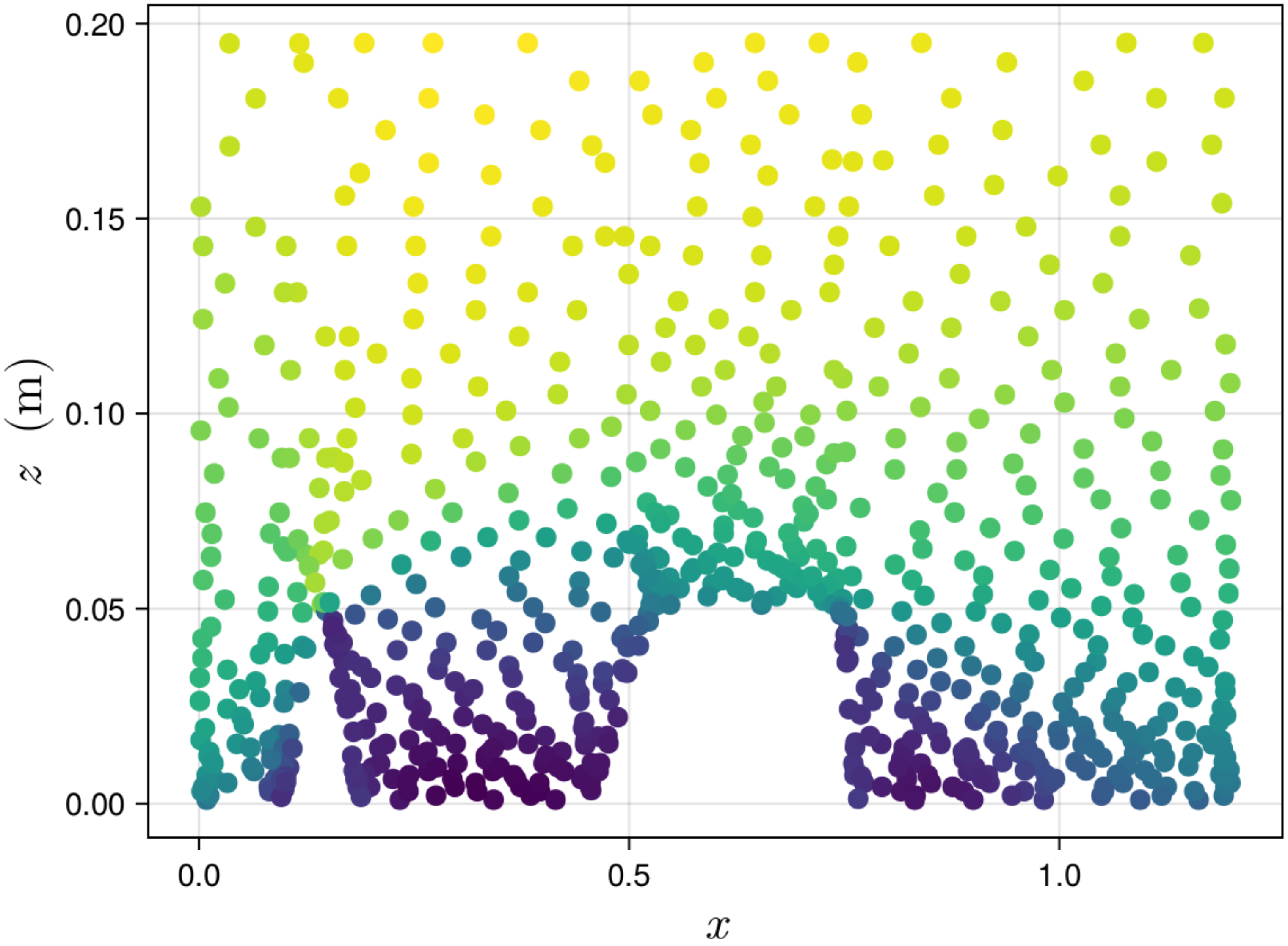
Functional CFD Output



- The dimension of the GP emulator is then:

  CFD input dimension + 2

Down Sampling

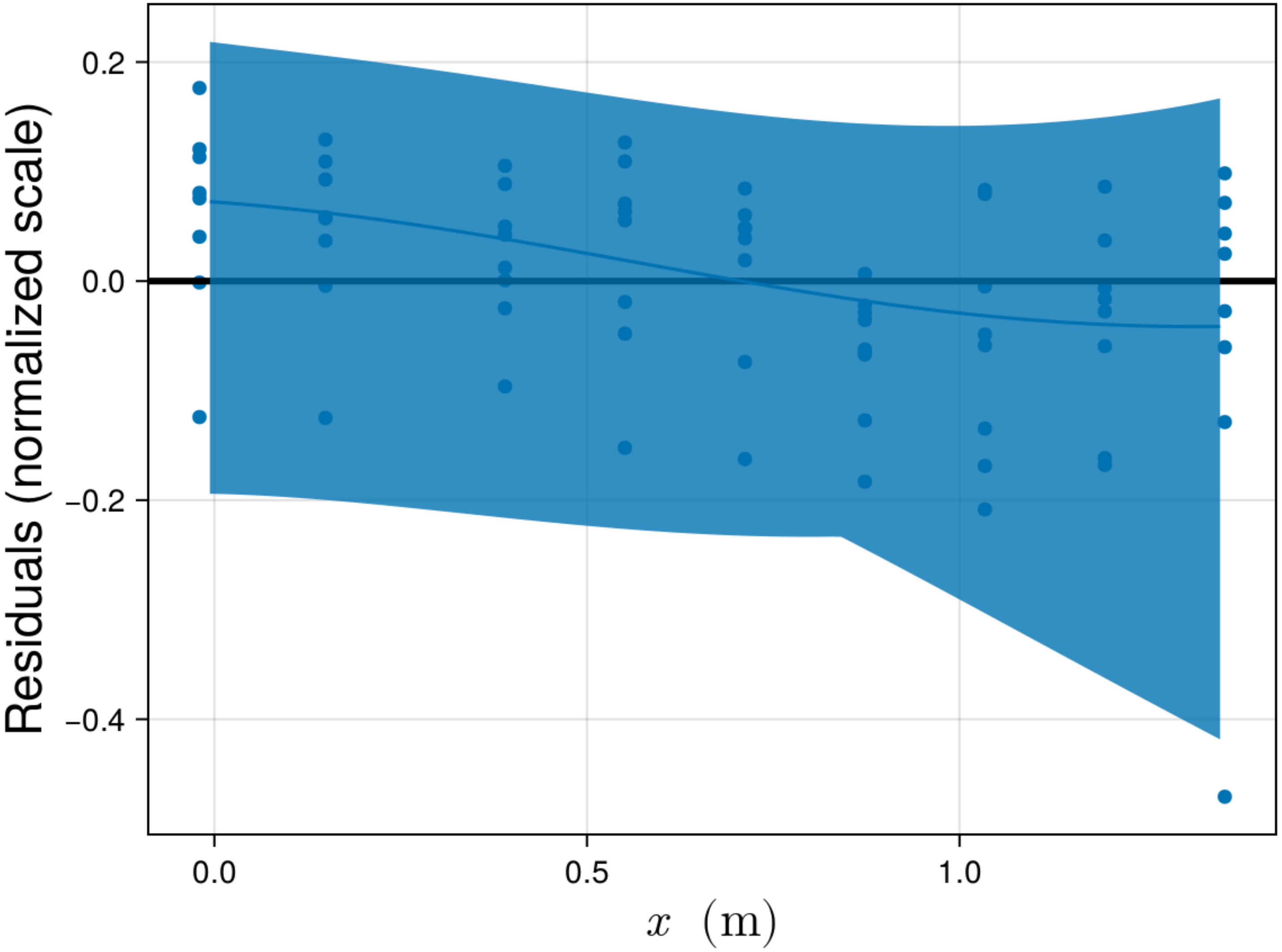


- Down sample from approximately 100k points to less than 1k
- Maximin design in x and $\log z$

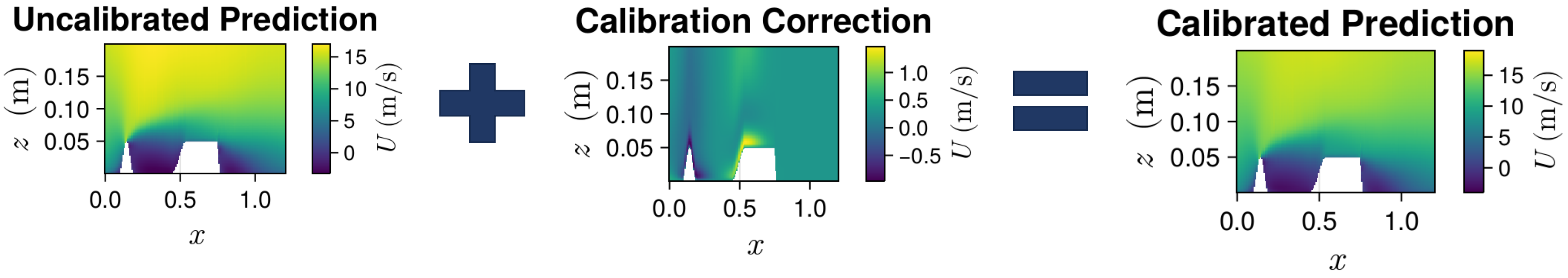
Optimize CFD Input Parameters to Wind Tunnel Data and Calibration

Optimization

- Two Criteria:
  1. Sum of squared residuals
  2. Fit of GP to residuals

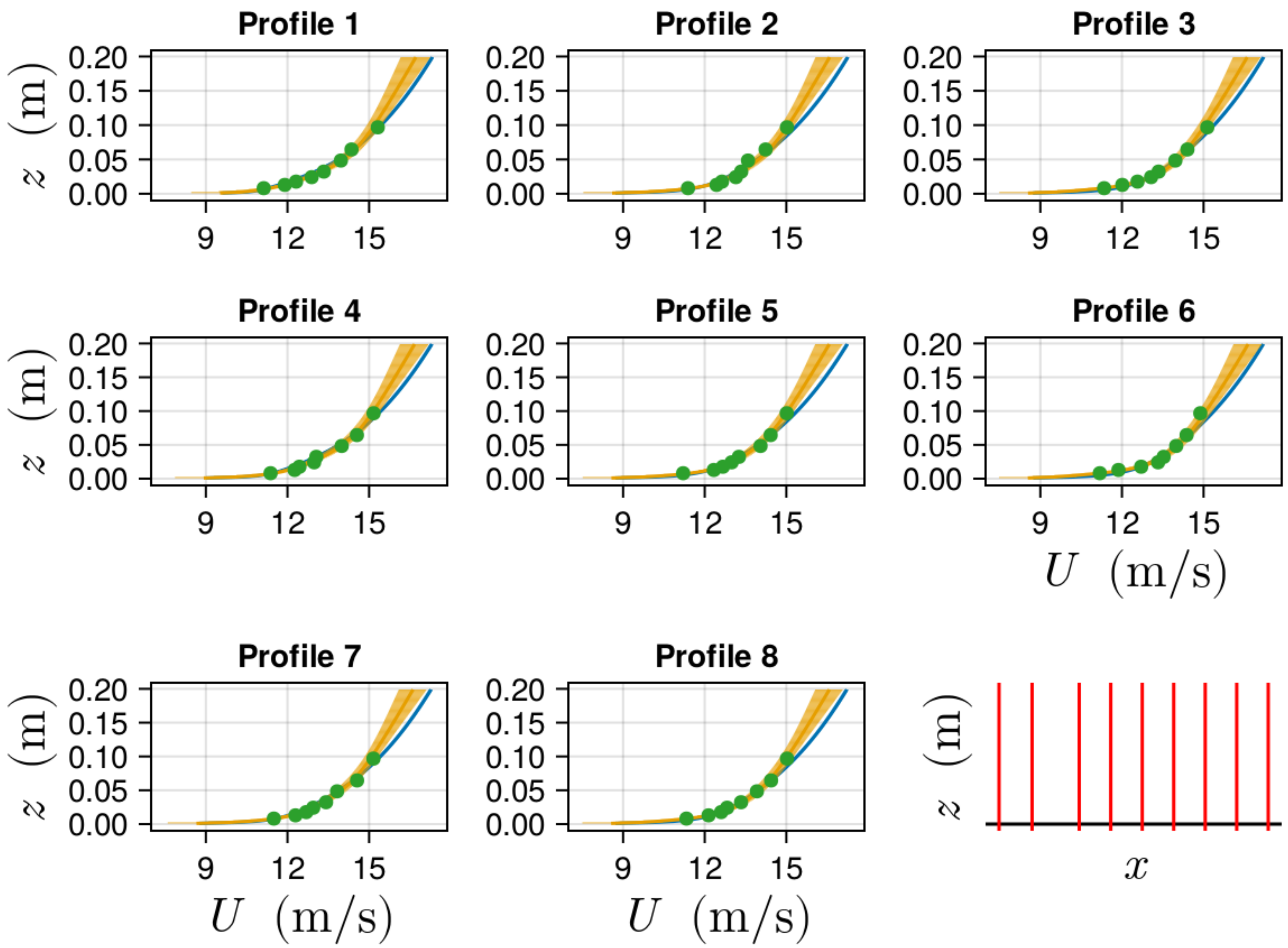


Calibration Function



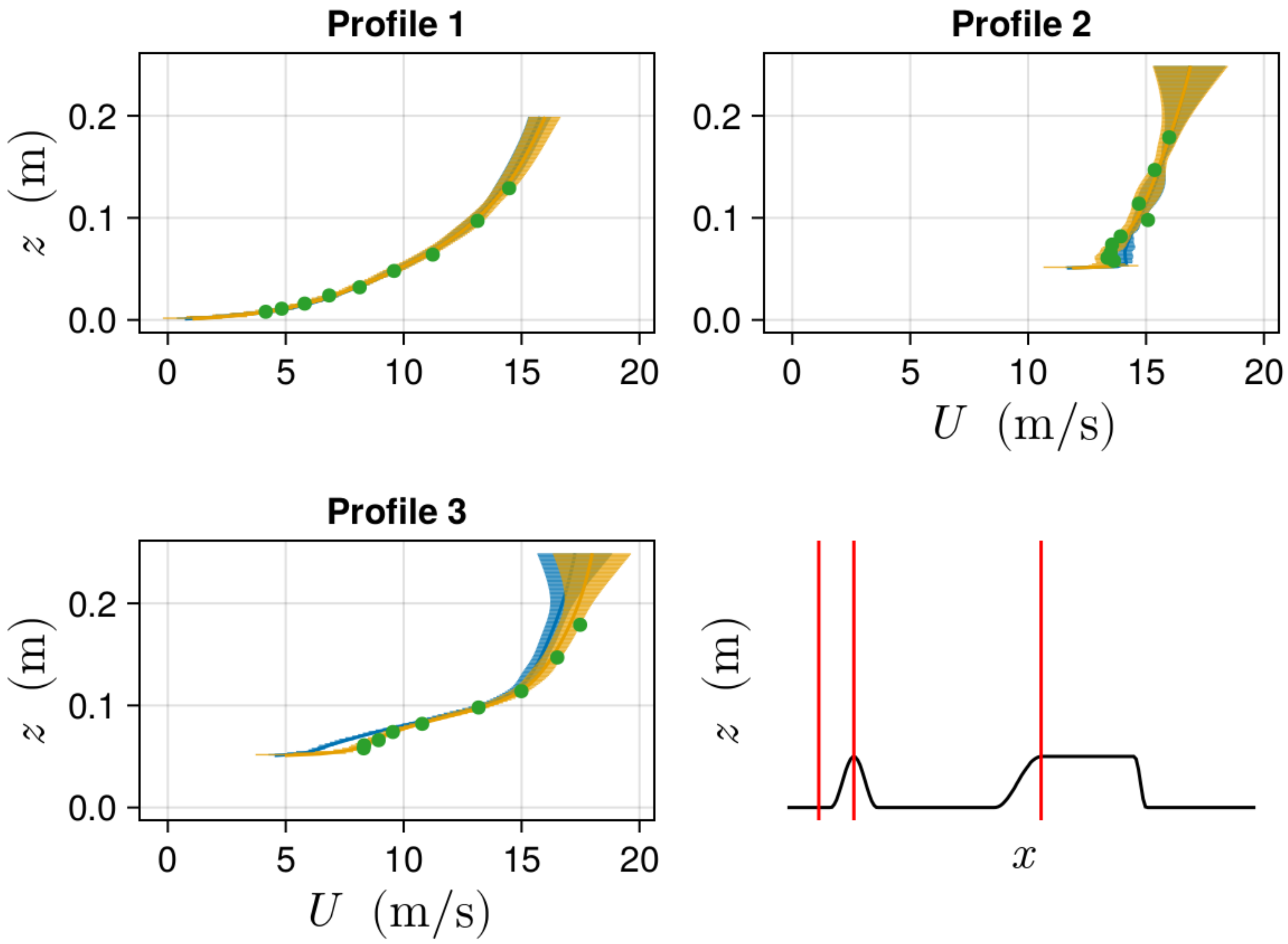
Calibrated Bare Floor Results

Points are representative simulated data.



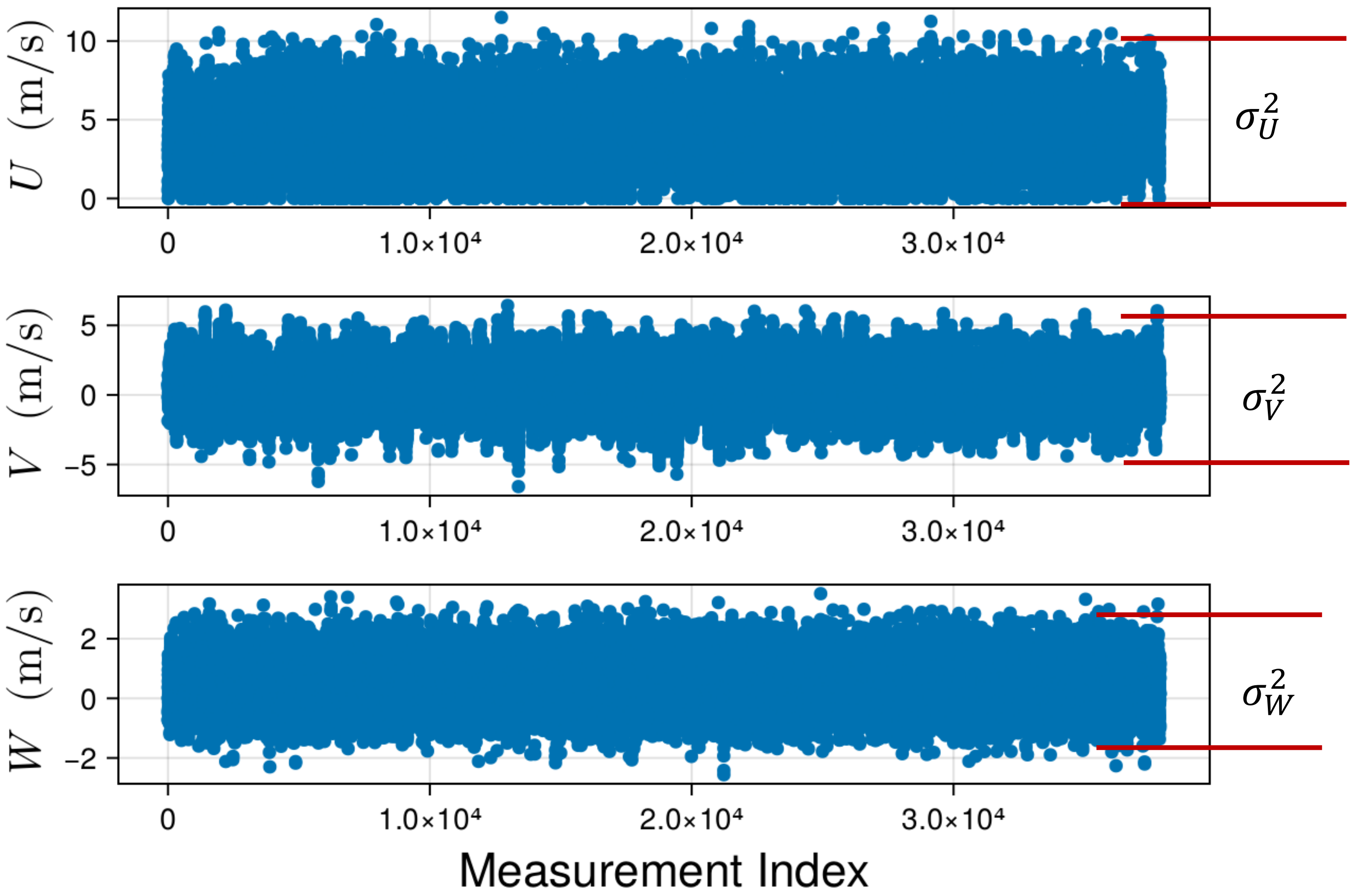
Calibrated Topographic Results

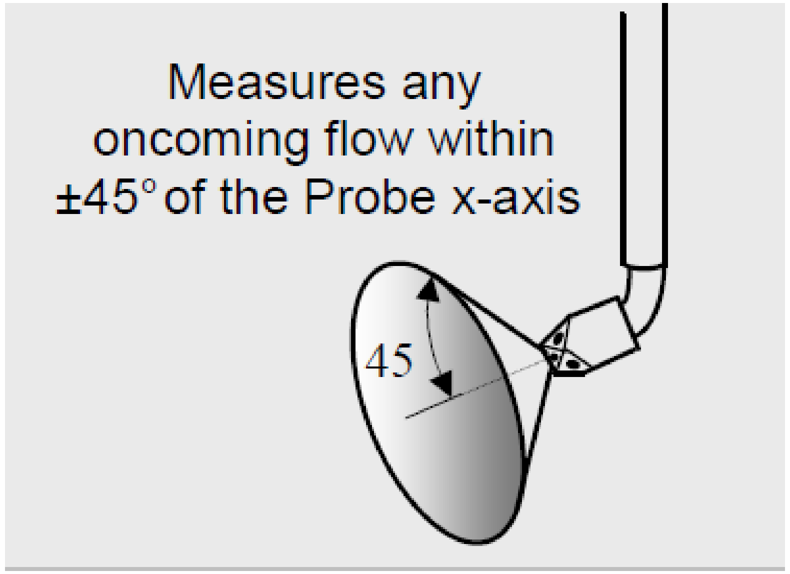
Points are representative simulated data.



Turbulent Kinetic Energy (TKE)

The rest of the story…



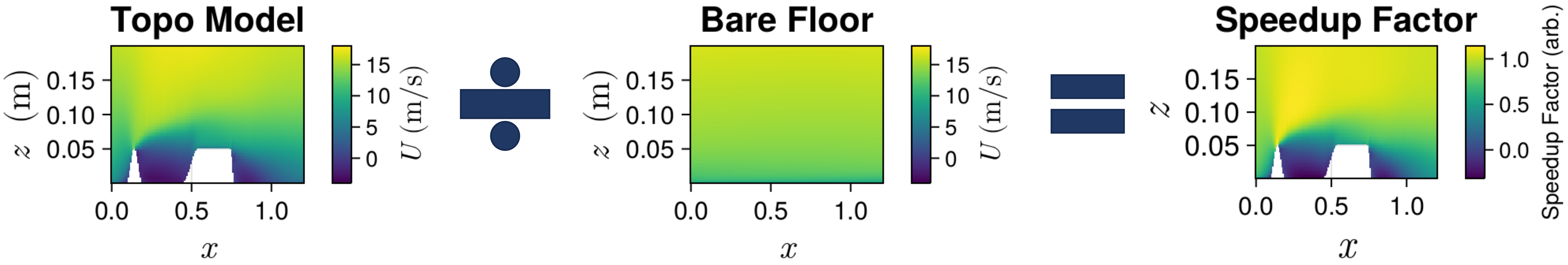


$$TKE = \frac{1}{2}(\sigma_U^2 + \sigma_V^2 + \sigma_W^2)$$

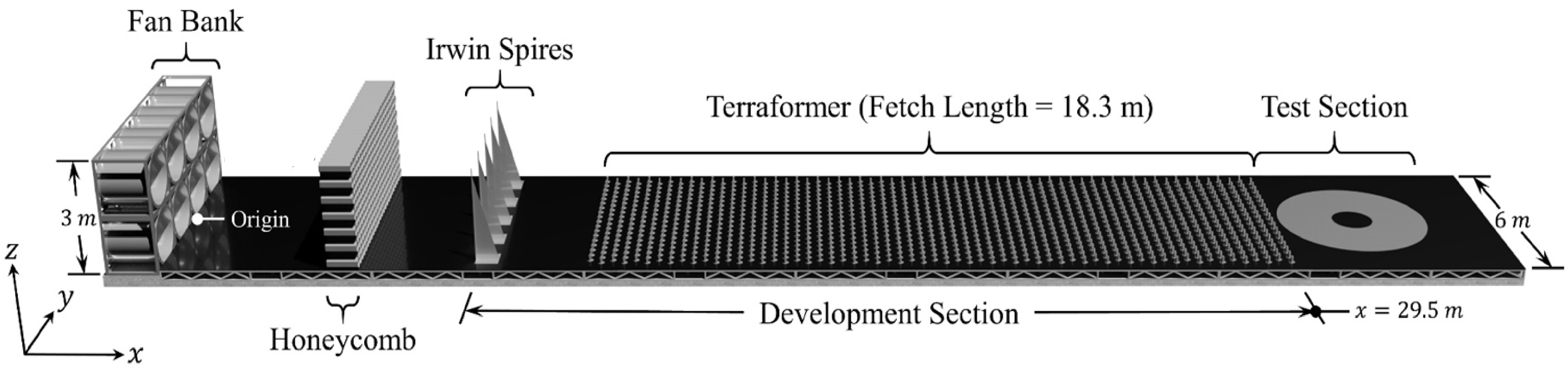
Points are representative simulated data.

Topographic Speedup Factor

Topographic Speedup Factor (TSF)



Differences in Input Wind Speed



- Separate experimental runs with and without (bare floor) the topographic model
- Wind velocity from the fans seems to have changed
- Account for it in both the uncalibrated prediction and the calibration correction

Sources of Uncertainty

- From GPs and wind tunnel data
- Finite sample size for emulator construction
- Finite size of wind tunnel data
- Difference between input wind speeds for the bare floor and topographic wind tunnel experiments
- Noise in wind tunnel data

Strengths and Weaknesses of Approach

- Strengths
  - TSF over whole computational domain (compared to wind tunnel alone)
  - Adjust for differences in inlet wind speeds (compared to wind tunnel alone)
  - Calibration and uncertainty quantification based on wind tunnel measurements (compared to CFD alone)
  - Lower computational burden (compared to CFD alone)
- Weaknesses
  - Cannot easily change the topographic model (compared to CFD alone)
  - Variability not observed in the wind tunnel data, e.g., differences between measuring instruments, is not reflected in the uncertainty estimate

Summary

- TSF is important for designing structures in mountainous regions
- For estimating the TSF, wind tunnel tests are common, but CFD modeling has benefits
- This work presents a combined approach where CFD models are calibrated to wind tunnel data
- More flexible than estimates based only wind tunnel measurements and similarly accurate because of calibration
- Less flexible than estimates based only CFD modeling but more accurate because of calibration
- Uncertainty based on wind tunnel data and GP models