4th International RAVE Workshop
Federal Maritime and Hydrographic Agency (BSH)
Hamburg, Germany

Healthy + Reliable Offshore Wind Turbines

Eric Hines, Babak Moaveni, and Chris Baxter
May 11, 2023

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Optimal Sensor Placement for Physics-Based Digital Twins

Wind Farm-Level Technology—2023

CVOW Instruments Installed—2022

BIWF Instruments Installed—2021

NOWRDC—2020

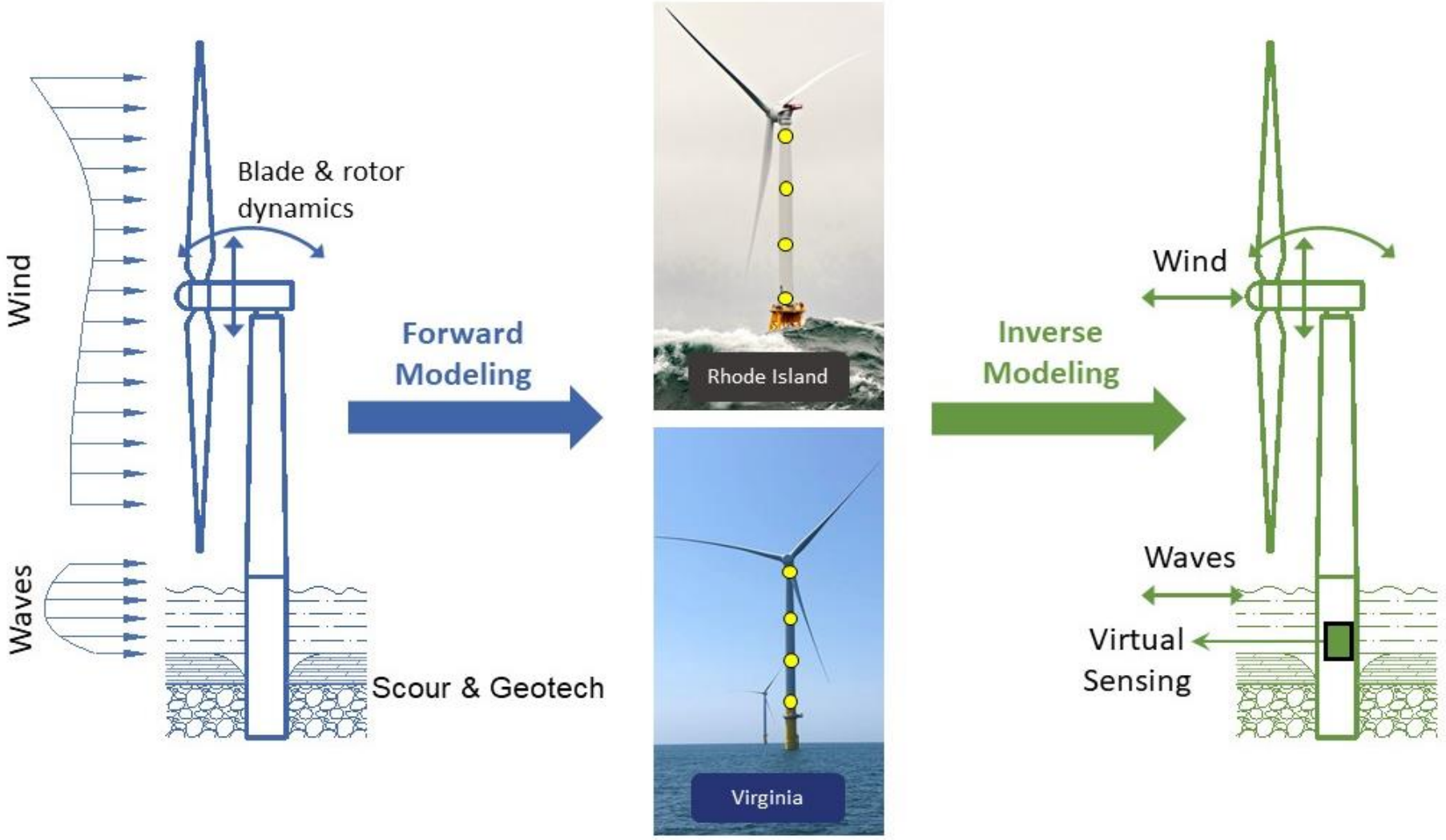
BISM-JP—2019

POWER-US—2018

BIWF Operational—2016

DOE Topic Area 1—2012

Physics-Based Digital Twins



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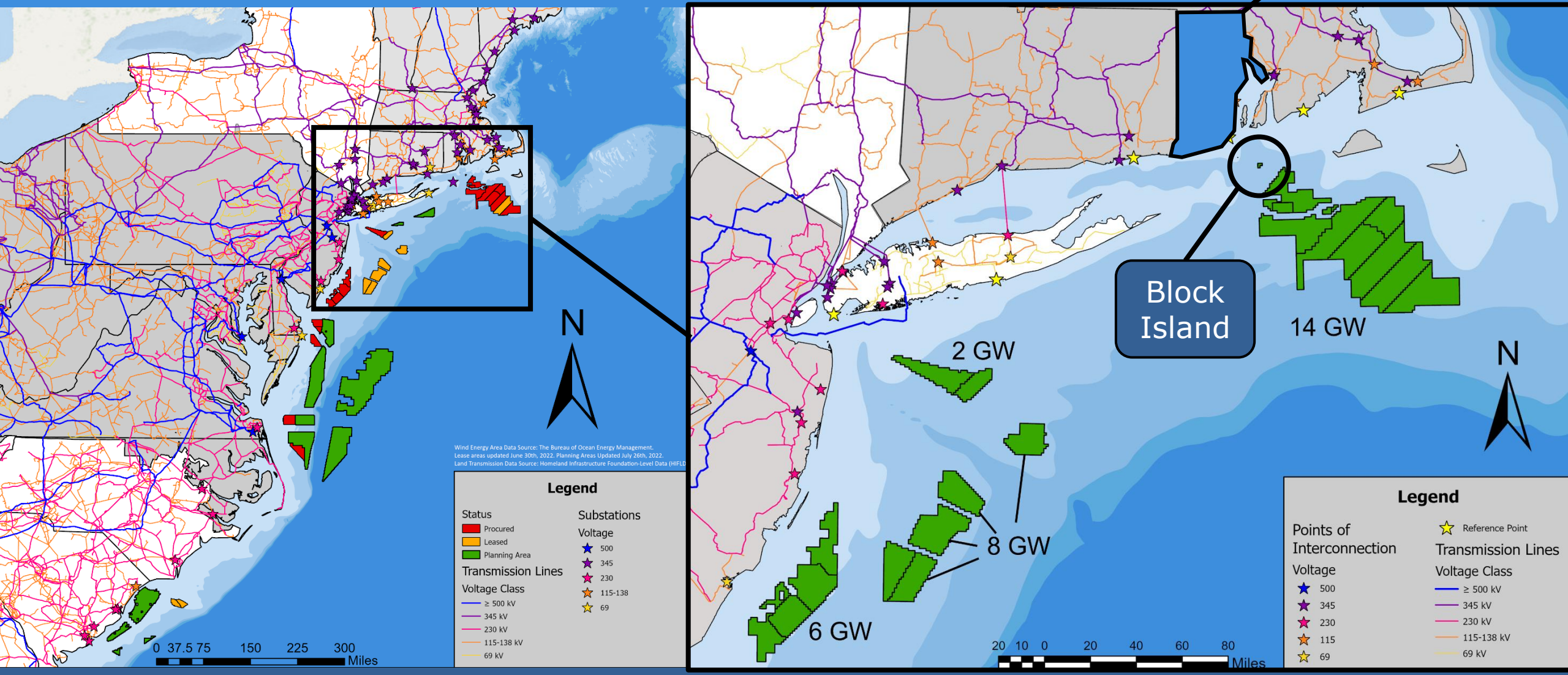
- Design Verification
- Predictive Maintenance
- Service Life Extension

U.S. East Coast Offshore Wind



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Block Island Wind Farm

With special recognition of Mingming Song, Nasim Partovi-Mehr

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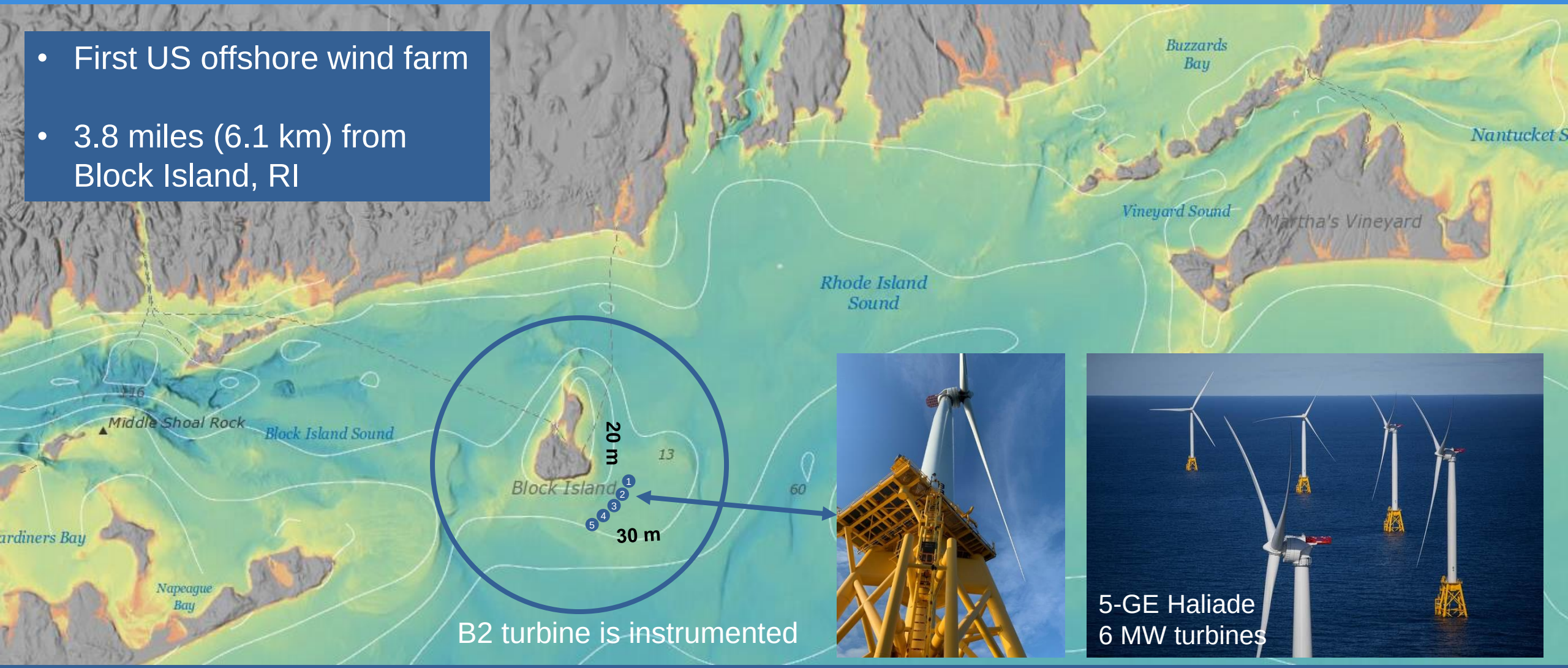
Block Island Wind Farm

- First US offshore wind farm
- 3.8 miles (6.1 km) from Block Island, RI



B2 turbine is instrumented

5-GE Haliade
6 MW turbines

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Block Island Optimal Sensing

- 9-accelerometers + 8-strain gages
- Sampling frequency of 50 Hz
- Data is saved every 10 min

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https://www.sciencedirect.com/science/article/pii/S0960148122017670

ELSEVIER

Renewable Energy

Volume 202, January 2023, Pages 1032-1045

Structural instrumentation and monitoring of the Block Island Offshore Wind Farm

Eric M. Hines [a], Christopher D.P. Baxter [b], David Ciochetto [c], Mingming Song [a f], Per Sparrevik [d], Henrik J. Meland [d], James M. Strout [d], Aaron Bradshaw [b], Sau-Lon Hu [b], Jorge R. Basurto [e], Babak Moaveni [a]

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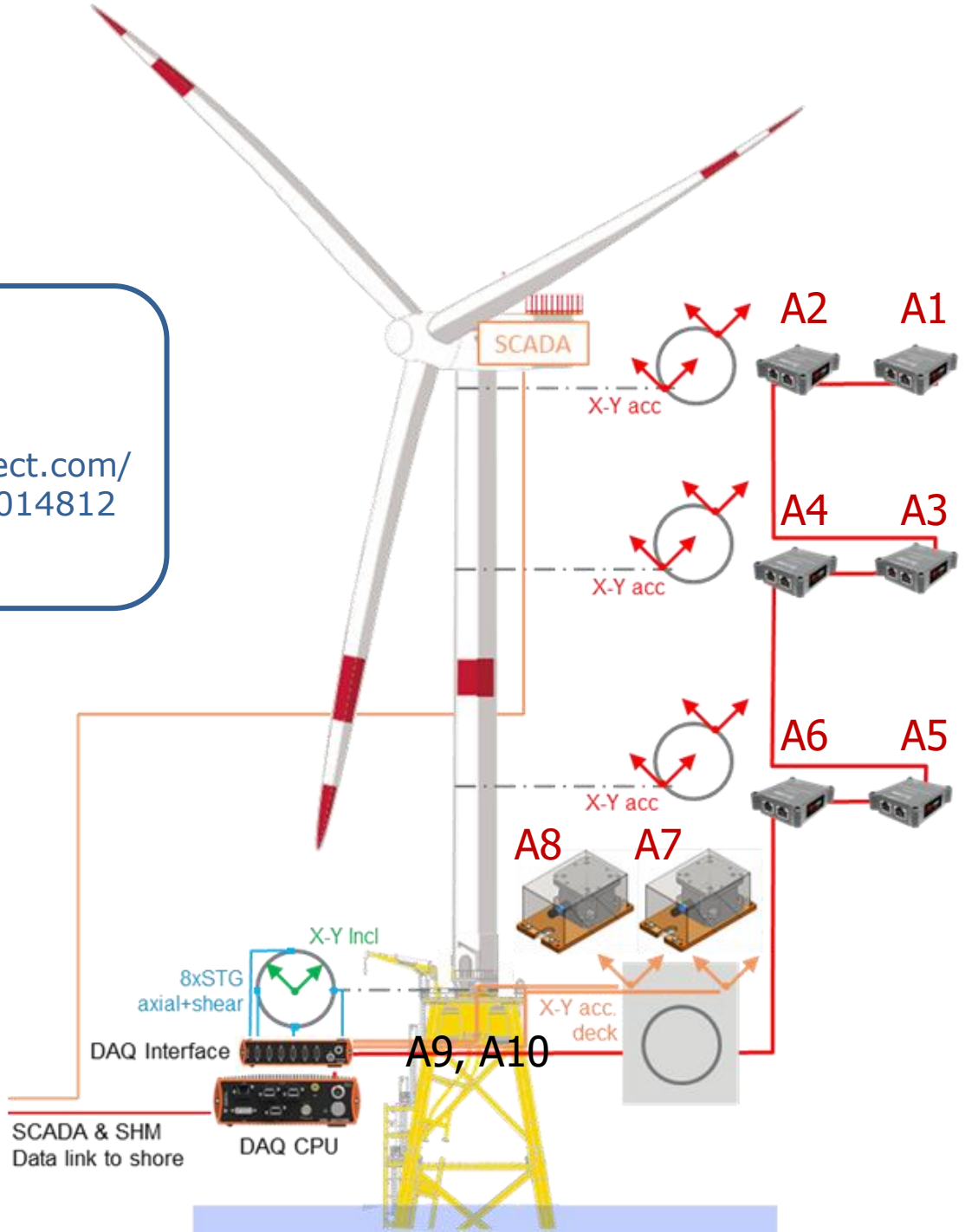
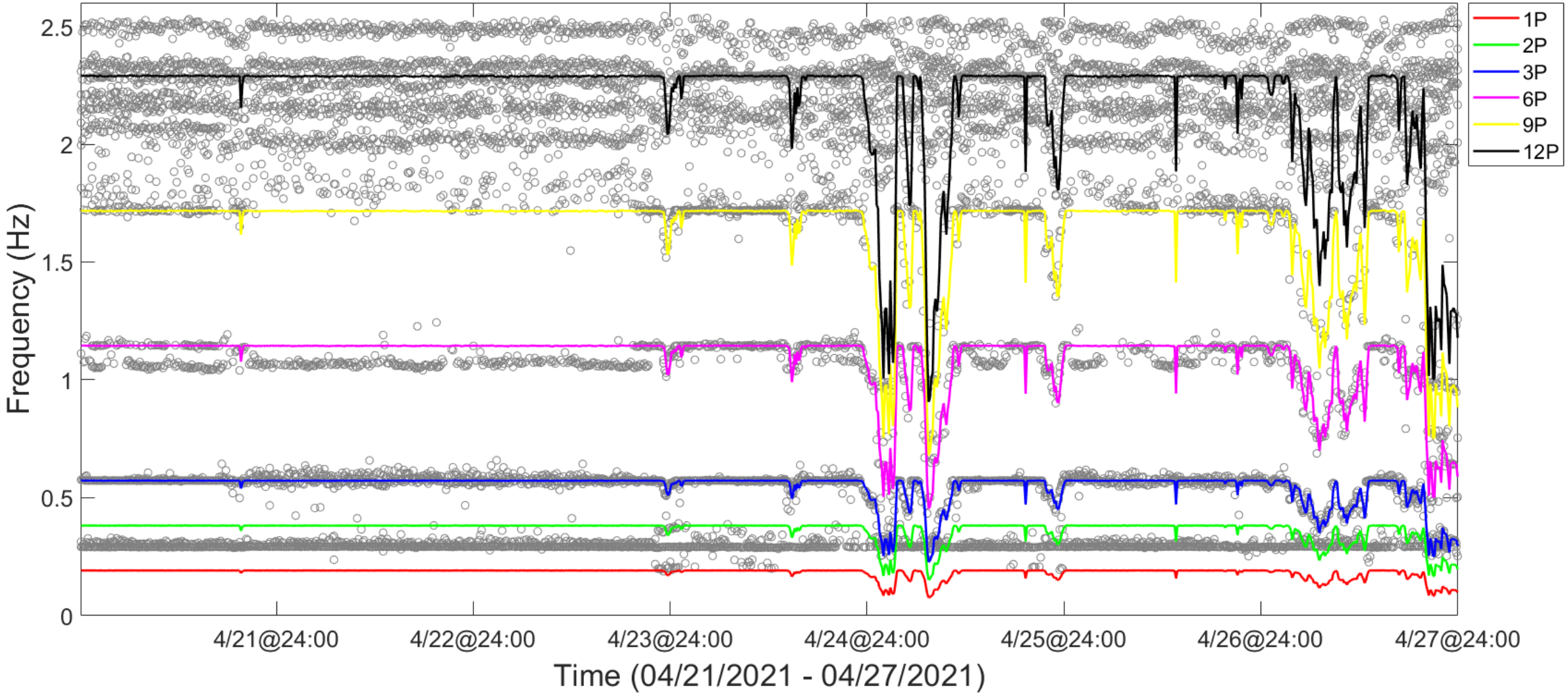


With special recognition of NGI

Monitoring the Turbine's Vital Signs



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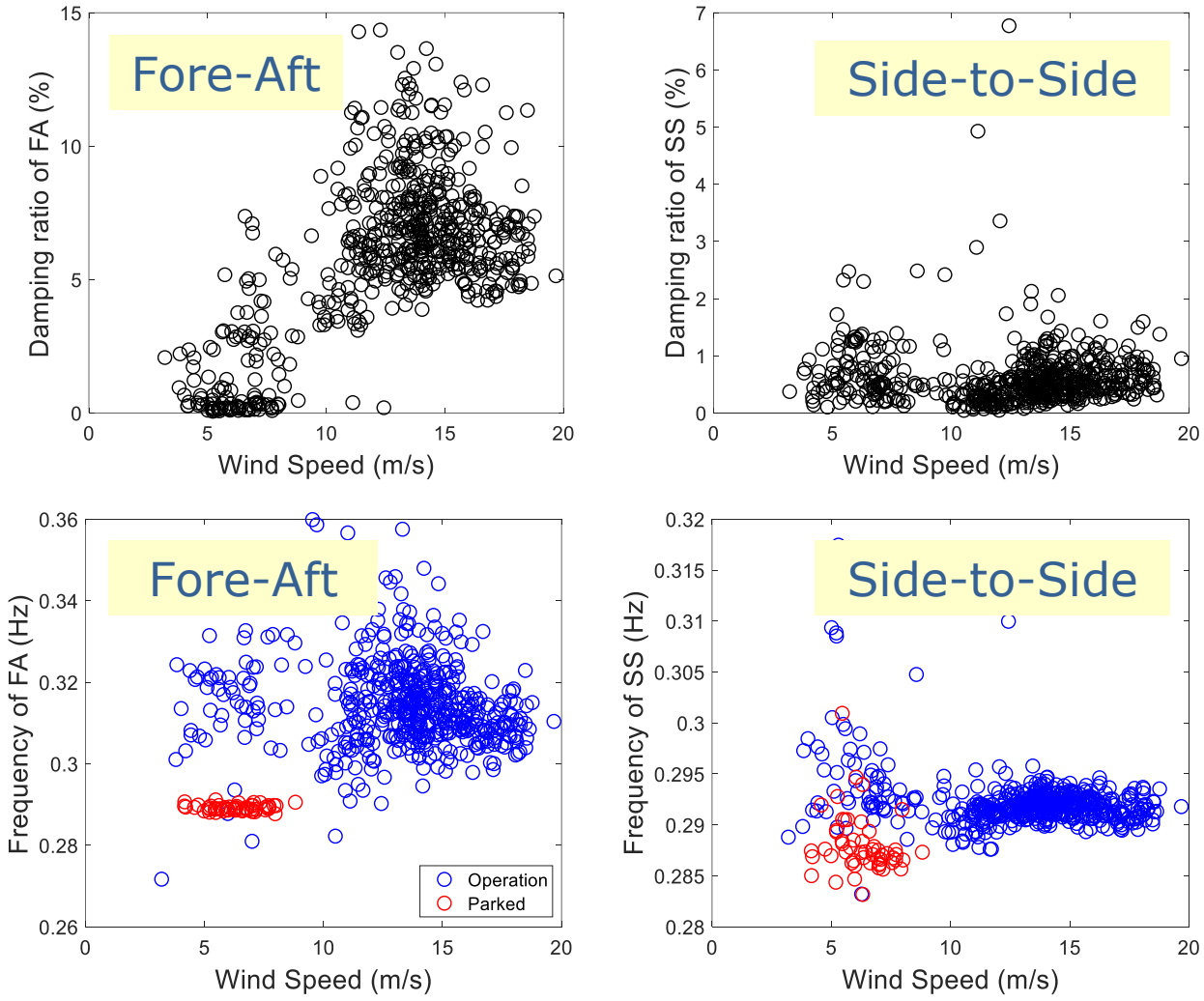
Variability with Operational Conditions

Modal parameters are sensitive to operational conditions

- First fore-aft (FA) frequencies and damping ratios show significant viability
- Side-to-side modal parameters are not sensitive to operational conditions



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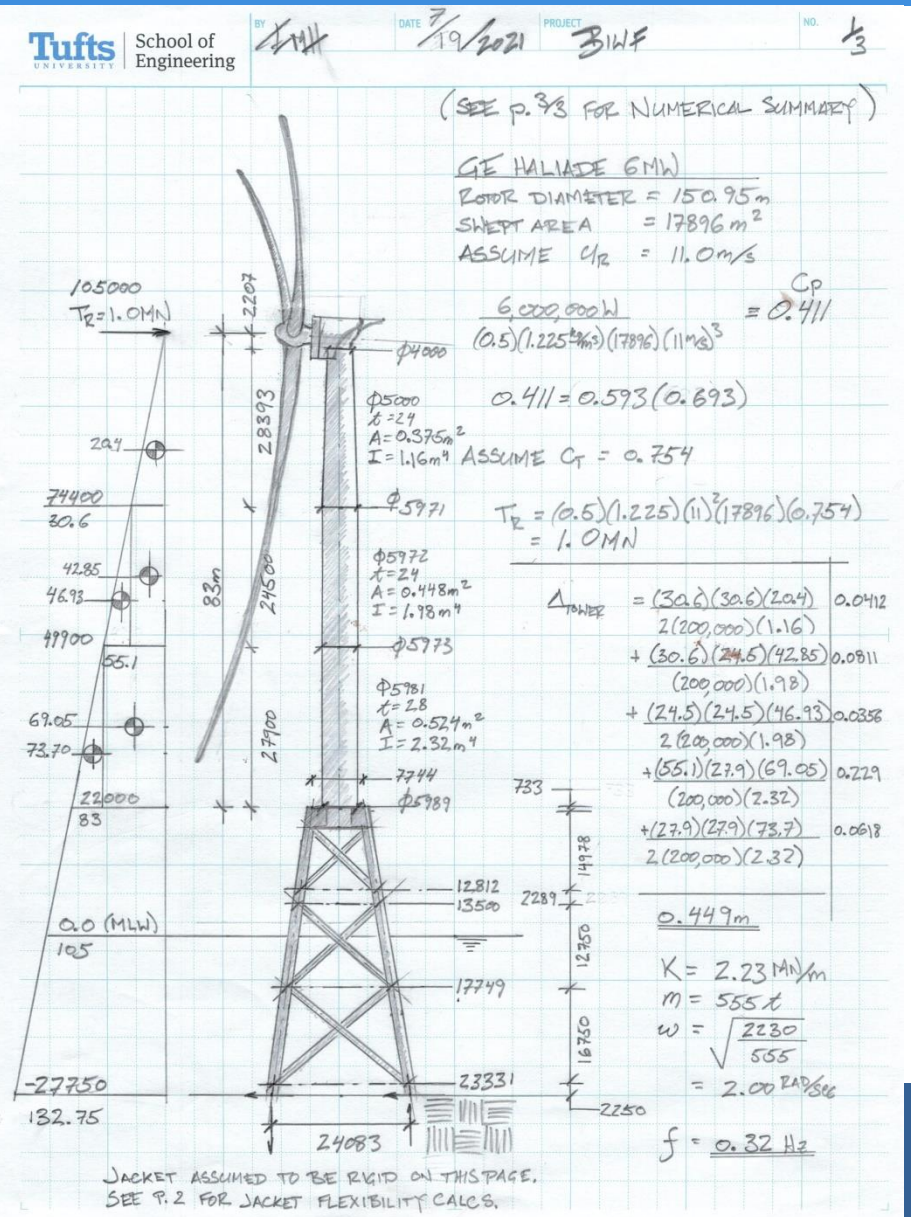
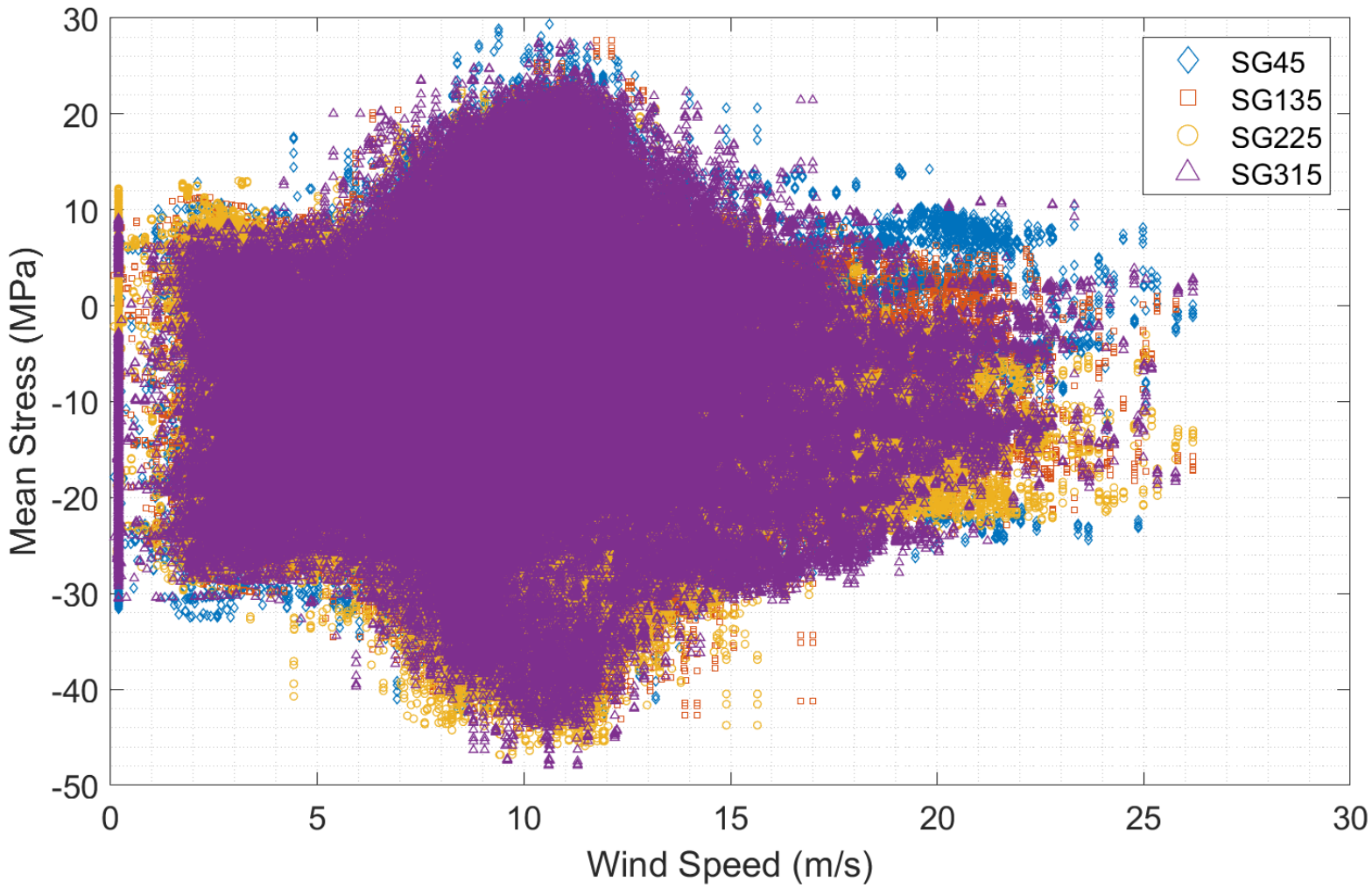
Stress vs. Wind Speed

With special recognition
of Nasim Partovi-Mehr





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University of Nevada, Reno

Digital Twinning for Load Estimation and Virtual Sensing

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Problem Statement

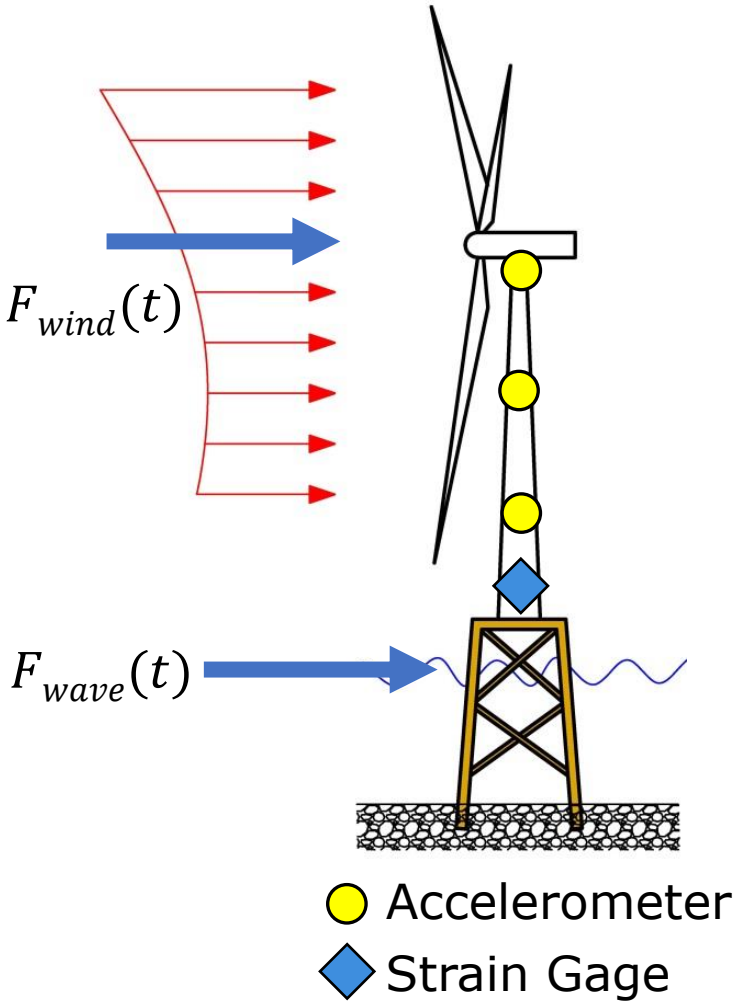
University of Nevada, Reno

Find:

- Uncertain model parameters (e.g., soil springs)
- Time history of input loads

Given:

- A validated model
- Measurements
- Parameters of interest to be estimated **q**: k_{soil}
- Locations of applied loads



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Recursive Bayesian Inference

Measurement

$\mathbf{y}$

Window-based EKF for Joint Estimation

Prediction error

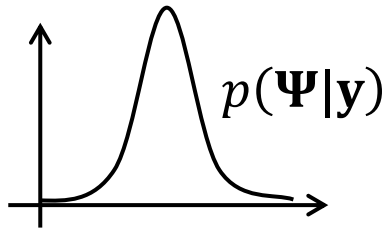
$\mathbf{y} - \hat{\mathbf{y}}(\boldsymbol{\psi}) \sim N(\mathbf{0}, \mathbf{R})$

Likelihood function

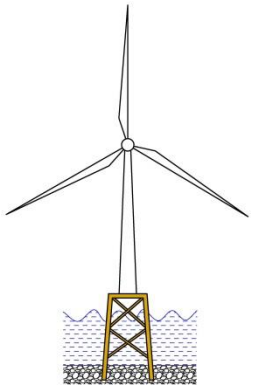
$p(\mathbf{y}|\boldsymbol{\Psi}) = N(\boldsymbol{\mu}_\mathbf{e}, \boldsymbol{\Sigma}_\mathbf{e})$

$p(\boldsymbol{\Psi}|\mathbf{y}) \propto p(\mathbf{y}|\boldsymbol{\Psi})\ p(\boldsymbol{\Psi})$

Posterior PDF



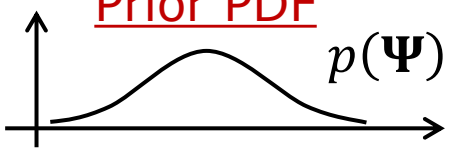
Next step



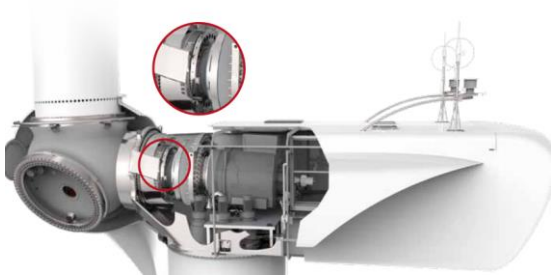
Model prediction

$\hat{\mathbf{y}}(\boldsymbol{\psi})$

Prior PDF



Recursive Bayesian Inference



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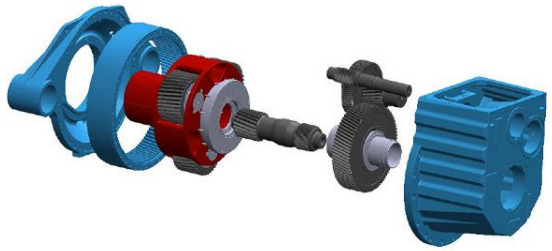
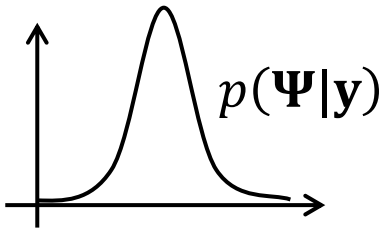


Model prediction

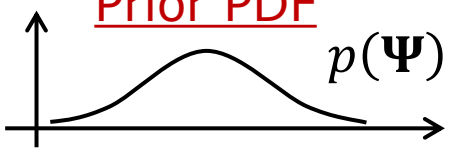
$\hat{\mathbf{y}}(\boldsymbol{\psi})$

Posterior PDF



Next step

Prior PDF

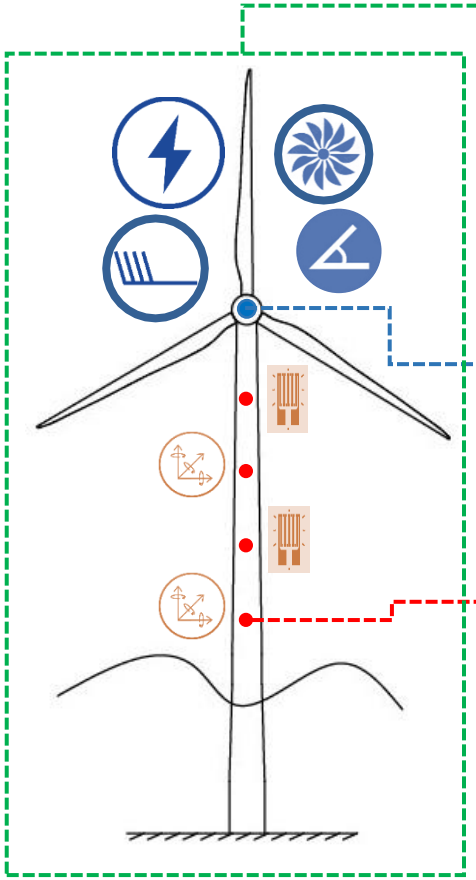


With special recognition of Hamed Ebrahimian, Vahid Jahangiri, and Mohammad Valikhani of UNR

Hybrid Machine Learning + Physics-Based for Wind-Farm Level Monitoring

With special recognition of Anna Haensch, Eleonora Tronci, Azin Mehrjoo, and Bridget Moynihan

Motivations



Structural details of turbine

SCADA system measurements

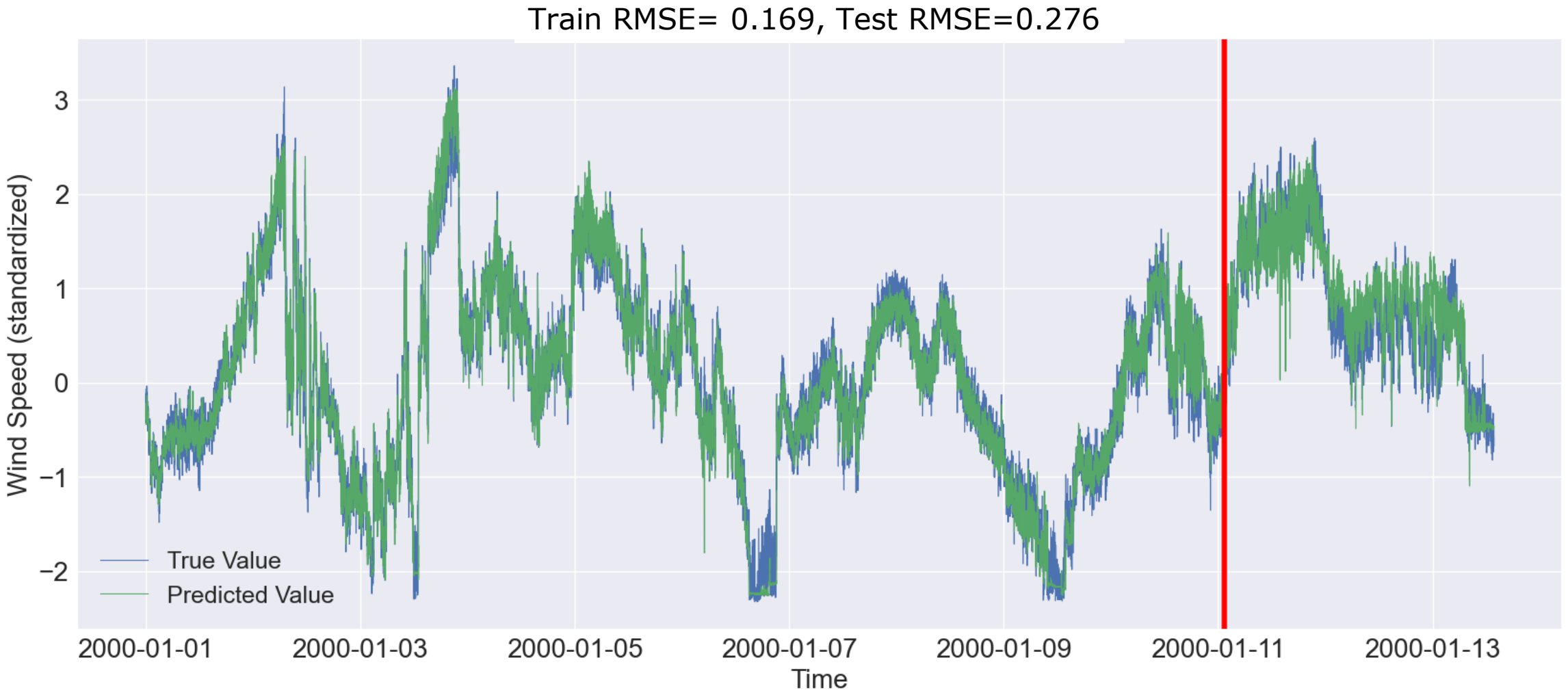
Measured structural response from instrumentation

Physics-Based Modeling and Analysis

Data-Driven Analysis and Machine Learning

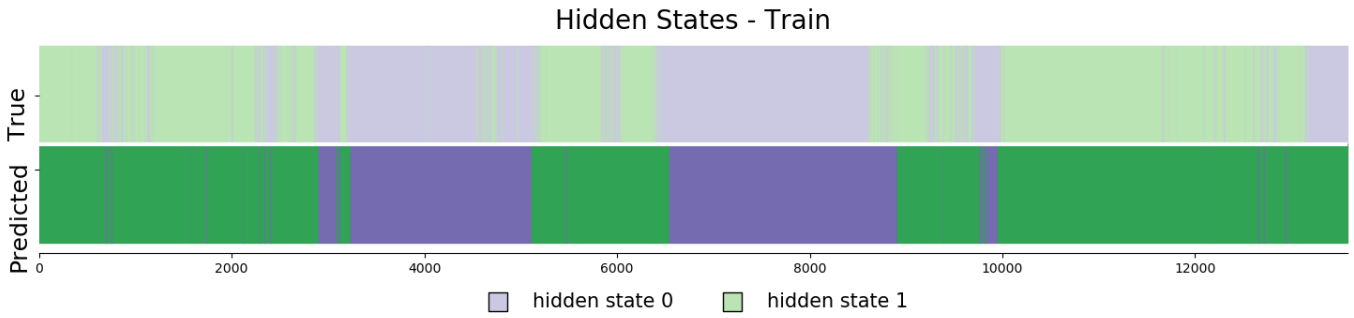
Hybrid Physics-Based Machine Learning Informed Analysis

Input Load Estimation

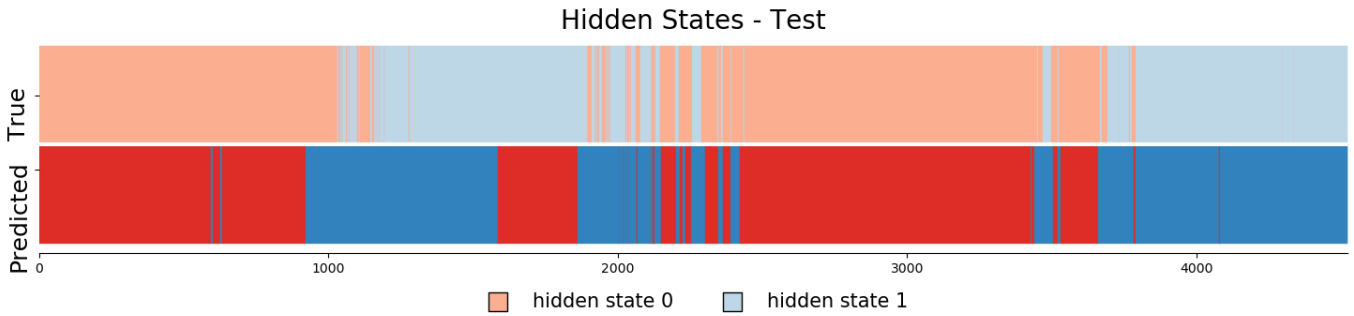


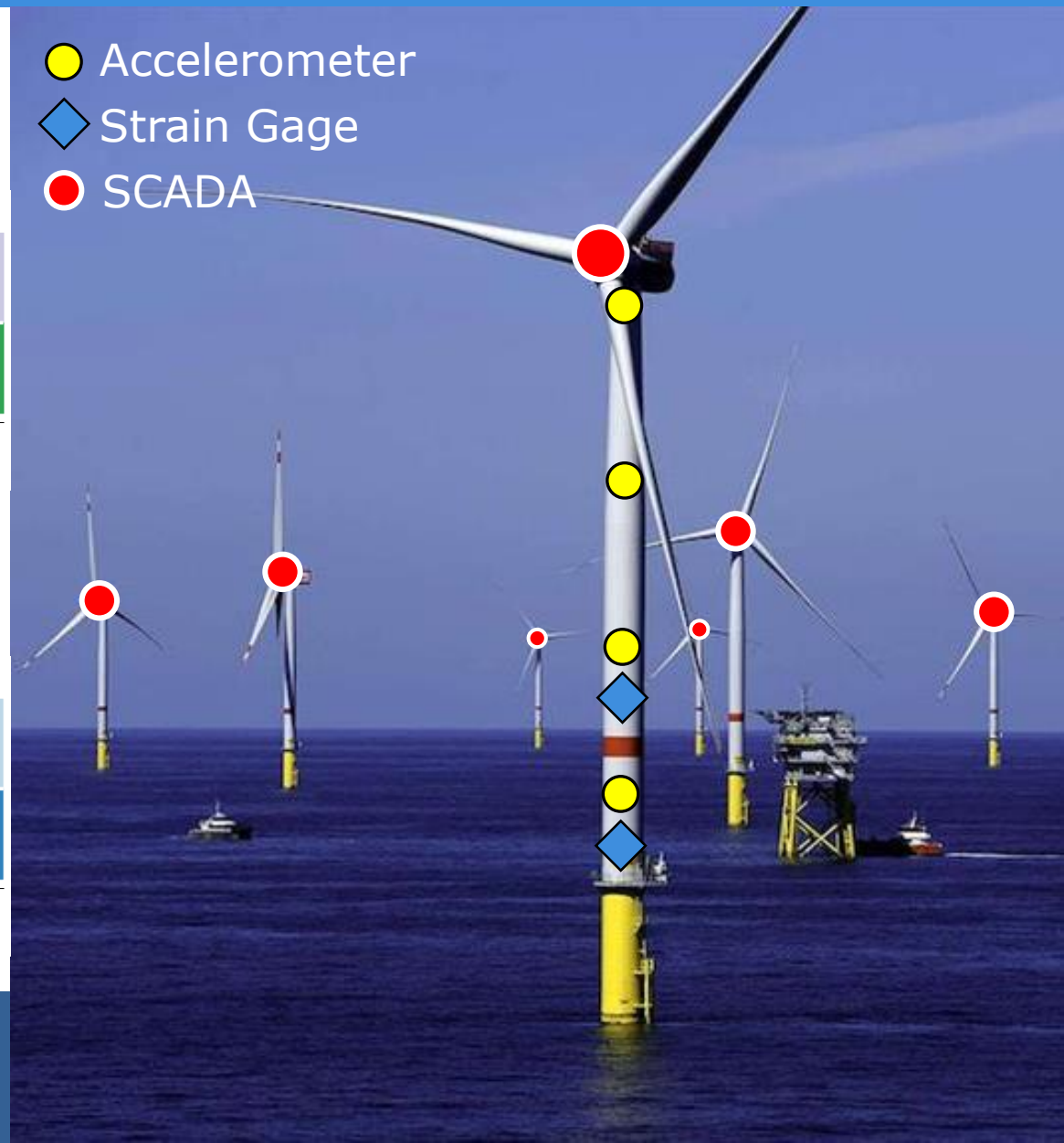
Hybrid ML + Physics-Based: Instrument 1 » Monitor 20

Accuracy
85.43%



Accuracy
84.17%





Thank You!

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