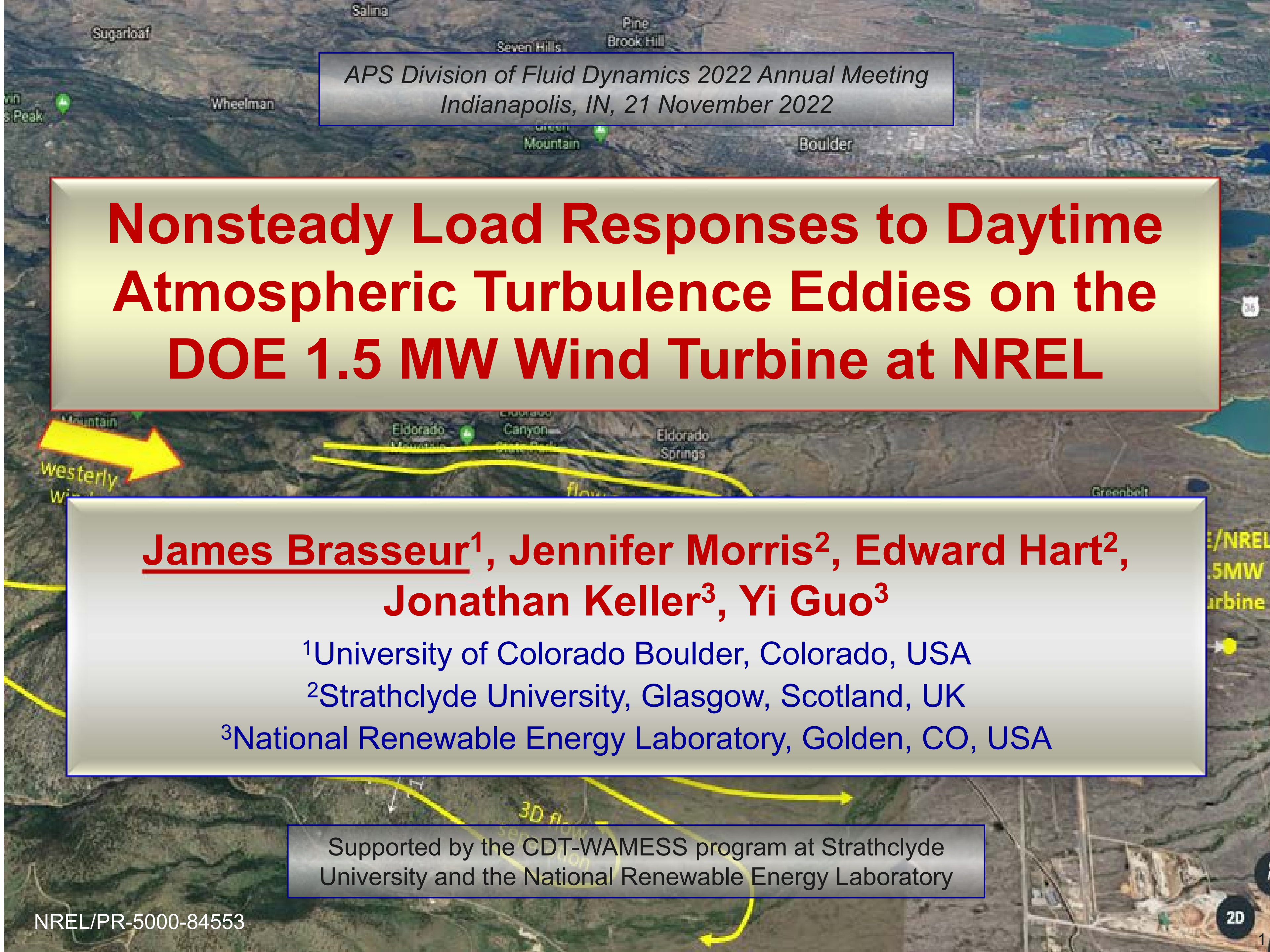


APS Division of Fluid Dynamics 2022 Annual Meeting
Indianapolis, IN, 21 November 2022

Nonsteady Load Responses to Daytime Atmospheric Turbulence Eddies on the DOE 1.5 MW Wind Turbine at NREL

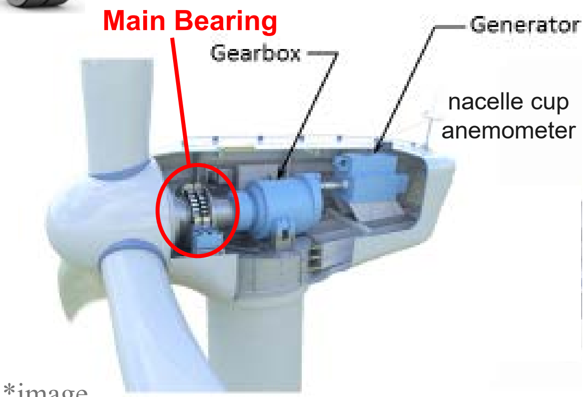
James Brasseur[1], Jennifer Morris[2], Edward Hart[2], Jonathan Keller[3], Yi Guo[3]

[1]University of Colorado Boulder, Colorado, USA
[2]Strathclyde University, Glasgow, Scotland, UK
[3]National Renewable Energy Laboratory, Golden, CO, USA

Supported by the CDT-WAMESS program at Strathclyde University and the National Renewable Energy Laboratory

NREL/PR-5000-84553

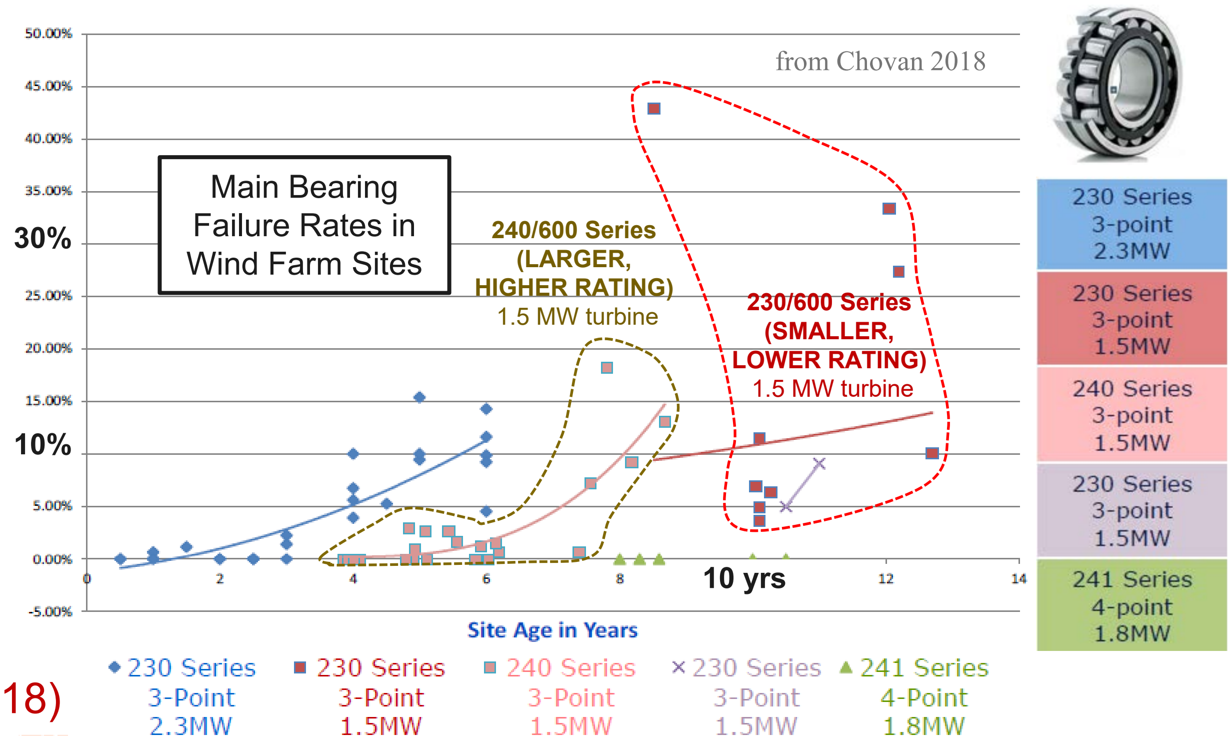
Main Bearing Failure Modes



*image

Levelized Cost of Energy (LCOE)

$$\frac{\text{Investment} + \textbf{20-yr Operating Costs}}{\text{20-yr Energy Production}}$$



- **Key Observations** (Chovan 2018)
  - failure rate is unacceptable
  - larger bearing (larger roller) fails earlier

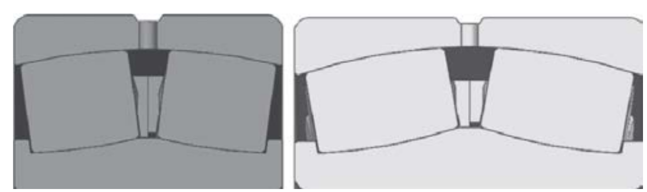
⇒ Attributed to adhesive wear rather than subsurface fatigue

⇒ However, a recent analysis of failure data suggests a stronger role of spalling (Hart, et al. 2022)

- **Key Elements** (Kotzalas & Doll 2010, Chovan 2019)
  - high loading, low speed, low lubrication layer thickness

  ⇒ ***repeated* metal-to-metal contact**

Chovan, TDI Mainshaft Bearing – Field Test Results, *AWEA 2018*
Chovan, Seven Years of Solid Results, *Wind Systems*, March 2019
Kotzalas & Doll, Tribological advancements for reliable wind turbine performance *Phil. Trans. R. Soc. A* (2010) 368, 4829-4850

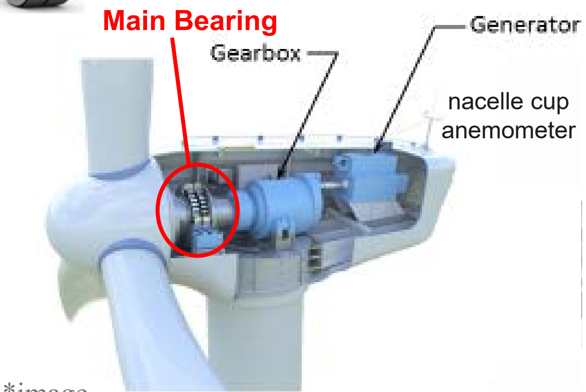


230/600 Series **240/600 Series**

Schaeffler Technologies

*image from: https://www.energy.gov/eere/articles/advanced-wind-turbine-drivetrain-trends-and-opportunities

Main Bearing Failure Modes



*image

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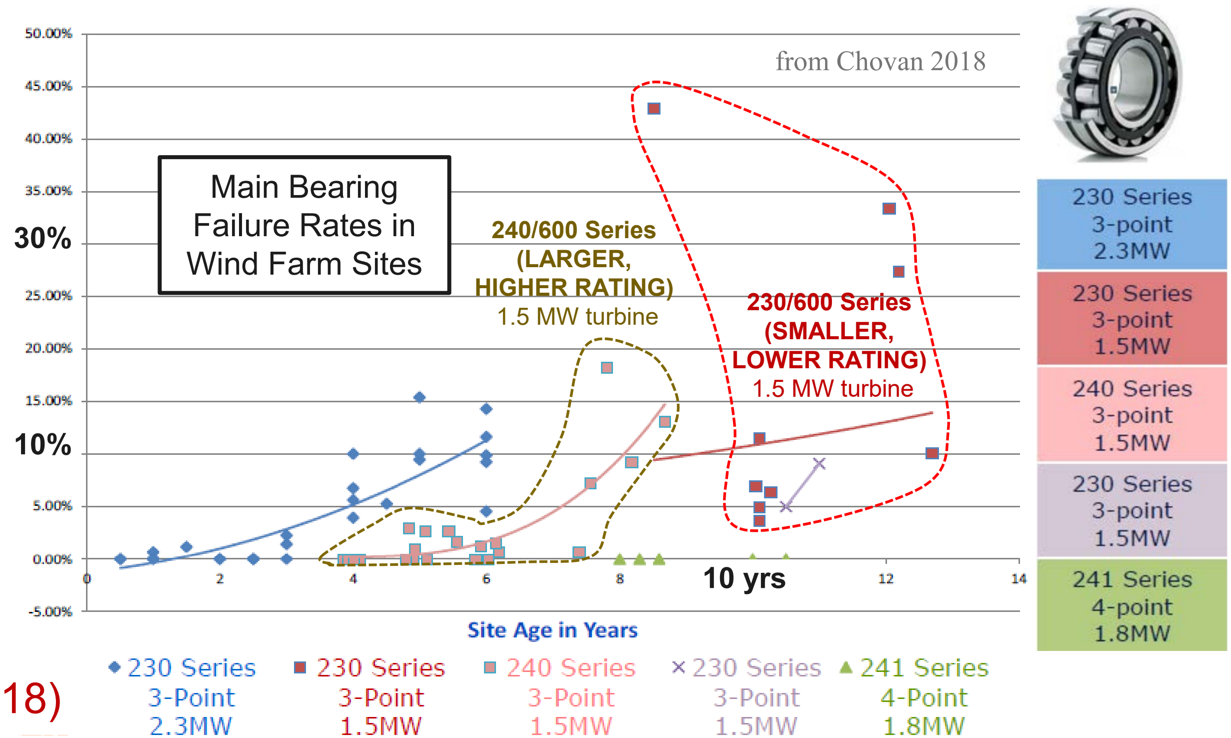

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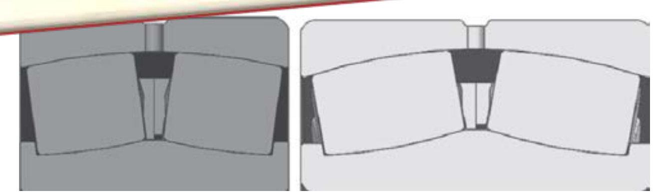
Chovan, TDI Mainshaft Bearing – Field Test Resul
Chovan, Seven Y

⇒ *search for temporally repeating load sources on bearing*

- **Key Elements** (Kotzalas & Doll 2010, Chovan 2019)
  - high loading, low speed, low lubrication layer thickness

  ⇒ ***repeated* metal-to-metal contact**

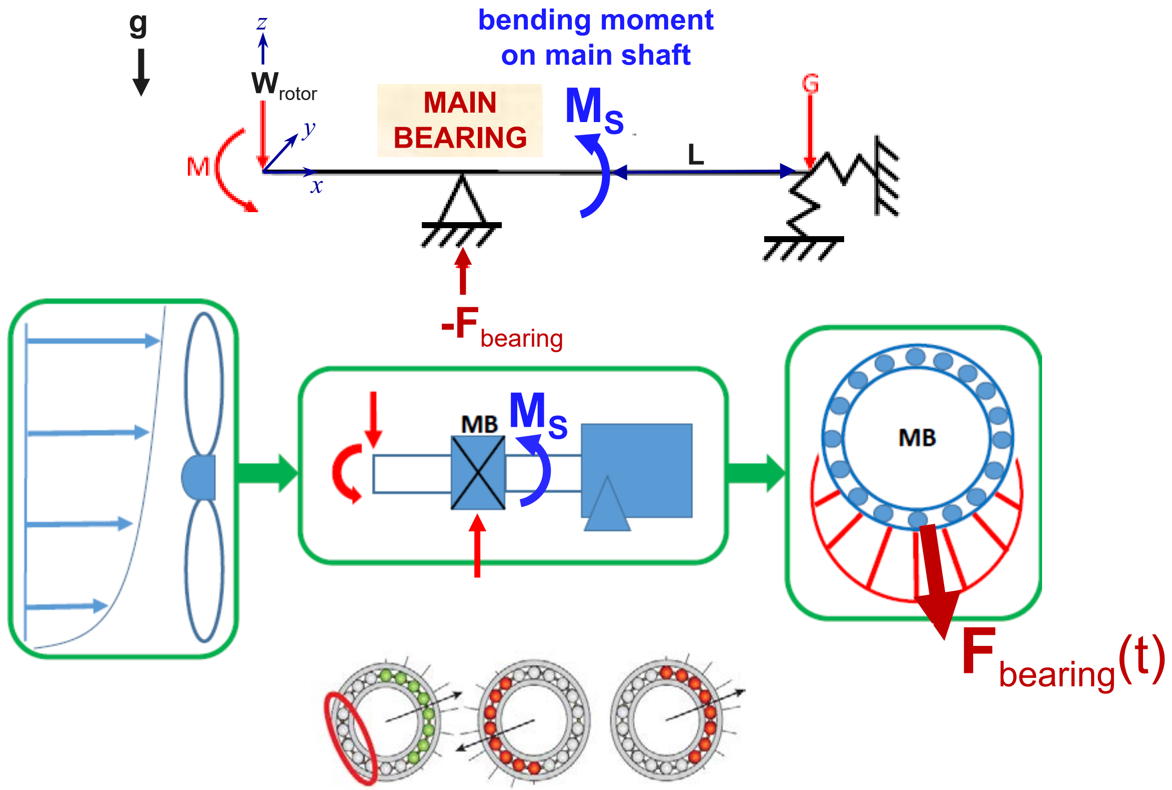


230/600 Series **240/600 Series**

Schaeffler Technologies

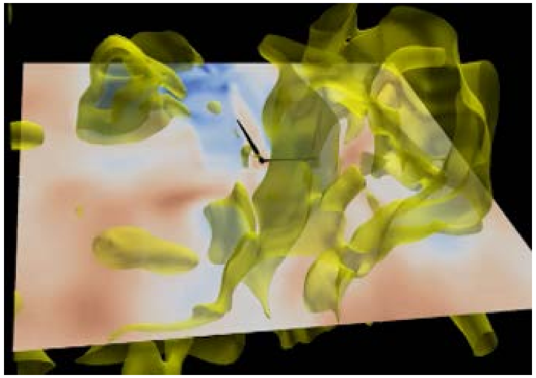
*image from: https://www.energy.gov/eere/articles/advanced-wind-turbine-drivetrain-trends-and-opportunities

Forcing of Main Bearing by Main Shaft Moments Driven by Atmospheric (and potentially wake) Turbulence



Hypothesis:

ATMOSPHERIC TURBULENCE



Time Changes in (out-of-plane) Bending Moments

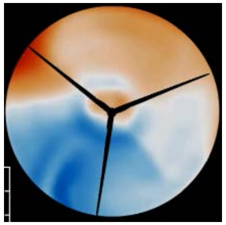
Drive Time Changes in Main Bearing Loadings

$$\mathbf{F}_{bearing}(t) - \mathbf{W}_{rotor} = \frac{1}{L}\left[M_{S_z}(t)\mathbf{e}_y + M_{S_y}(t)\mathbf{e}_z\right]$$

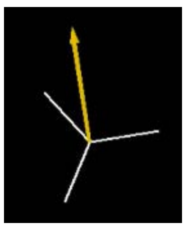
BEARING FORCE relative to rotor weight ← **(out-of-plane) BENDING MOMENT ON MAIN SHAFT**

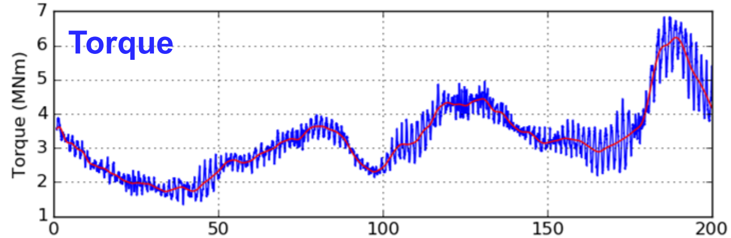
An Important Prediction
from Large-Eddy Simulation (LES) of Daytime Atmospheric Turbulence with Embedded Actuator Line Model of 5 MW Wind Turbine

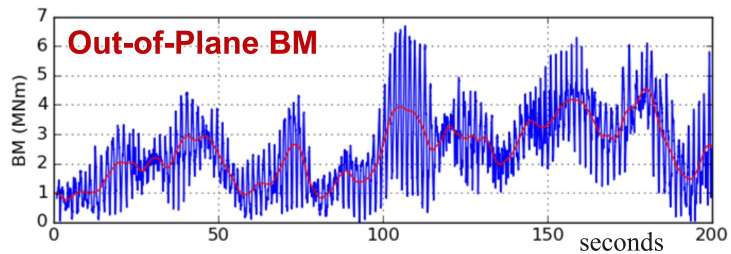
Horizontal Velocity over Rotor Disk



Out-of-Plane Bending Moment (BM)



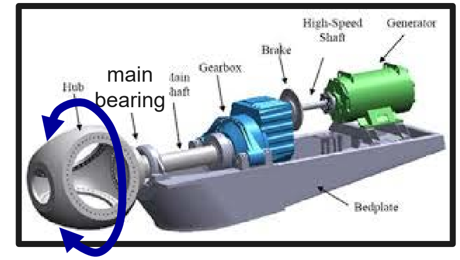


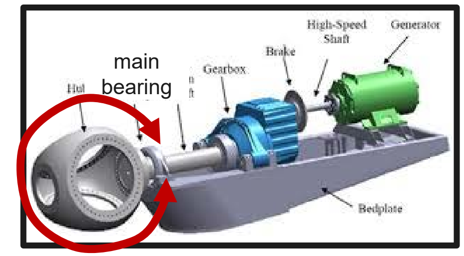


Torque (power) on main shaft

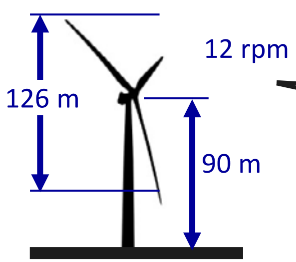
corr.coeff. = 0.06

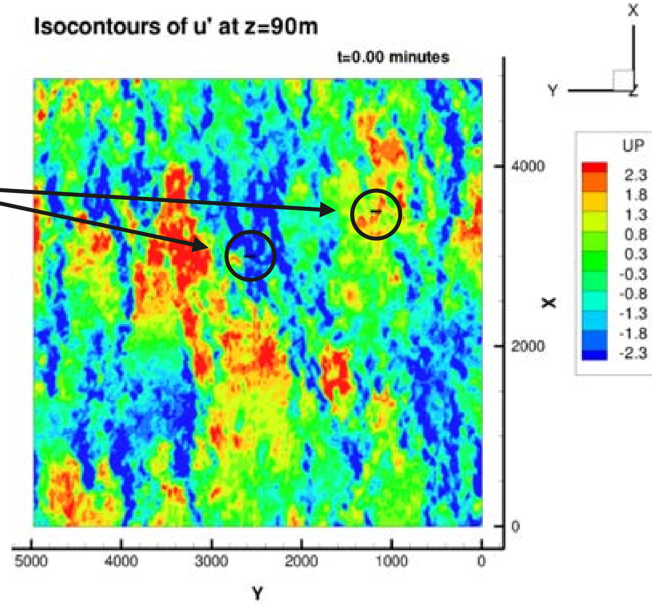
Out-of-Plane Bending Moment on main shaft





NREL 5 MW Wind Turbine



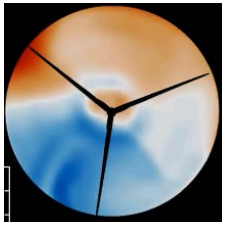


Simulation Assumptions
- constant RPM, pitch, yaw
- no blade deformation

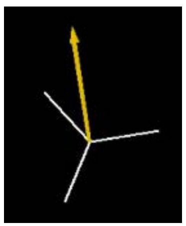
from PhD Thesis of : Adam Lavely, Penn State University, August 2017.

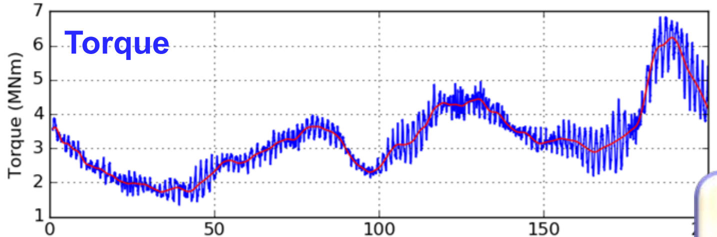
An Important Prediction
from Large-Eddy Simulation (LES) of Daytime Atmospheric Turbulence with Embedded Actuator Line Model of 5 MW Wind Turbine

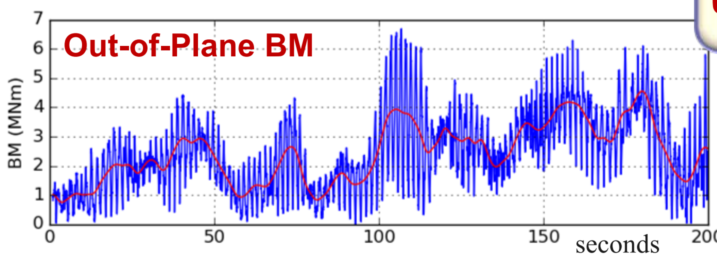
Horizontal Velocity over Rotor Disk

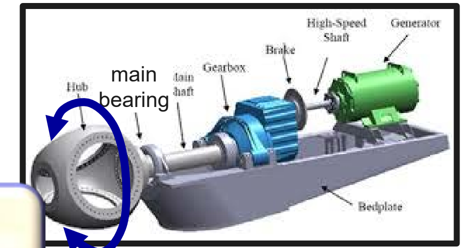


Out-of-Plane Bending Moment (BM)





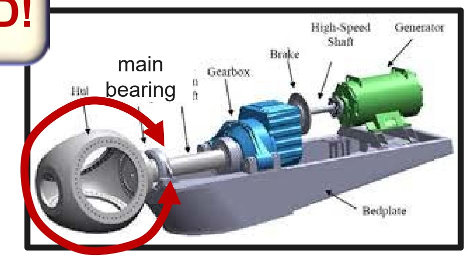




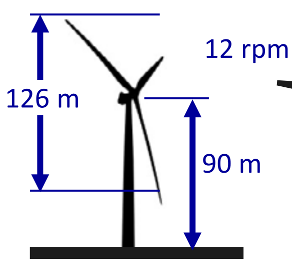
Torque (power) on main shaft

fully UNCORRELATED!

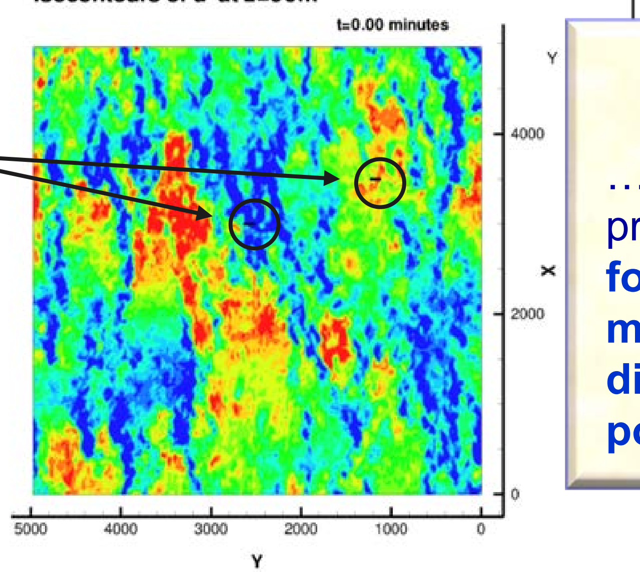
Out-of-Plane Bending Moment on main shaft



NREL 5 MW Wind Turbine



Isocontours of u' at z=90m



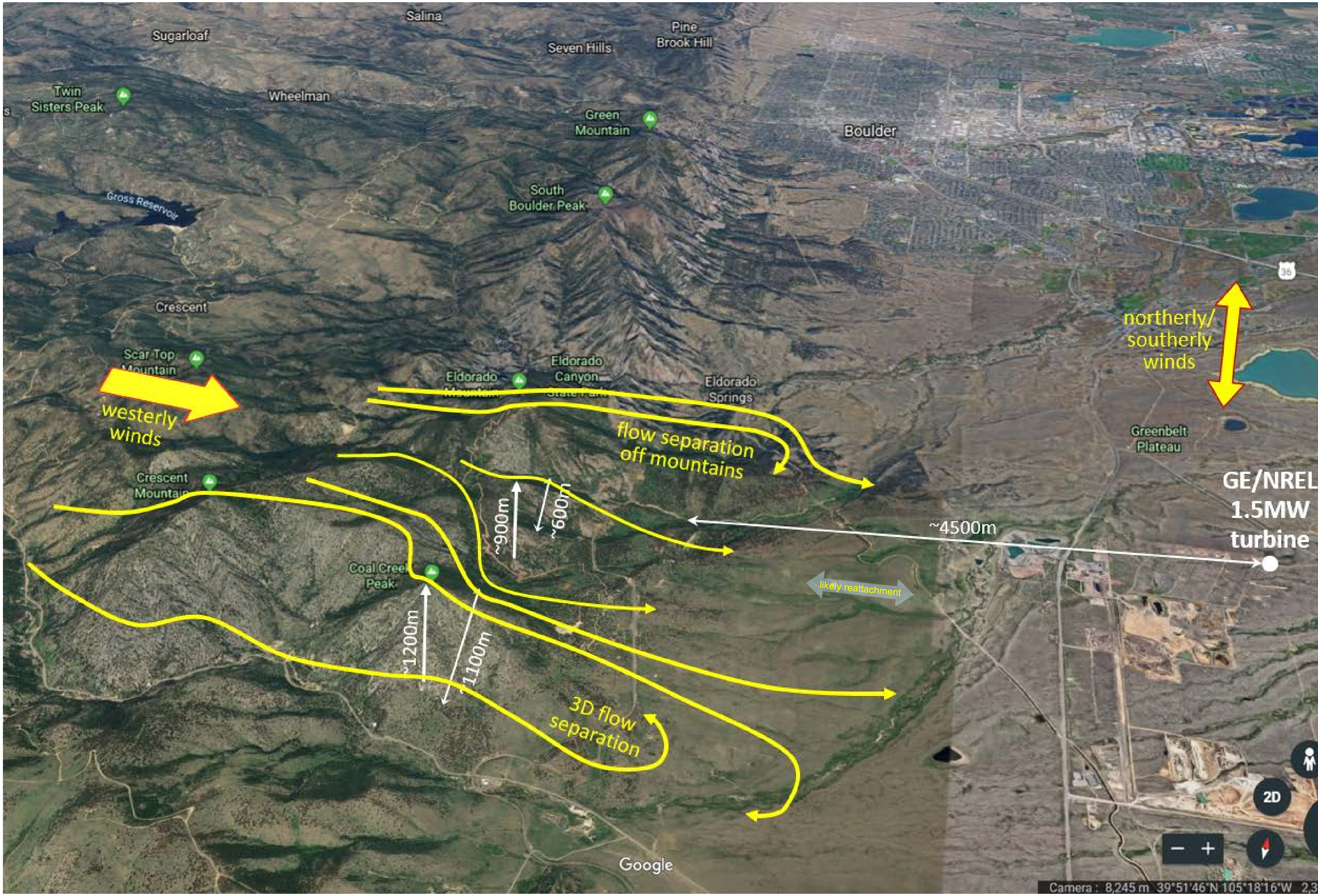
Simulation Assumptions

- Constant RPM, pitch, yaw
- No blade deformation

ANALYSIS OF DATA FROM THE NREL/GE 1.5 MW WIND TURBINE

… to verify with field data the LES prediction that **atmospheric turbulence forces the main bearing with a mechanism that is fundamentally different from that for torque and power generation.**

Field Analysis: Modeling Atmospheric Eddies with Eddies Generated by Front Range Mountains



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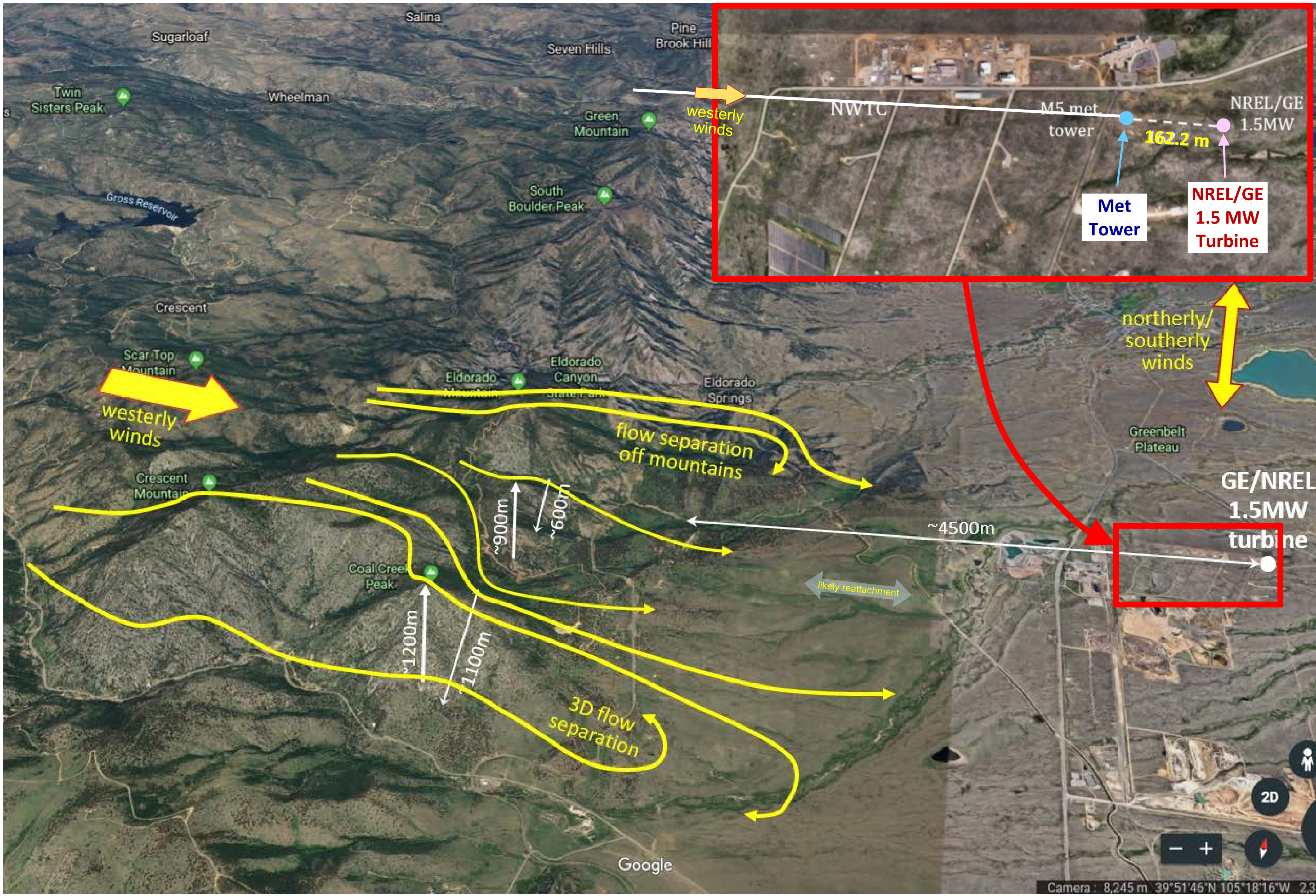
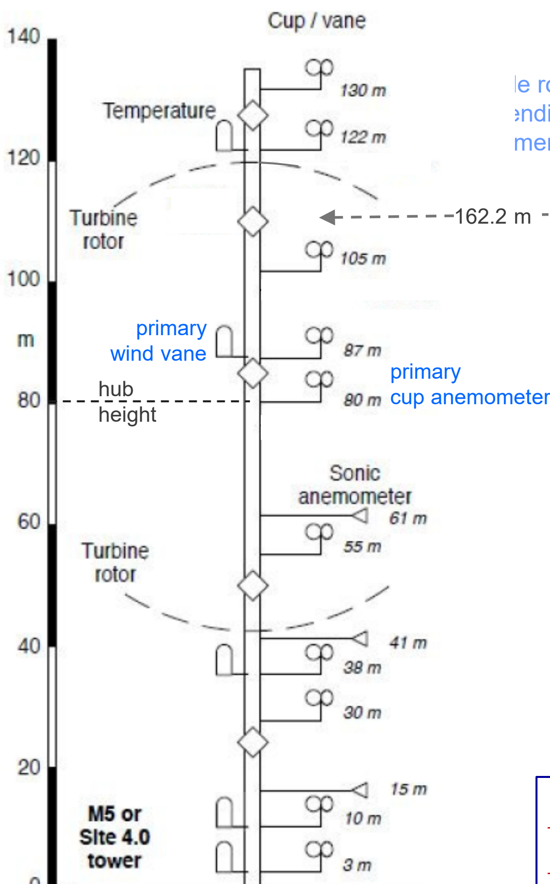
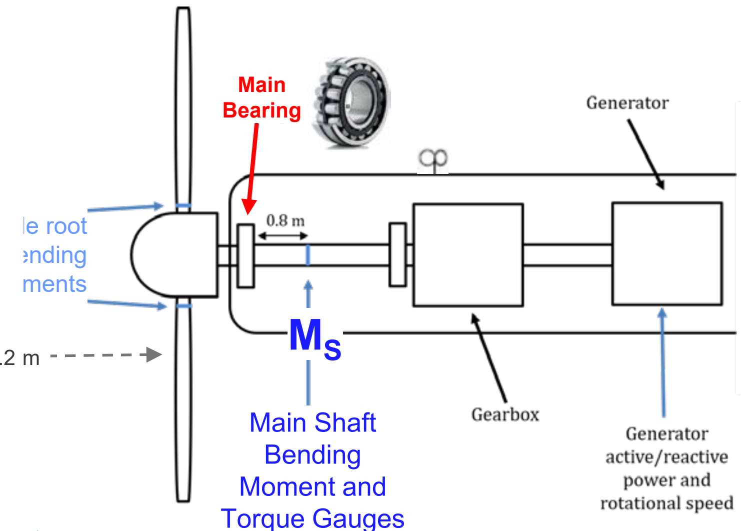
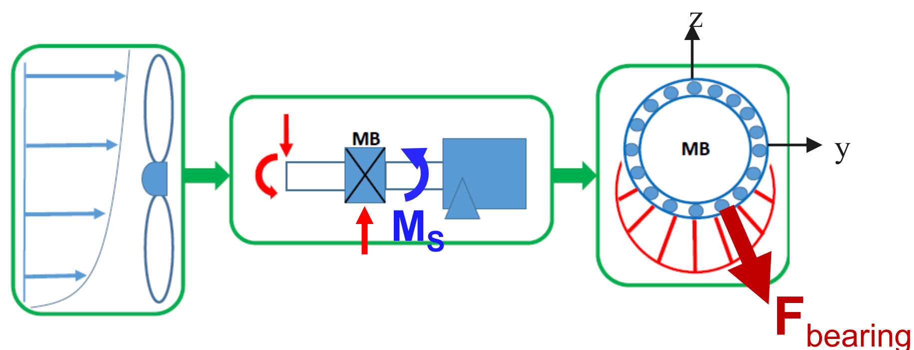


Met Tower and NREL/GE 1.5 MW Wind Turbine Instrumentation (in addition to SCADA)





GE 1.5 MW Turbine Specs
Hub height: 80 m
Rotor Diameter: 77 m
Rated wind speed: 14 m/s
Rotor period at RWS: 3.3 s
Cut-in wind speed: 3.5 m/s

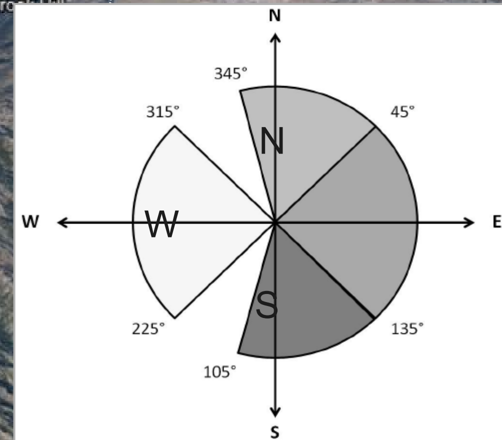


$$\mathbf{F}_{bearing} - \mathbf{W}_{rotor} = \frac{1}{L}\left(M_{S_z}\mathbf{e}_y + M_{S_y}\mathbf{e}_z \right)$$

Segregation of Data in Westerly vs. Northerly/Southerly Directions

Period chosen: 14 June–4 October 2018
- Anemometer calibrations and data available

Period Characteristics (to match LES)
- No precipitation
- Relatively constant wind speed
- Constant RPM ⇒ region 2 of power curve
- Constant pitch, yaw ⇒ U10 < ~9.5 m/s



Separation of Westerly Winds from Northerly/ Southerly Winds

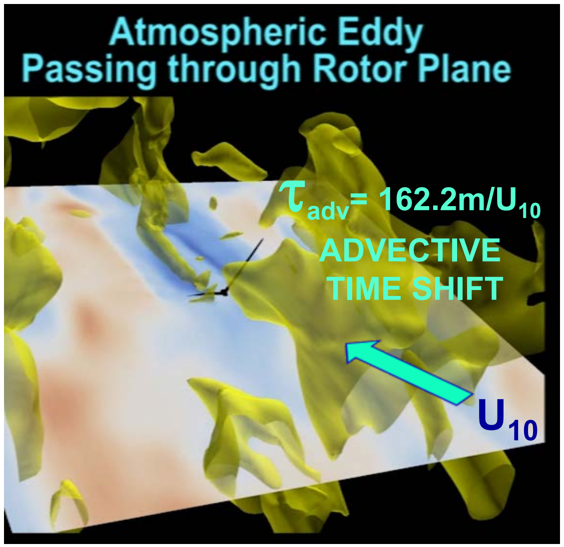
10-MINUTE DATASETS:
- **Total number Westerly datasets: 139 (81%)**
- **Total number Northerly/Southerly datasets: 33 (19%)**

APPROACH:

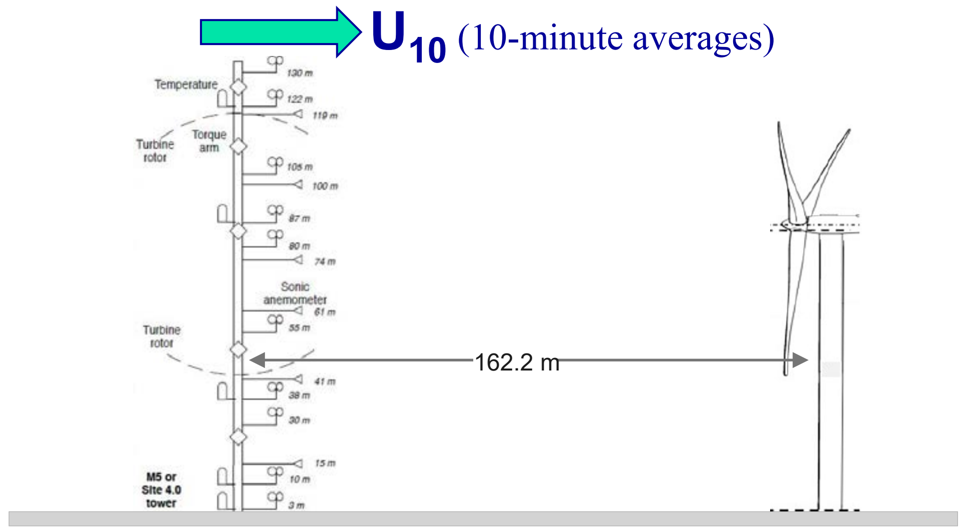
(1) Analyze Westerly data using both met tower and nacelle anemometers

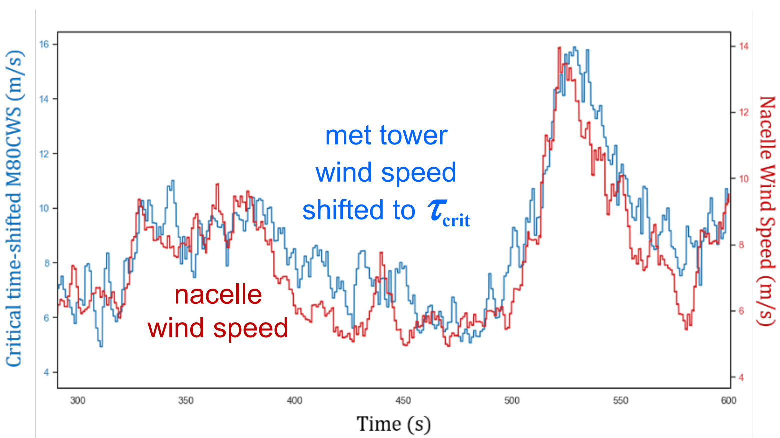
(2) If met and nacelle anemometers are in statistical agreement*, repeat analysis for Northerly/Southerly data using the nacelle anemometer. (*they are)

Identification of a “Turbulence Eddy” in Westerly Winds - Advection from Met Mast to Turbine -

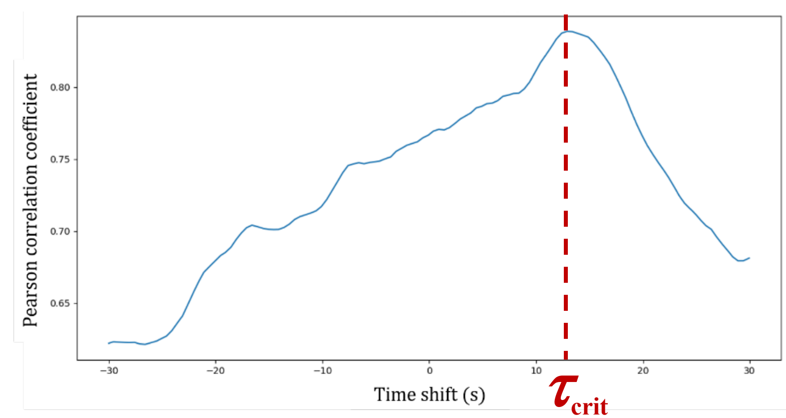


From a movie of ABL turbulence-rotor interactions using the Lavely large-eddy simulations





CRITICAL time shift



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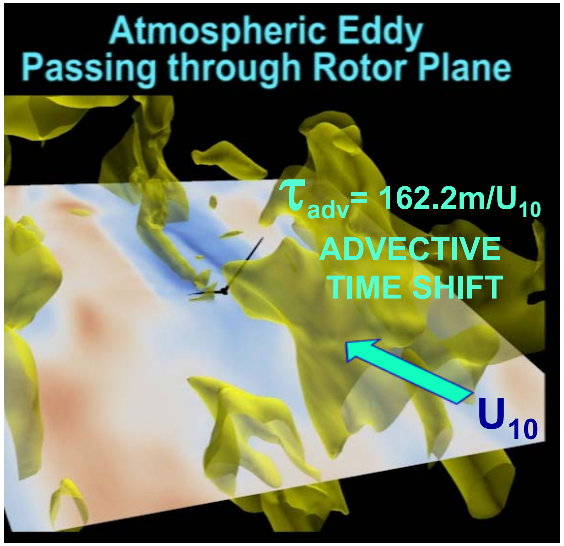

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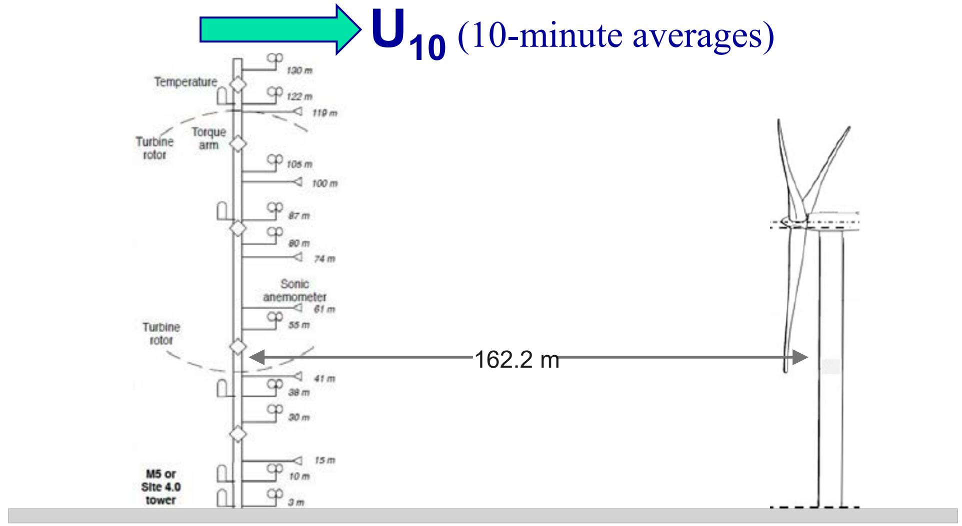
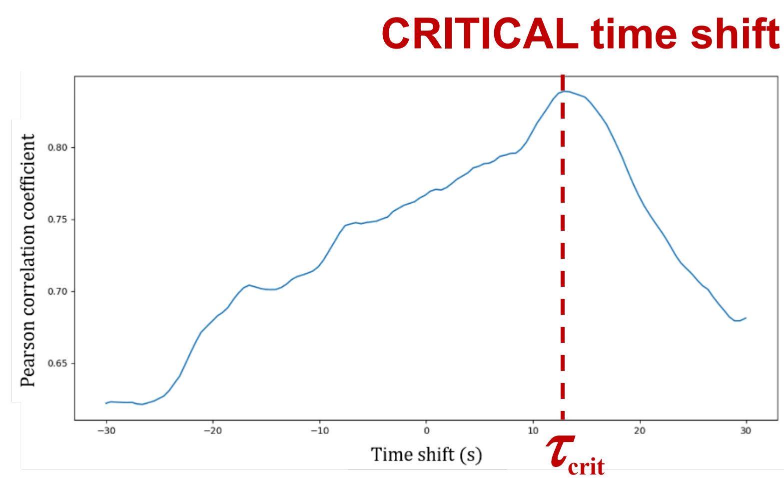


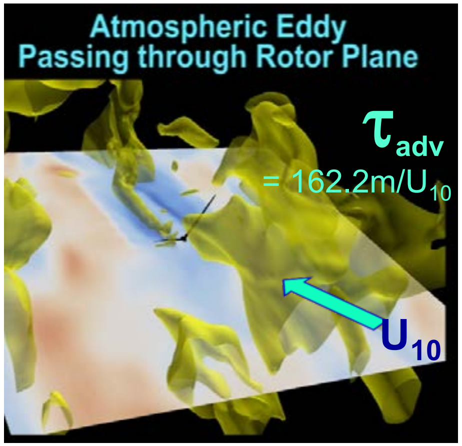
Criteria to Identify a Turbulence Eddy:

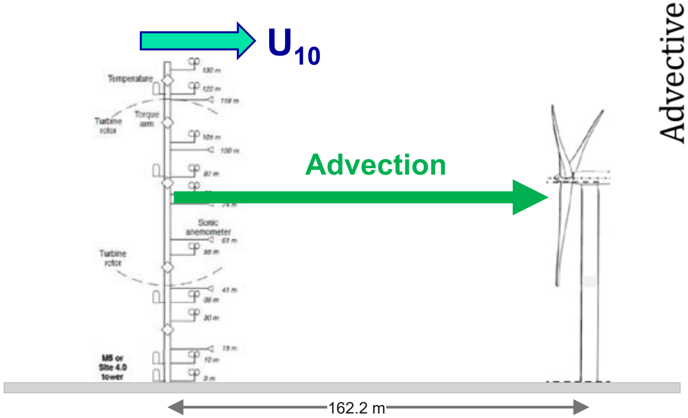
- **Well-defined peak in time-shifted correlation coefficient**
- **The advection time based on U_{10} ≈ the optimal time shift τ_{crit}**

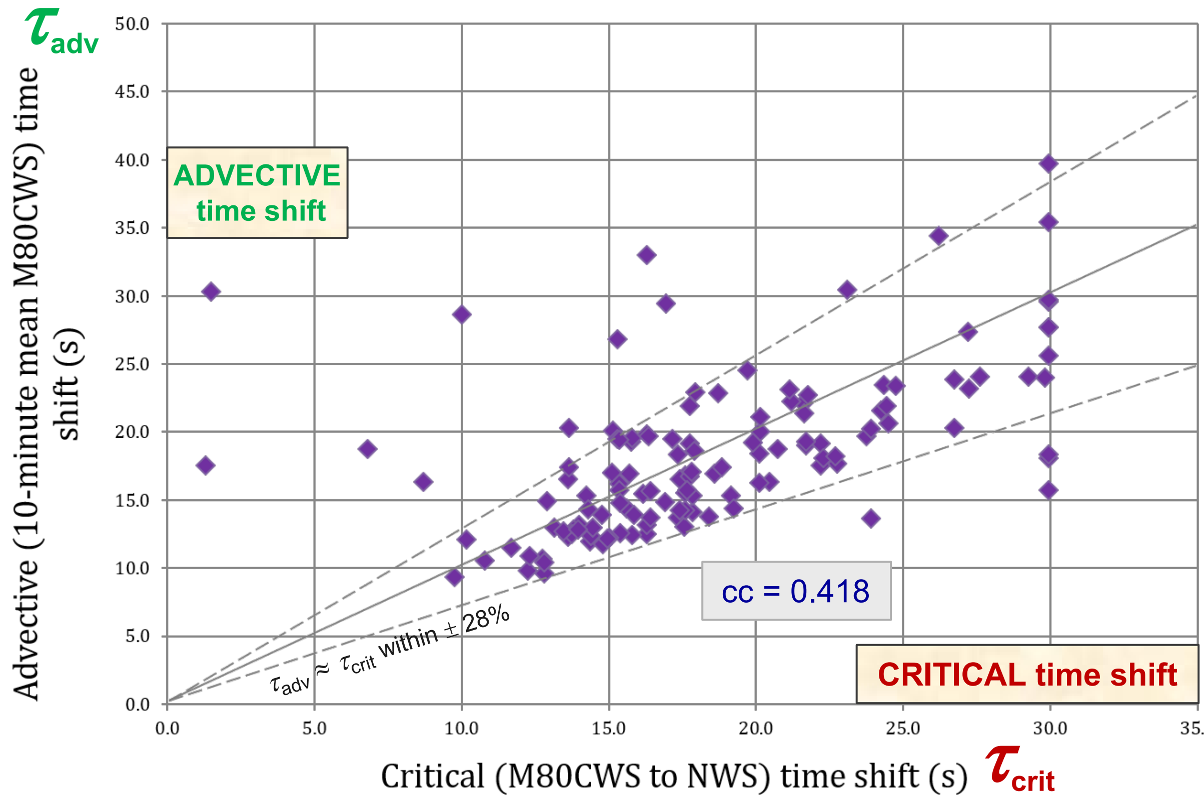
⇒ A turbulence eddy is likely carrying the fluctuations from met mast to turbine

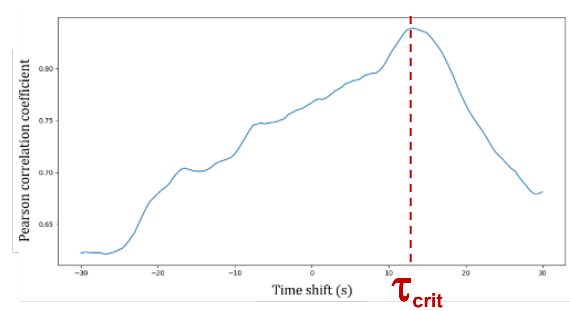


139 10-minute Datasets with Potential Advection of Turbulence Eddies from Met Mast to Wind Turbine

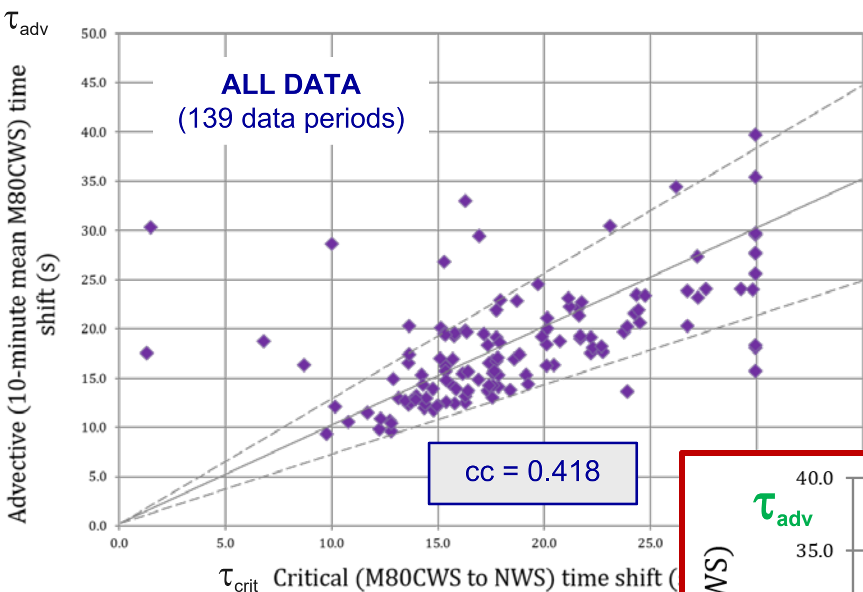






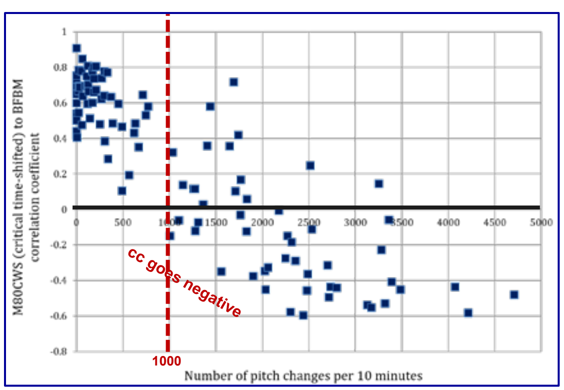


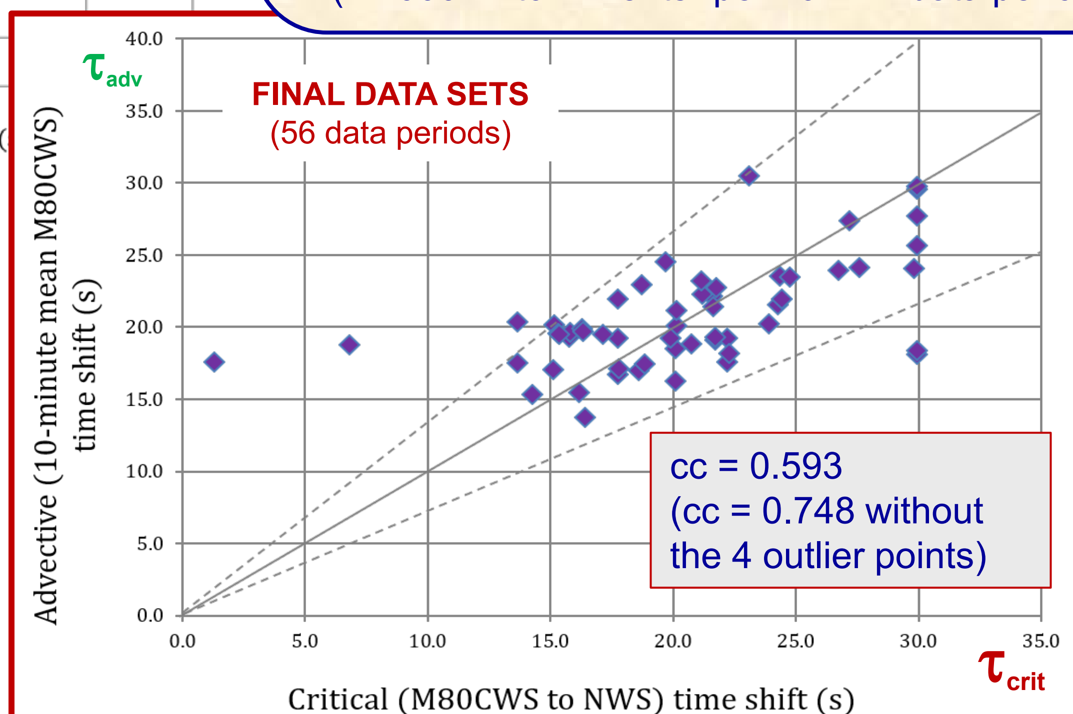
Final Data Set Analyzed for Westerly Winds



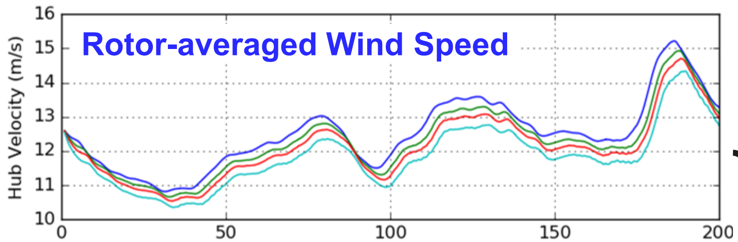
Criteria to Accept Data as Representing Turbulence Eddy Passage from Met Tower to Wind Turbine

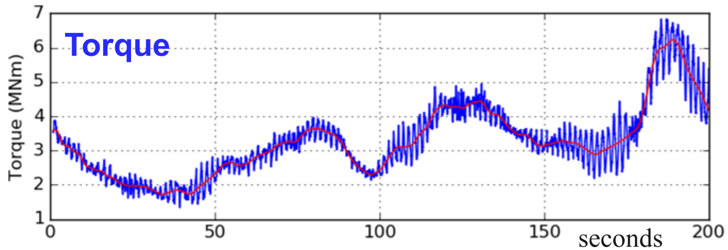
1. **Misalignment in Wind Direction**
2. **Too Low Wind Speed**
3. **Pitch Events**
   (< 1000 "Pitch Events" per 10 min. data period)





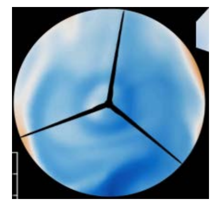
Analysis of the Lavely Result Using Large-Eddy Simulation with the Actuator Line Model

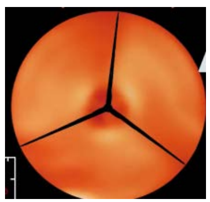




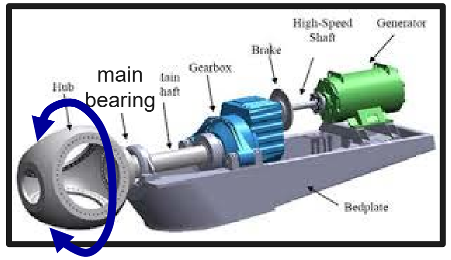
HIGHLY CORRELATED

corr.coeff. = 0.98





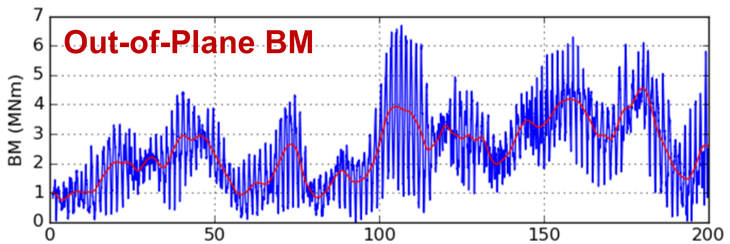
MAGNITUDE of **Average Horizontal Velocity over Rotor Disk**

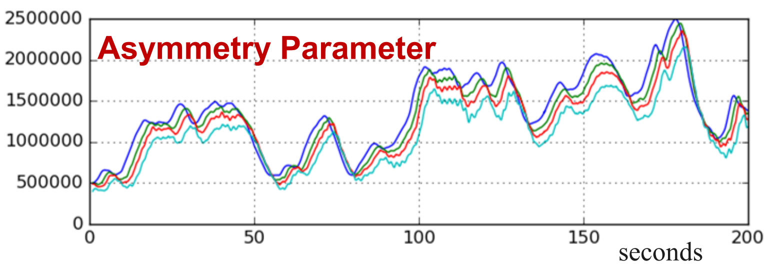


Torque on main shaft and **Power**

UNCORRELATED

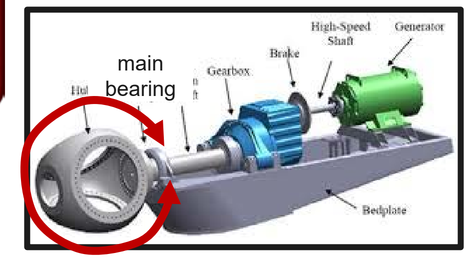
Nontorque Bending Moment on main shaft and **Forcing of Main Bearing**

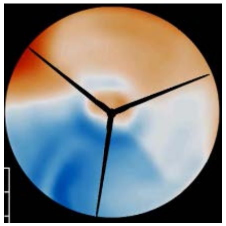




HIGHLY CORRELATED

corr.coeff. = 0.96



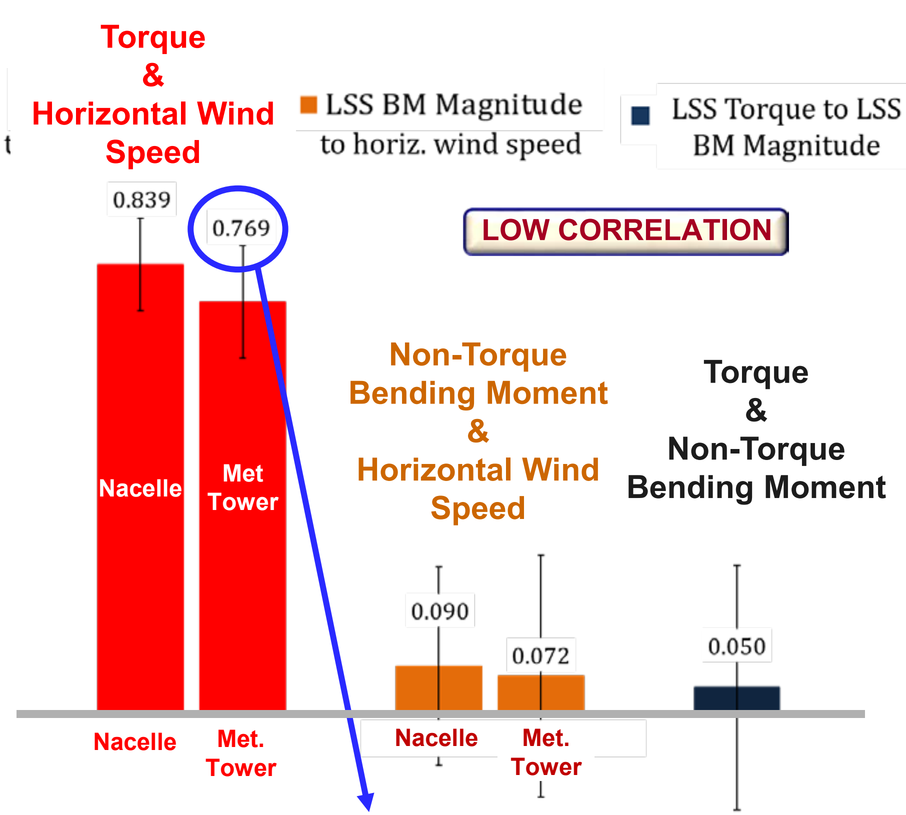


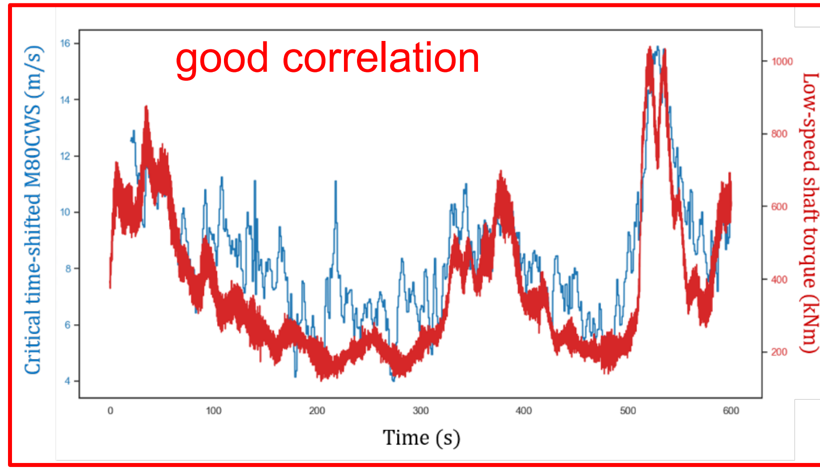
ASYMMETRY of **Velocity Distribution over Rotor Disk**

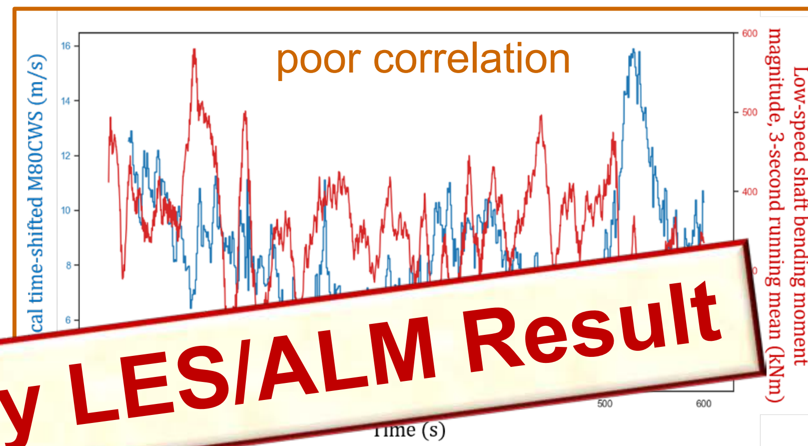
$$I_A = \iint_A r(y,z) \cdot \delta U_{xT} \, \mathrm{d}A$$

Result: Correlations between Time Variations in Main Shaft and Wind Anemometer on Met Tower

HIGH CORRELATION







correlation increases to 0.828
when wind

avely

⇒ Validates the Lavely LES/ALM Result

Conclusions

1. Lavely Thesis Simulation-based Analysis shows that:

(a) The passage of turbulence eddies creates very large fluctuations in all moments, torque and non-torque.

(b) Whereas time changes in torque correlate very strongly with fluctuations in horizontal wind speed within eddies, non-torque bending moments do not correlate with horizontal wind speed fluctuations.

... Instead, they correlate with the asymmetry of horizontal wind fluctuations over the rotor disk.

2. Analysis using westerly winds where mountain turbulent eddies pass from met tower to the NREL/GE wind turbine:

(a) Wind turbine response to eddy passage

(b) Met tower vs. nacelle anemometers

(c) Wind turbine response from mountain turbulence vs. atmospheric boundary layer turbulence

(d) Segregation of data.

Conclusions

3. Correlations are consistent with the LES results of Lavely & Brasseur:

- High correlation between main shaft torque and rotor-averaged horizontal wind velocity fluctuations
- Low correlation between main shaft torque and out-of-plane bending moment fluctuations
- Low correlation between main shaft bending moment and horizontal wind velocity fluctuations

Levelized Cost of Energy (LCOE)

$$\frac{\text{Investment} + \textbf{20-yr Operating Costs}}{\text{20-yr Energy Production}}$$

The aerodynamics mechanism that generates power (LCOE denominator) **is fundamentally different from the turbulence mechanisms that force the main bearing** (LCOE Numerator)

$\Rightarrow$ **Mitigation and control must be correspondingly different**

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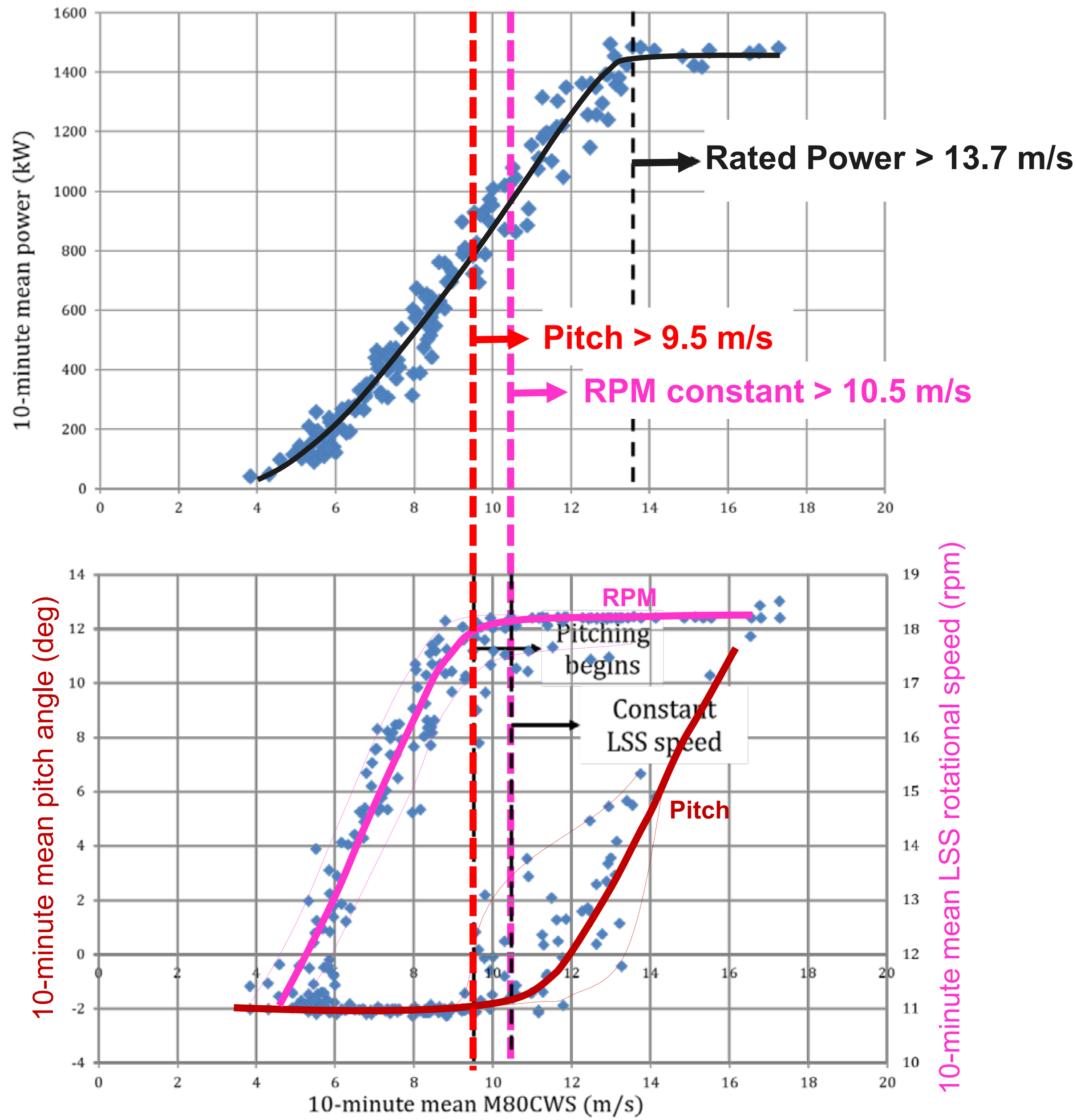
- **NSF XSEDE Program for HPC Resources**: for the large-eddy simulation results shown

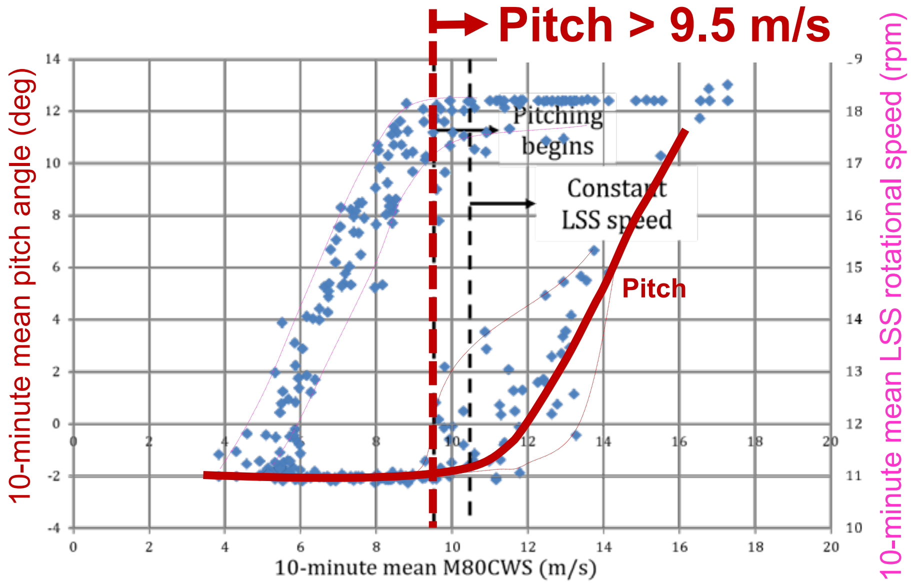
Extra Slides

Regimes for the NREL/GE 1.5 MW Turbine

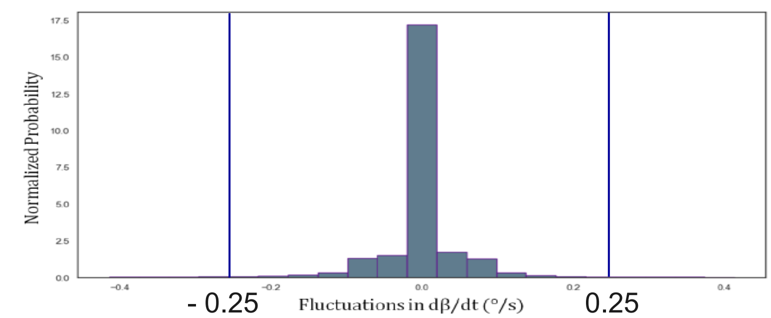
(all data)



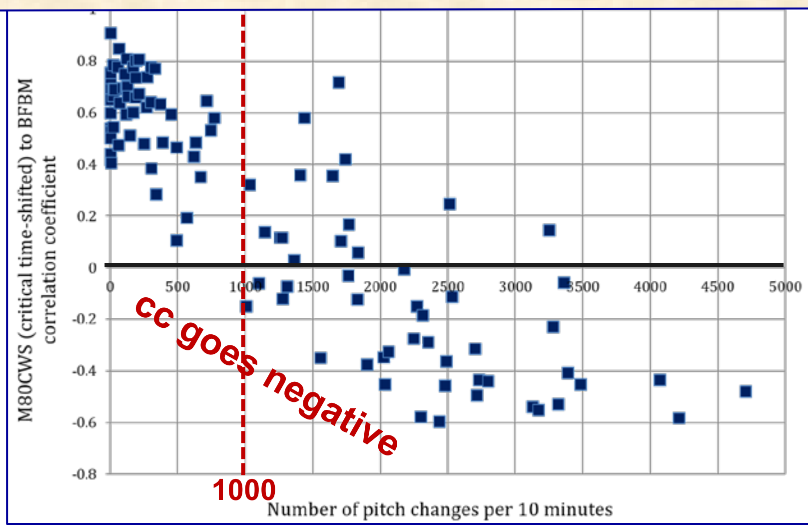
Reduction due to Pitch Events



A "pitch event": $\left|\frac{d\beta}{dt}\right| > 0.25\,\mathrm{deg}/s$



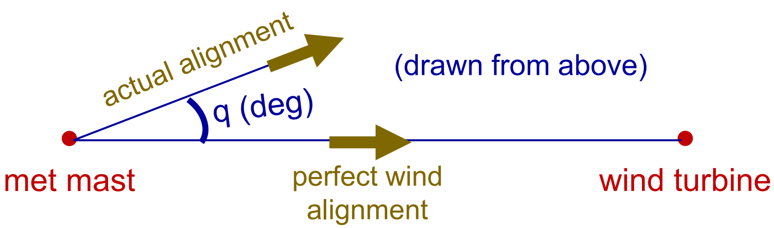
cc between wind speed and blade-flap-bending-moment
vs. no. pitch events in 10-minute period

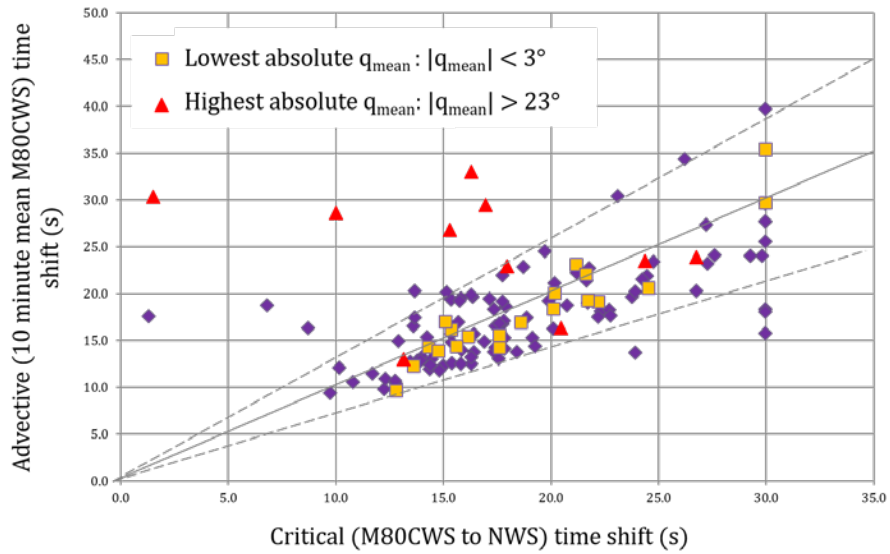


- **definition of a pitch event:** $\left|\frac{d\beta}{dt}\right| > 0.25\,\mathrm{deg}/s$
- **Criterion: Pitch changes in 10 min are < 1000**

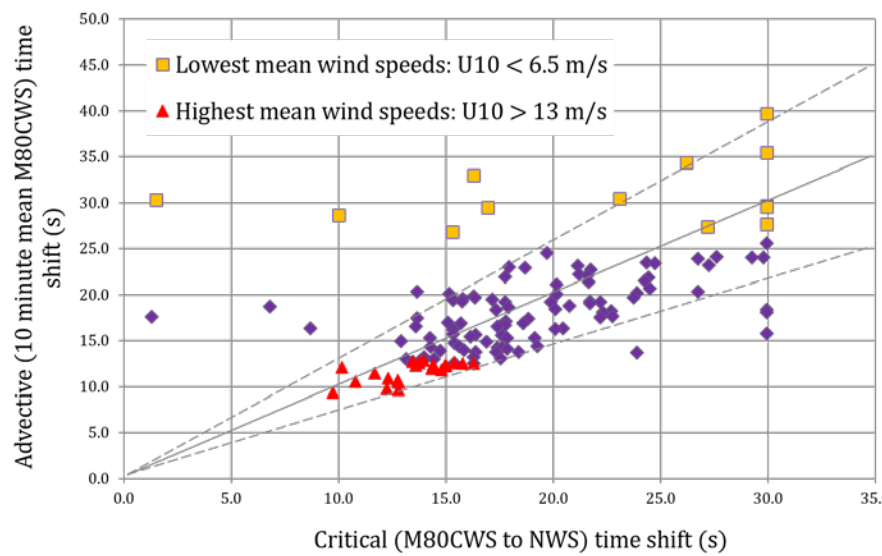
Reduction in Viable Datasets due to Likely Incorrect τ_{crit}

Misalignment in Wind Direction

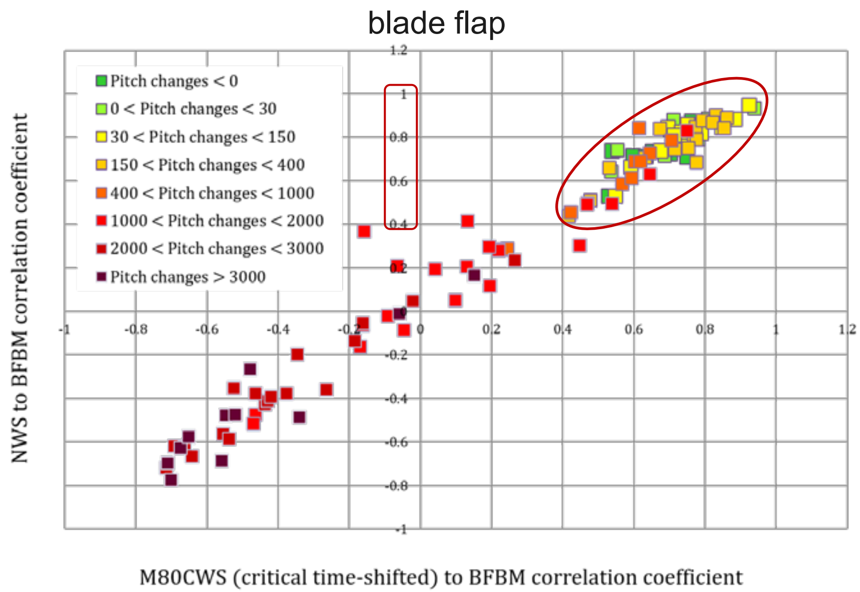


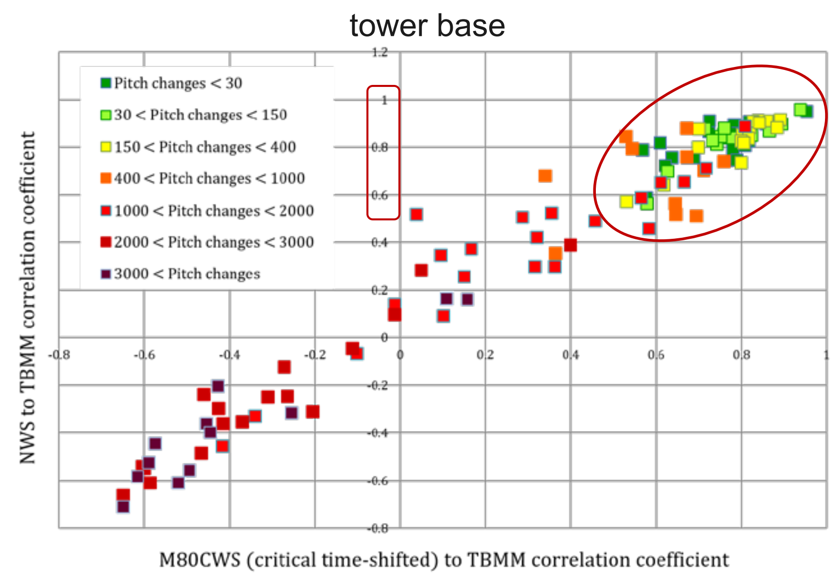


Too Low Wind Speed



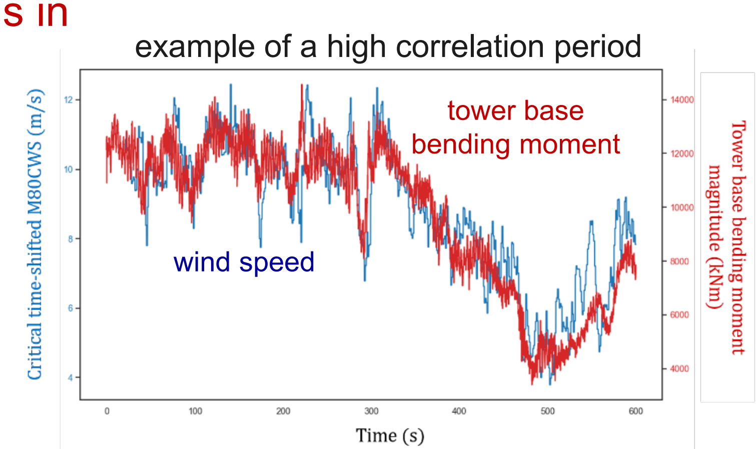
Result: Time-Correlations between WIND SPEED and BLADE ROOT and TOWER BASE Moments





Average Correlation Coefficients between time fluctuations in **THE WIND SPEED** at the met mast (shifted by τ_{crit}) and:

- **BLADE FLAP** Bending Moment: **0.614**
- **TOWER BASE** Bending Moment : **0.736**
- **BLADE EDGE** Bending Moment : **0.066**

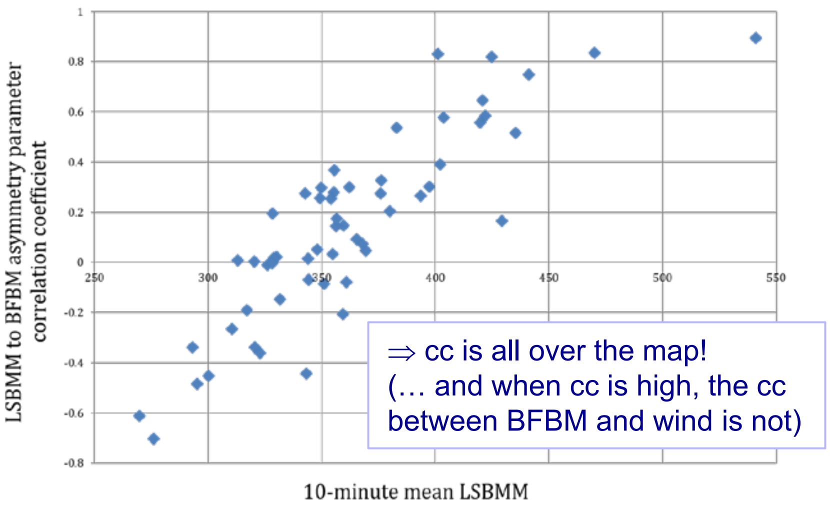


Insufficient Data for a Viable "Wind Asymmetry Parameter" (as per Lavely/Brasseur)

These wind-based parameters did not provide significant correlation:

1. Wind shear across the rotor (30-130 m)
2. Wind veer across the rotor (38-122 m)
3. Standard deviation of wind speed with height (30-130 m)
4. Mean vertical wind speed across the rotor (41-119 m)

"Blade Flap BM Asymmetry Parameter" - BFBM as a proxy for horizontal wind in a parameter similar to Lavely, but only over a circle on the rotor plane:



Conclusion: The available met tower wind data (6 pts along a vertical line) provides insufficient coverage to design an asymmetry parameter:
- the Lavely parameter requires azimuthal integrations over the rotor area.