Wind Energy Science Conference 2023

Glasgow, Scotland, 25 May 2023

Nonsteady Load Responses to Mountain-Generated Turbulence Eddies on the DOE 1.5 MW Wind Turbine at the National Wind Technology Center

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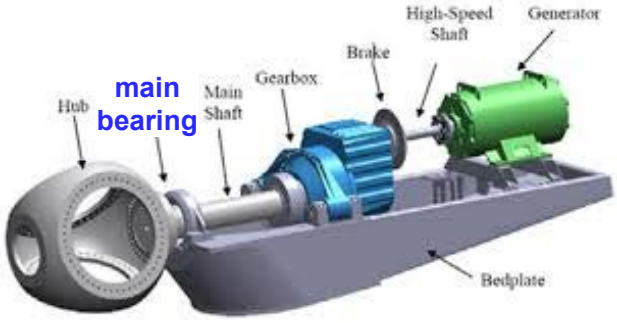
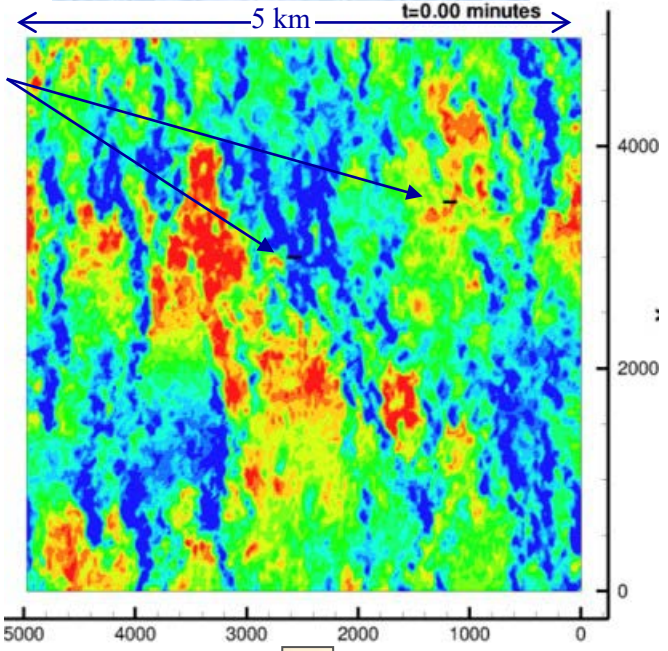
University of Strathclyde, Glasgow, Scotland

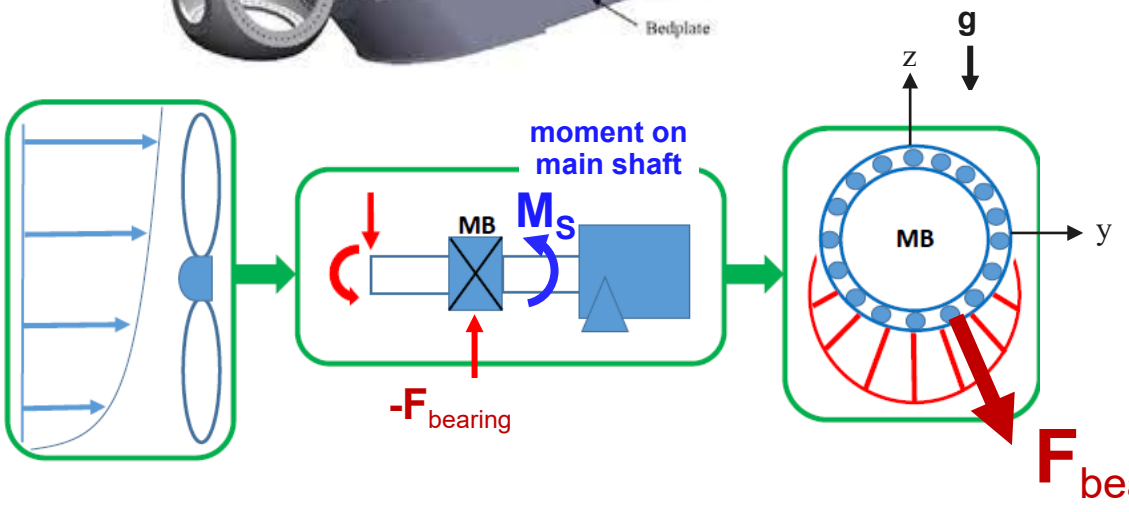
[3]National Renewable Energy Laboratory
Golden, Colorado, USA

Impacts of Nonsteady Load Response on Main Shaft Moments and Forcing of Main Bearing



daytime atmospheric turbulence





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

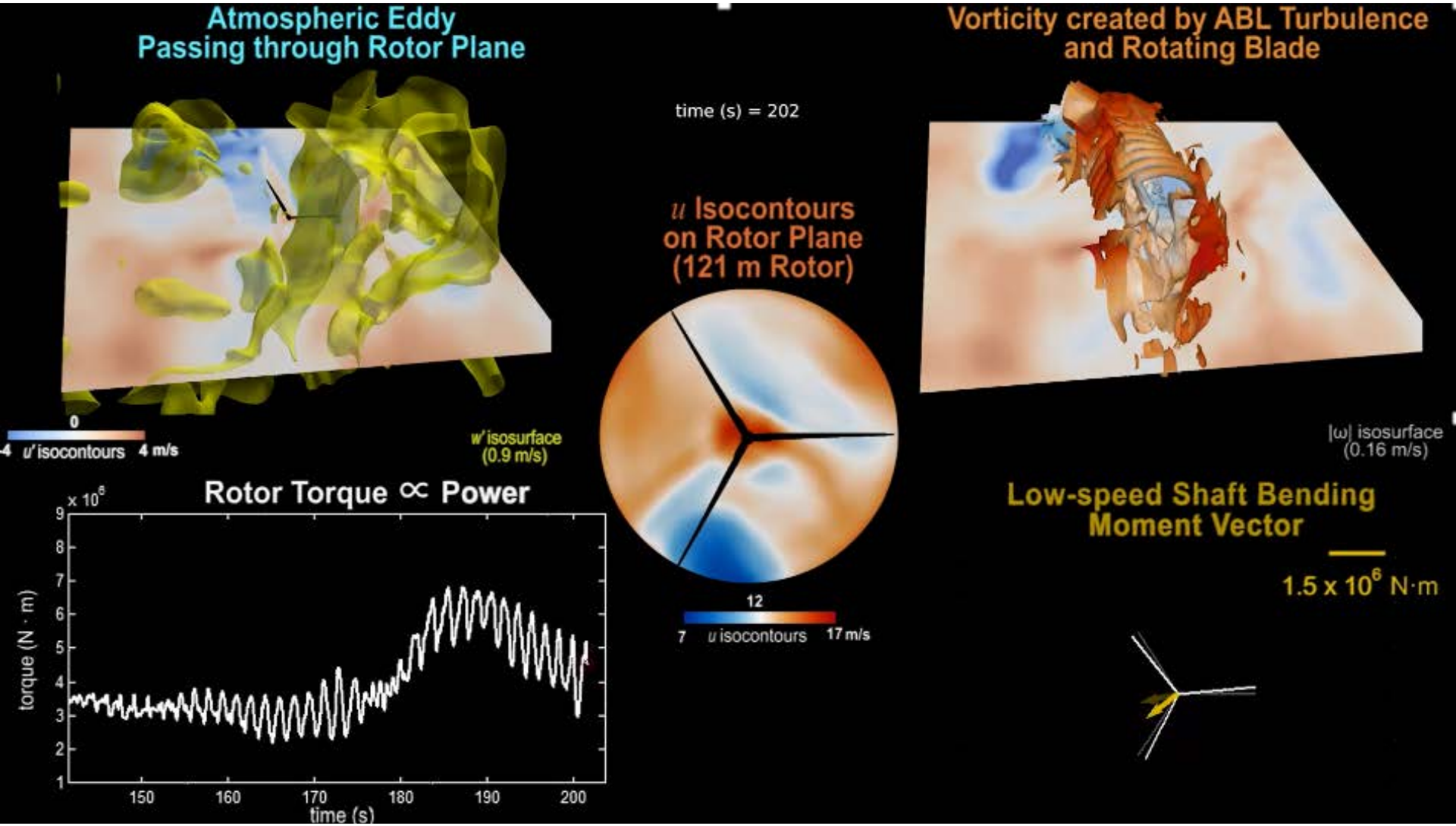
BEARING FORCE relative to rotor weight ← **MOMENT ON MAIN SHAFT**

TIME CHANGES IN NON-TORQUE MAIN SHAFT BENDING MOMENTS

… DRIVE TIME CHANGES IN FORCE ON MAIN BEARING

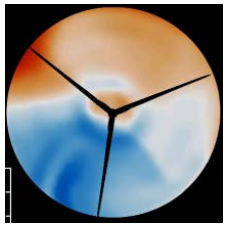
(Lavely, PhD Thesis, Penn State University, 2017)

Large-Eddy Simulation of the Interaction Between Turbulence Eddies in the Daytime Atmospheric Boundary Layer and the Rotor of the NREL 5 MW Wind Turbine (Actuator Line Model)

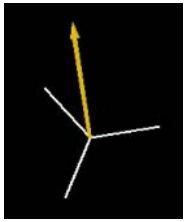


A Key Result: Temporal Variations in Torque vs. Non-Torque Bending Moments From Atmospheric Turbulence Eddies Are Uncorrelated

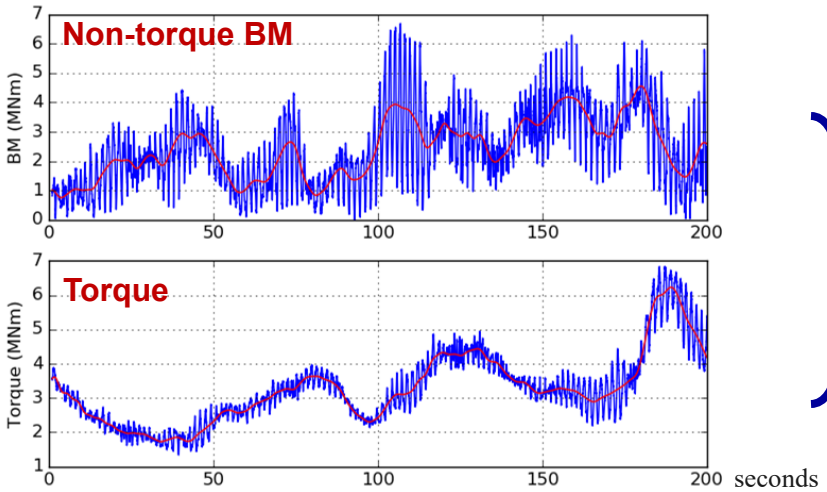
Wind Asymmetry



Bending Moment (BM)

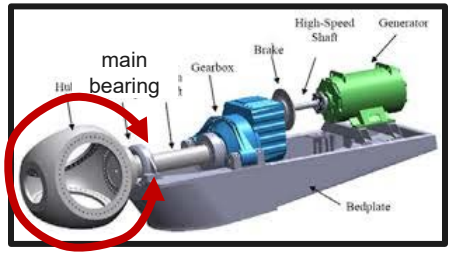


Based on large-eddy simulation of the daytime atmospheric boundary layer with embedded actuator line model of the NREL 5 MW wind turbine



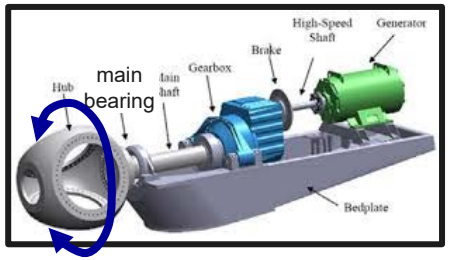
corr. coeff. = 0.06

Bending moment on main shaft



Lavely, Adam, PhD Thesis, Penn State, August 2017.

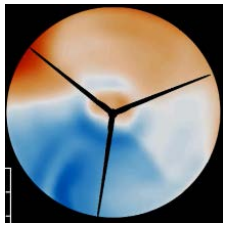
Torque on main shaft



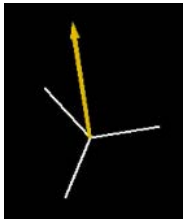
Lavely (2017):
large-eddy simulation (LES) with actuator line model (ALM)

A Key Result:
Torque and Thrust Variations Are Correlated With Rotor-Averaged Wind Speed

Wind Asymmetry

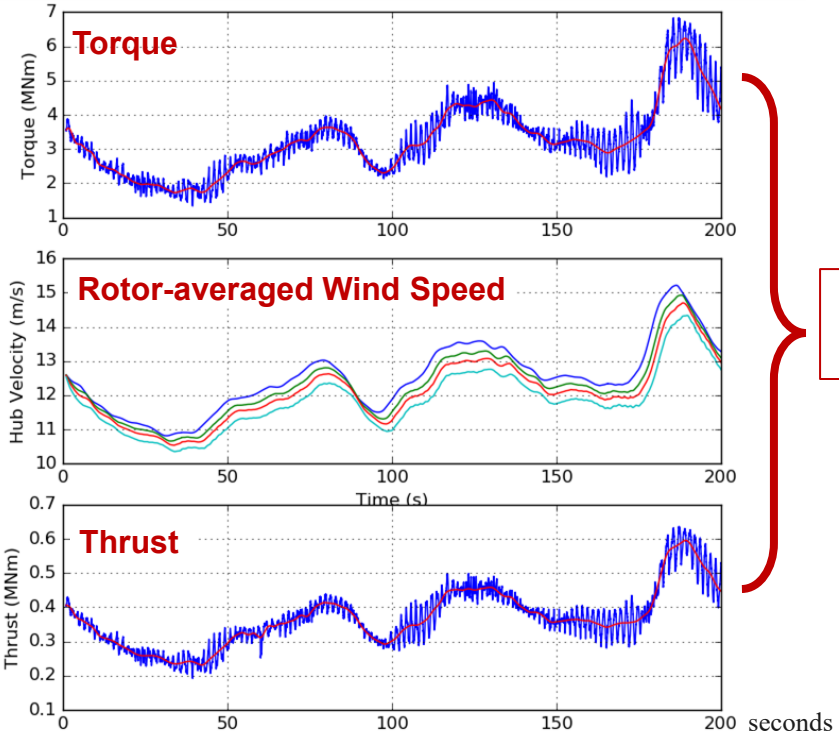


Bending Moment (BM)



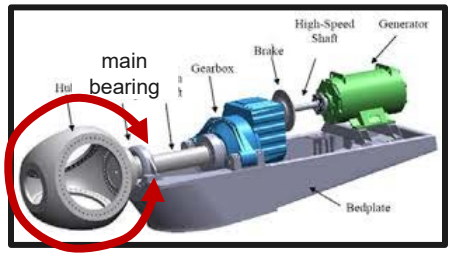
Based on large-eddy simulation of the daytime atmospheric boundary layer with embedded actuator line model of the NREL 5 MW wind turbine

Lavely (2017): LES with ALM



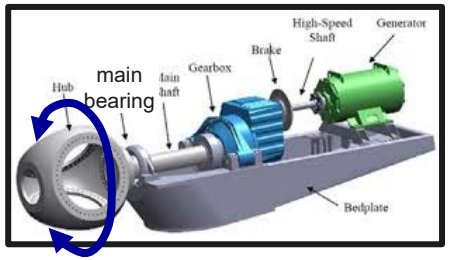
corr. coeff. = 0.96-0.98

Bending moment on main shaft



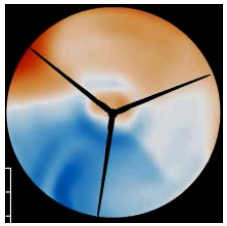
Lavely, Adam, PhD Thesis, Penn State, August 2017.

Torque on main shaft

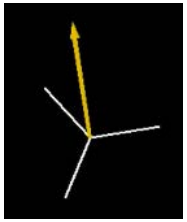


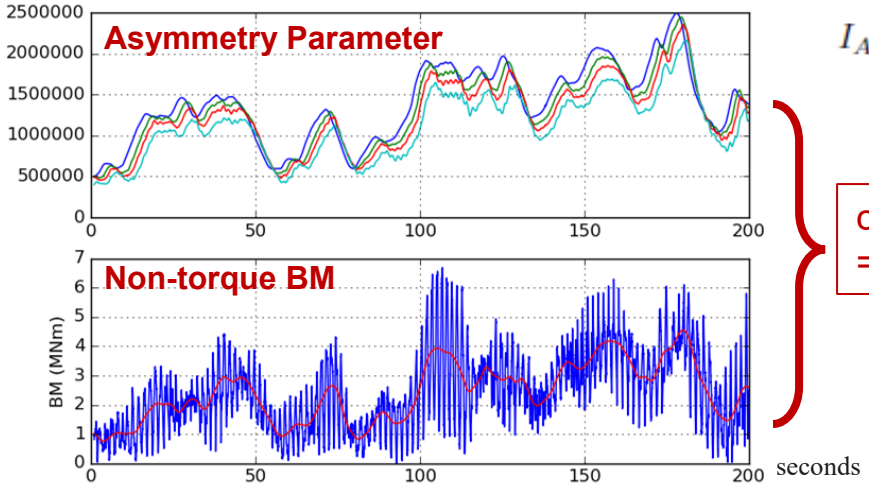
A Key Result: Non-Torque Out-of-Plane Bending Moment Variations Are Correlated With Wind Asymmetry Over Rotor Plane

Wind Asymmetry



Bending Moment (BM)

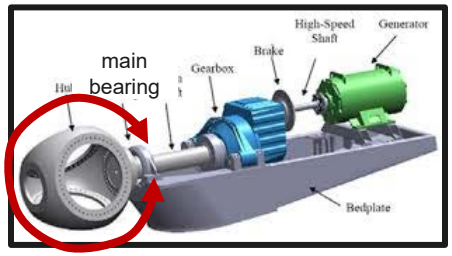




corr. coeff. = 0.96

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

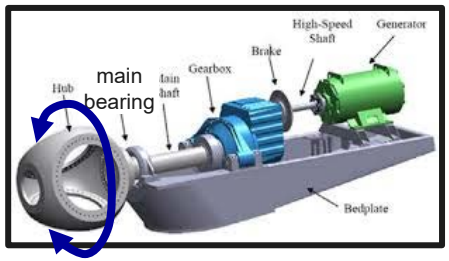
Bending moment on main shaft



Lavely, Adam, PhD Thesis, Penn State, August 2017.

Based on large-eddy simulation of the daytime atmospheric boundary layer with embedded actuator line model of the NREL 5 MW wind turbine

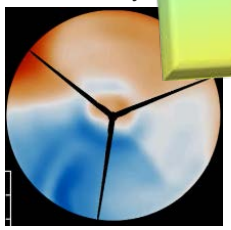
Torque on main shaft



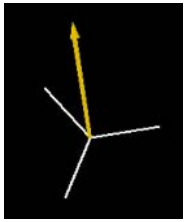
Lavely (2017): LES with ALM

Analyzing the Key Result With Field Analysis of the Interactions Between the NREL/GE 1.5 MW Wind Turbine and Mountain-Generated Turbulence Eddies

Wind Asym



Bending Moment (BM)



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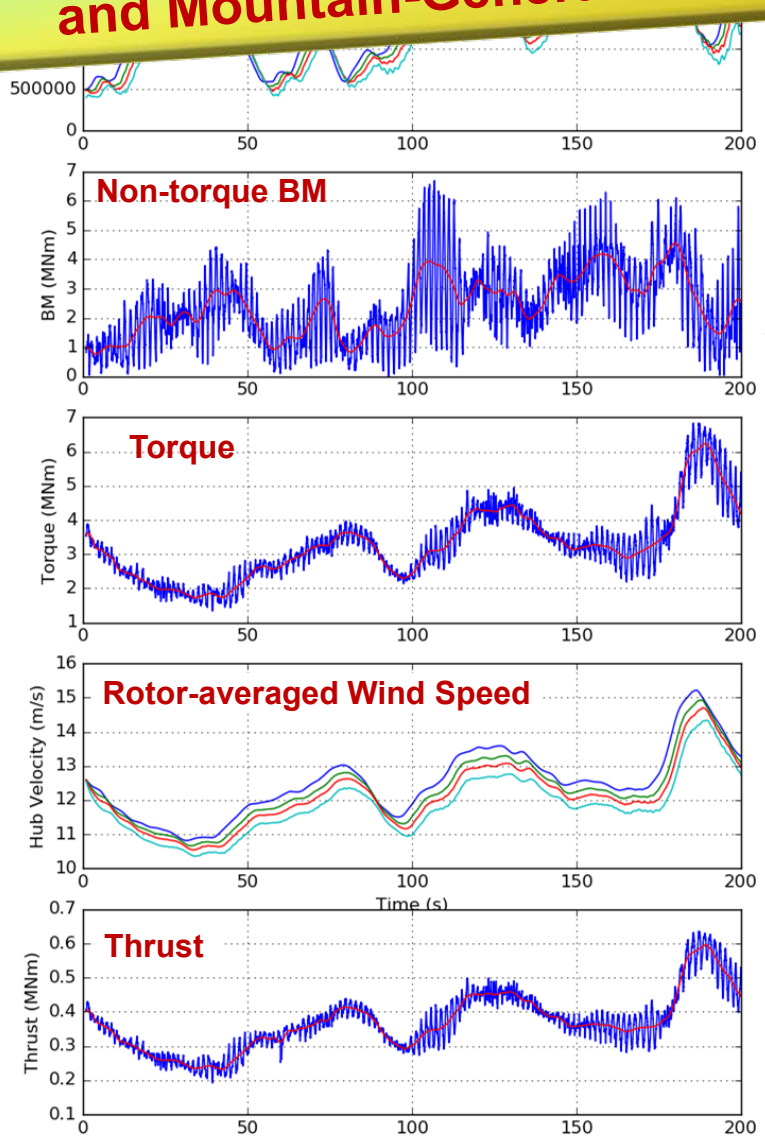
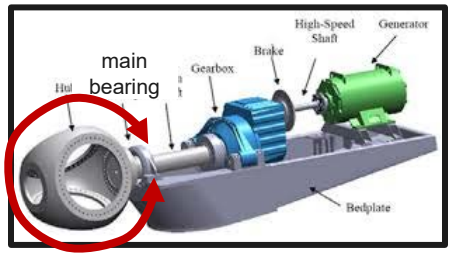


corr. coeff. = 0.96

corr. coeff. = 0.06

corr. coeff. = 0.96-0.98

Bending moment on main shaft



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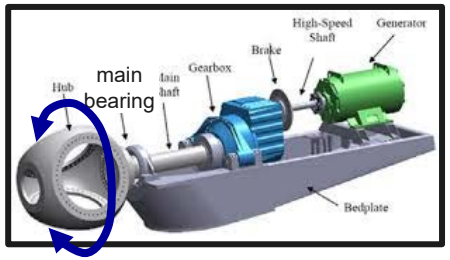
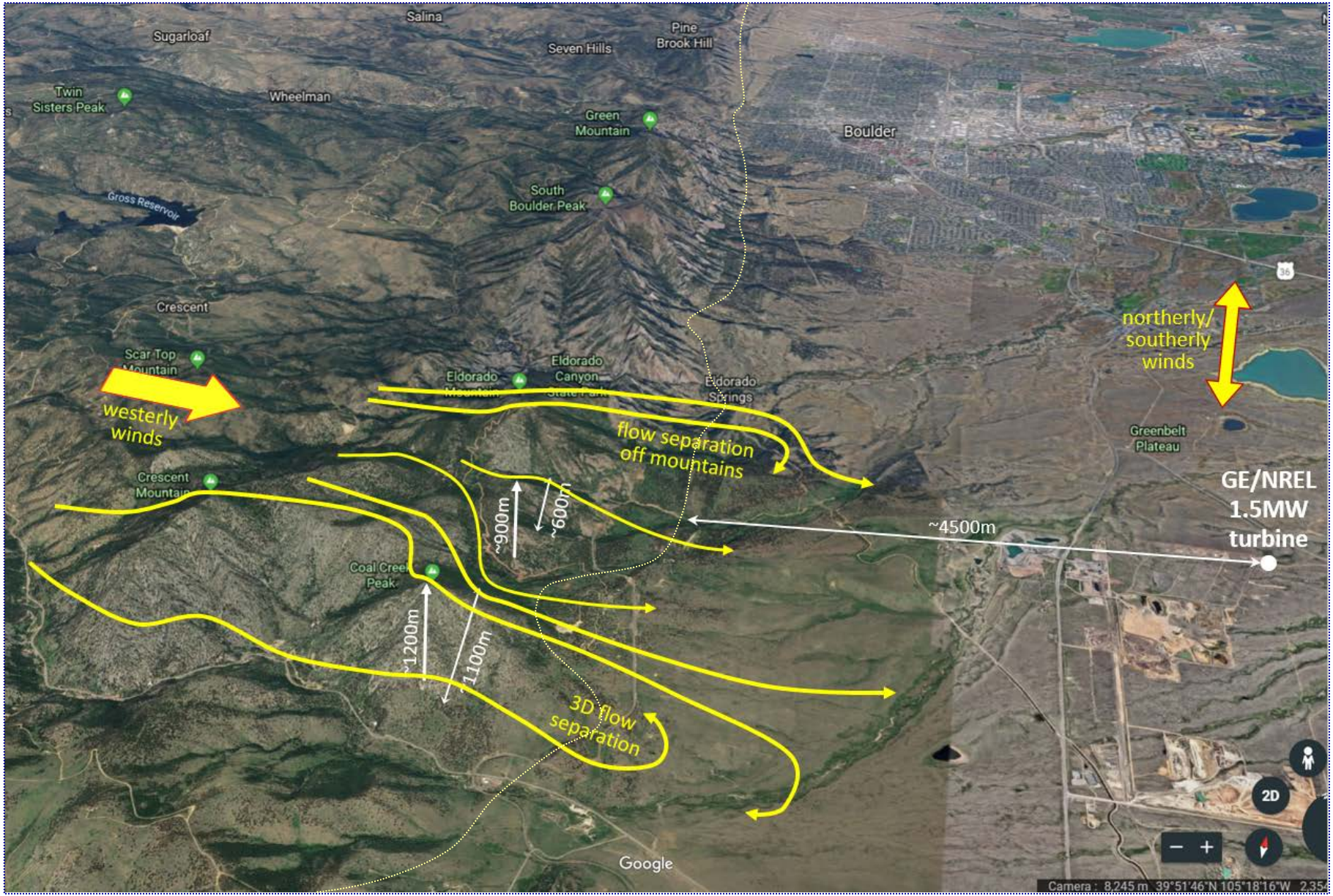
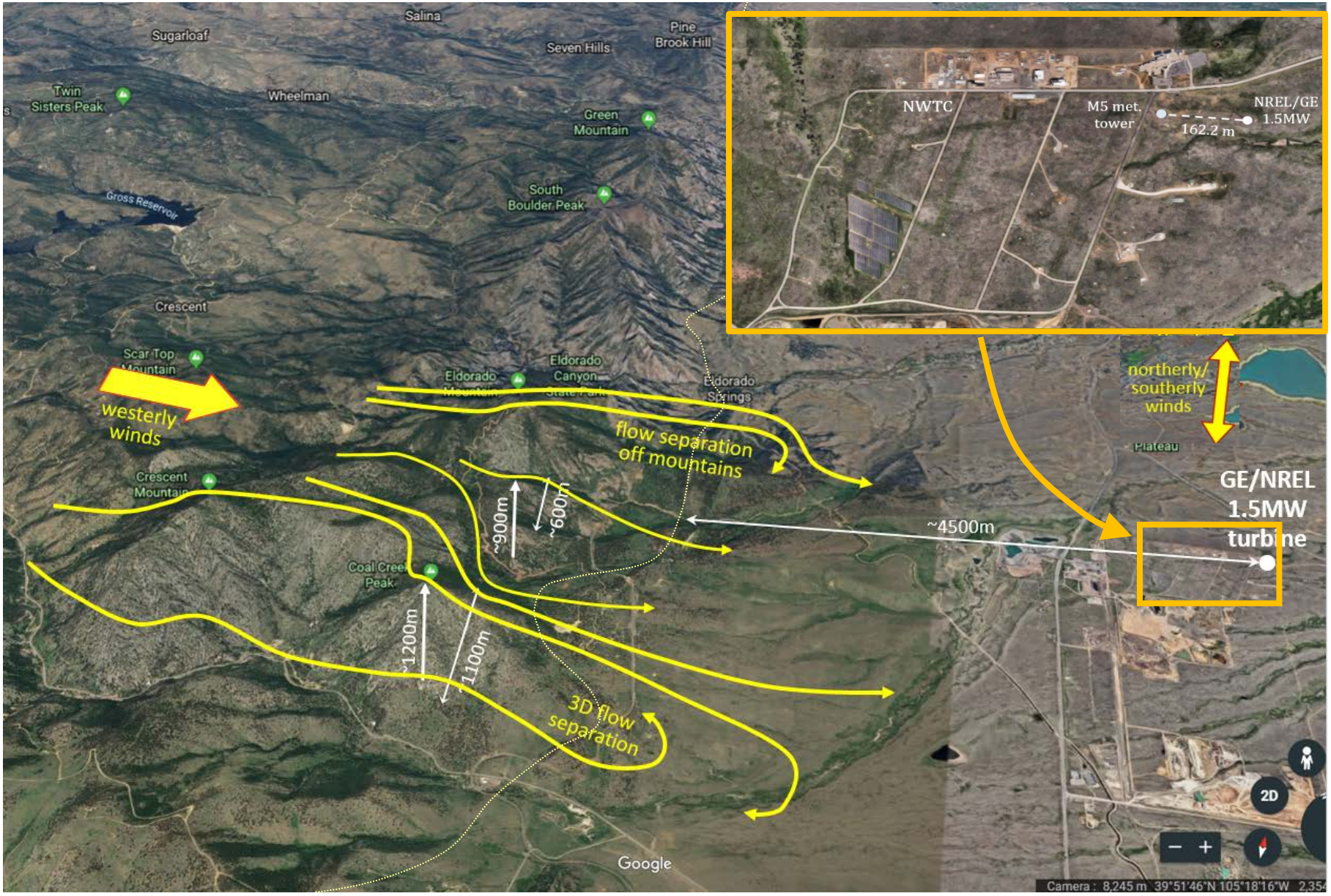
Torque on main shaft



The GE/NREL Wind Turbine Relative to the "Front Range" of the Rocky Mountains

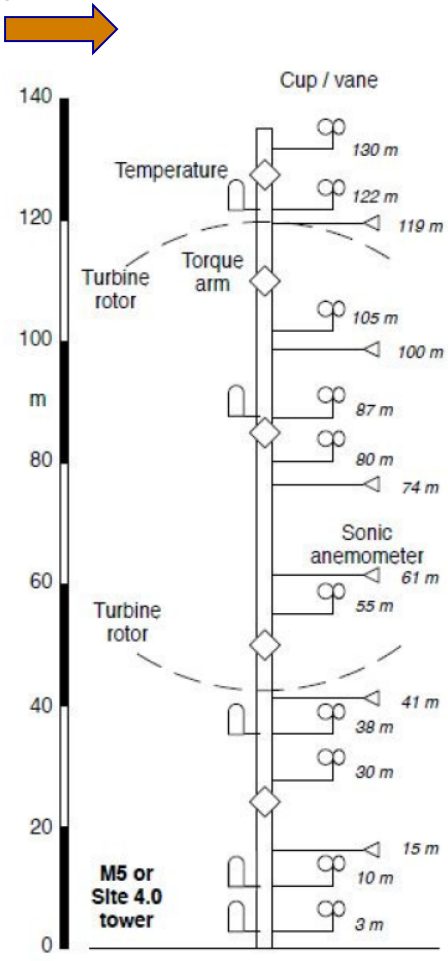


The Site: The NREL Wind Site and Met Tower Relative to the Front Range of the Rocky Mountains

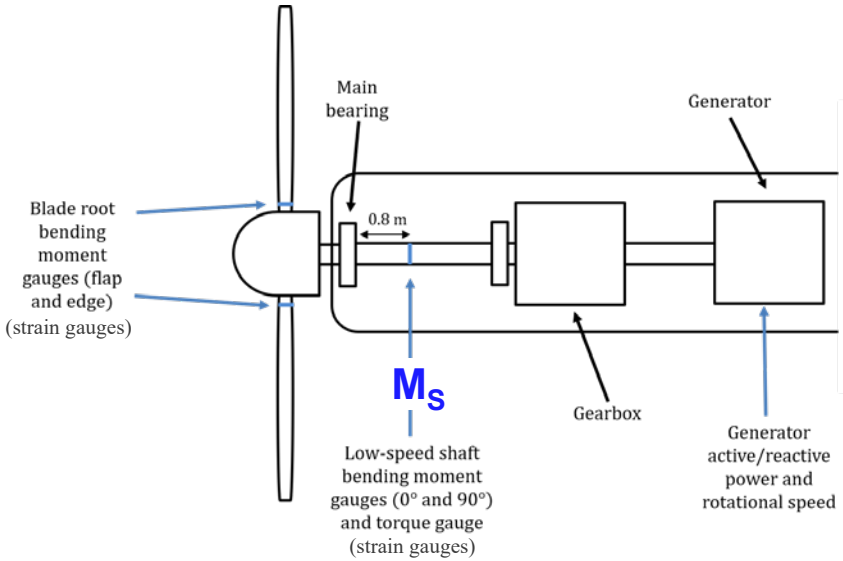


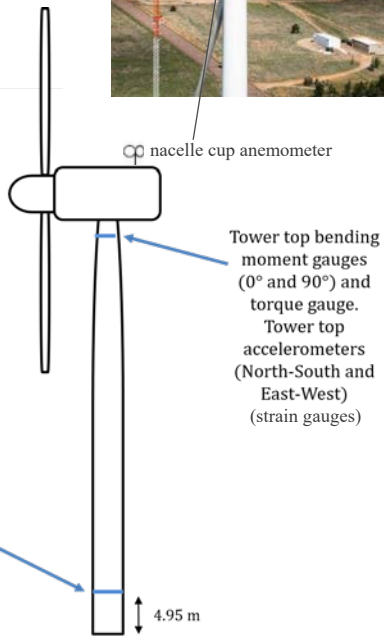
Met Tower and NREL/GE Wind Turbine Instrumentation

Westerly winds carrying mountain eddies



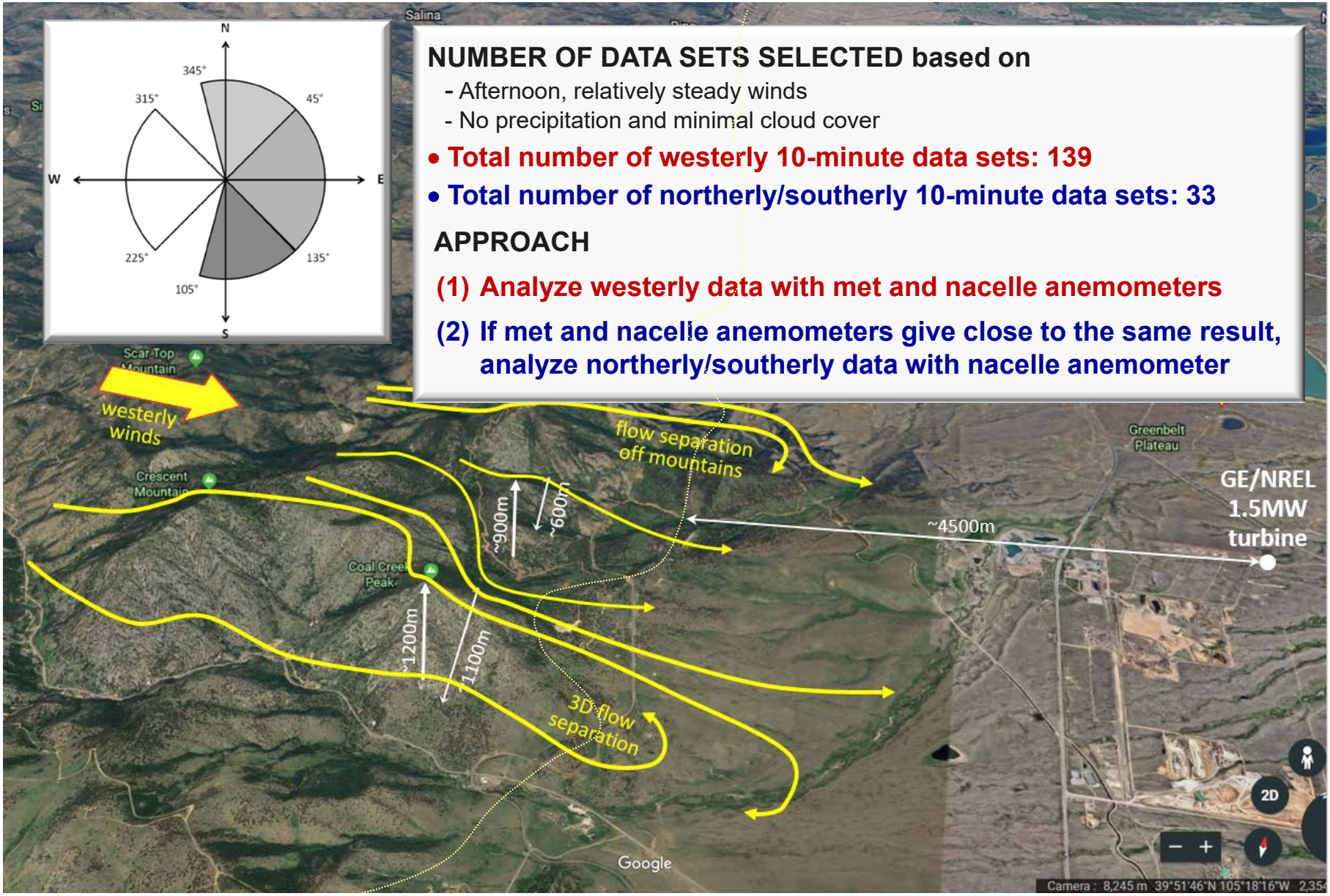
$$\mathbf{F}_{bearing} - \mathbf{W}_{rotor} = \frac{1}{L}\left(M_{S_z}\mathbf{e}_y + M_{S_y}\mathbf{e}_z\right)$$



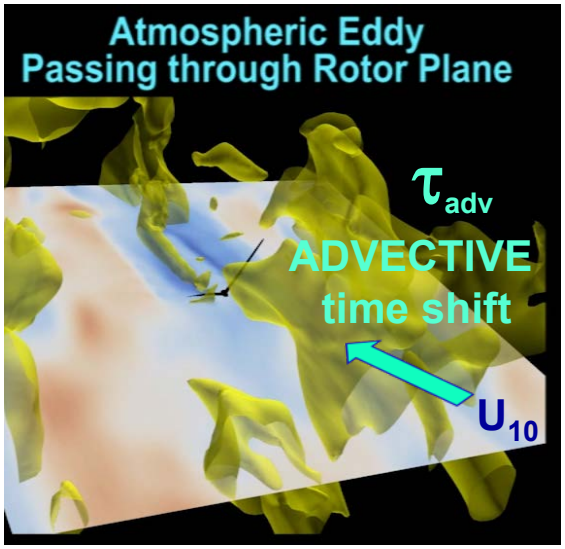


162.2 m

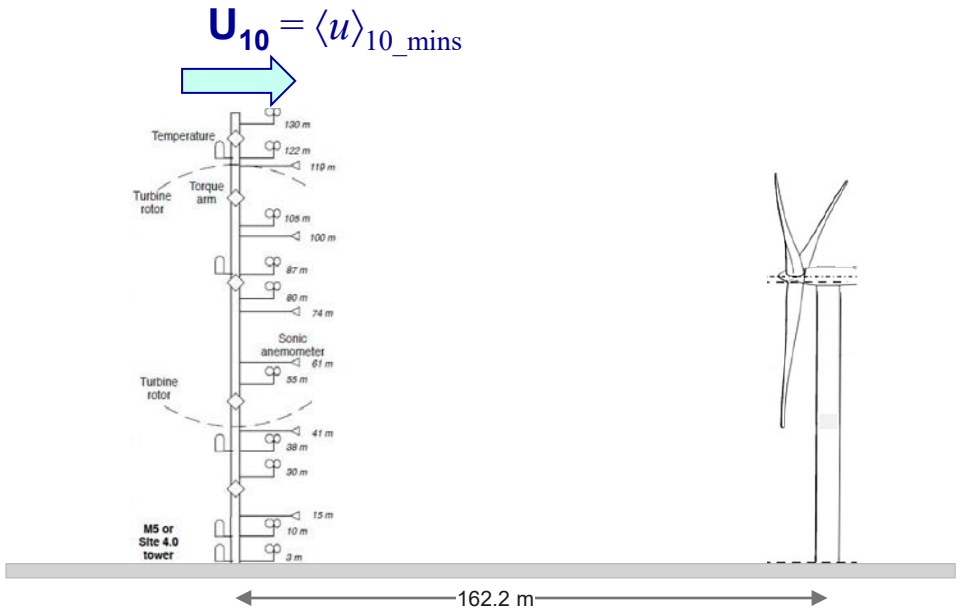
The 10-Minute Data Sets From the Wind Turbine



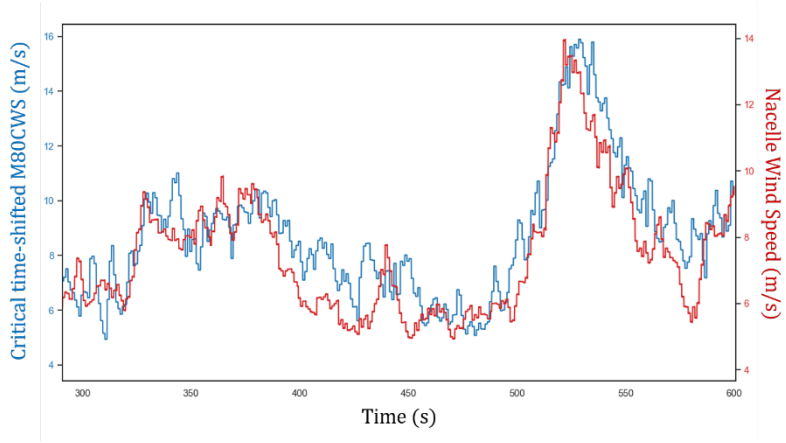
Identification of Turbulence Eddies as Advected Signal From Met Mast to Turbine

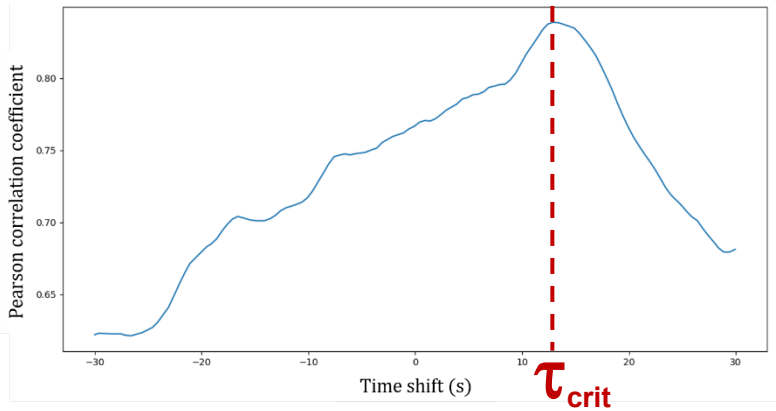


From a movie of ABL turbulence-rotor interactions using the Lavely large-eddy simulations



CRITICAL time shift





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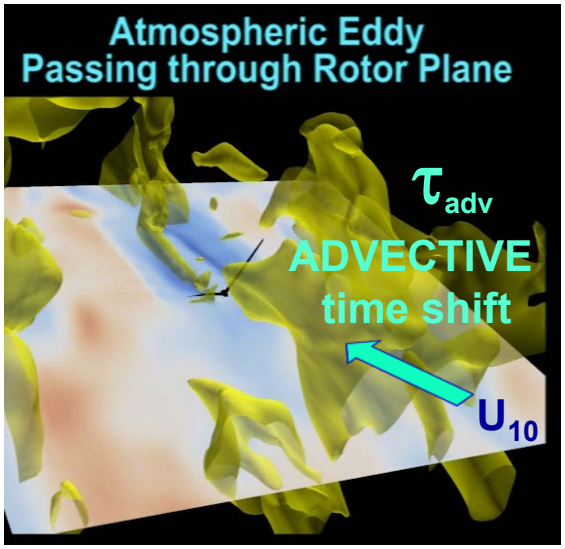
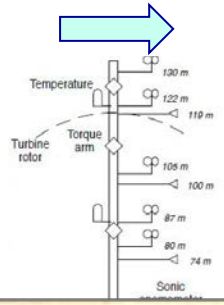


From a movie of ABL turbulence-rotor interactions using the Lavely large-eddy simulations

$U_{10} = \langle u \rangle_{10\_mins}$

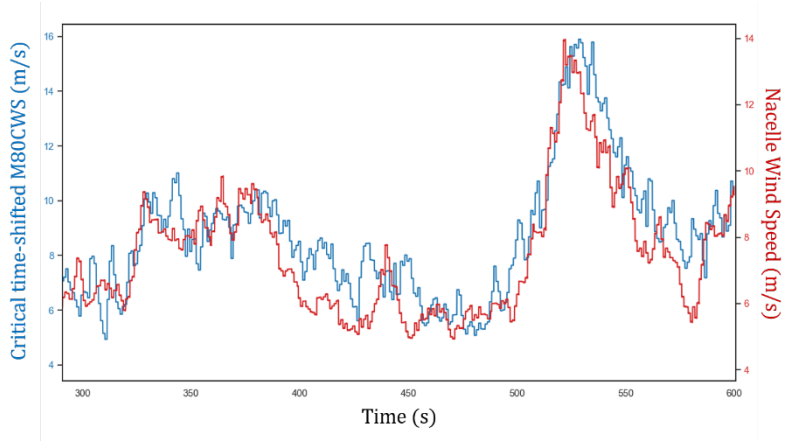


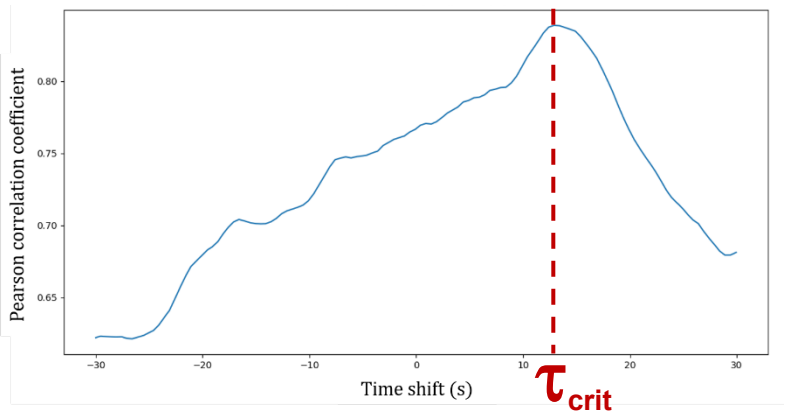
If Advection Time = Critical Time Shift

⇒ **suggests that a turbulence eddy is carrying the fluctuation to the turbine**

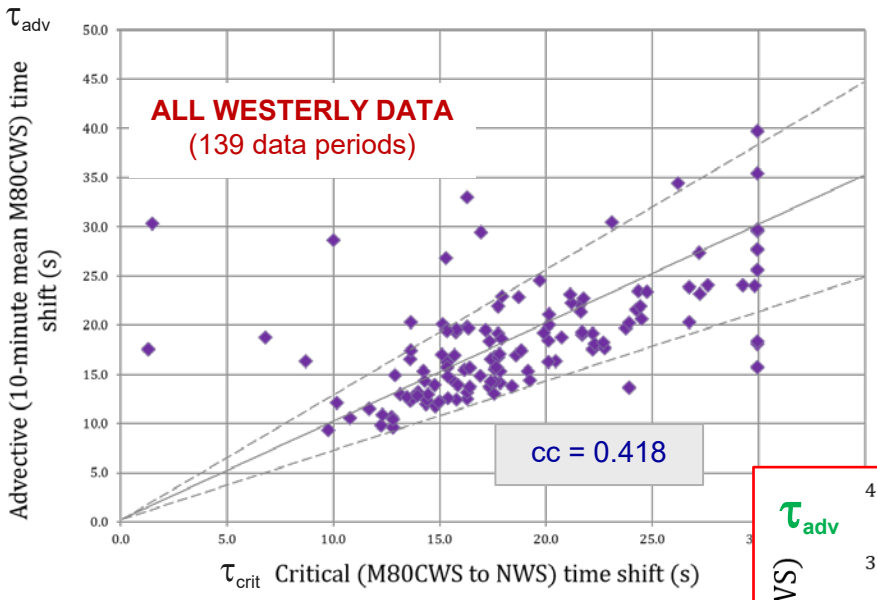
162.2 m

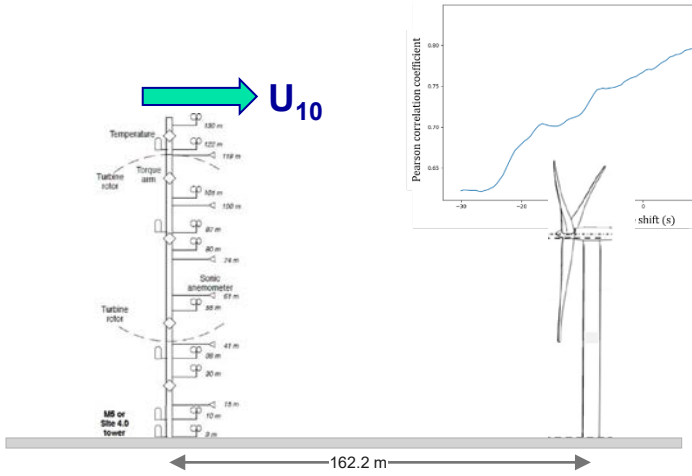
CRITICAL time shift





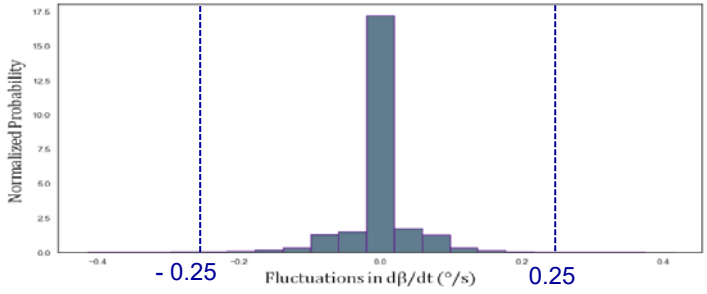
Full Segregation of Data

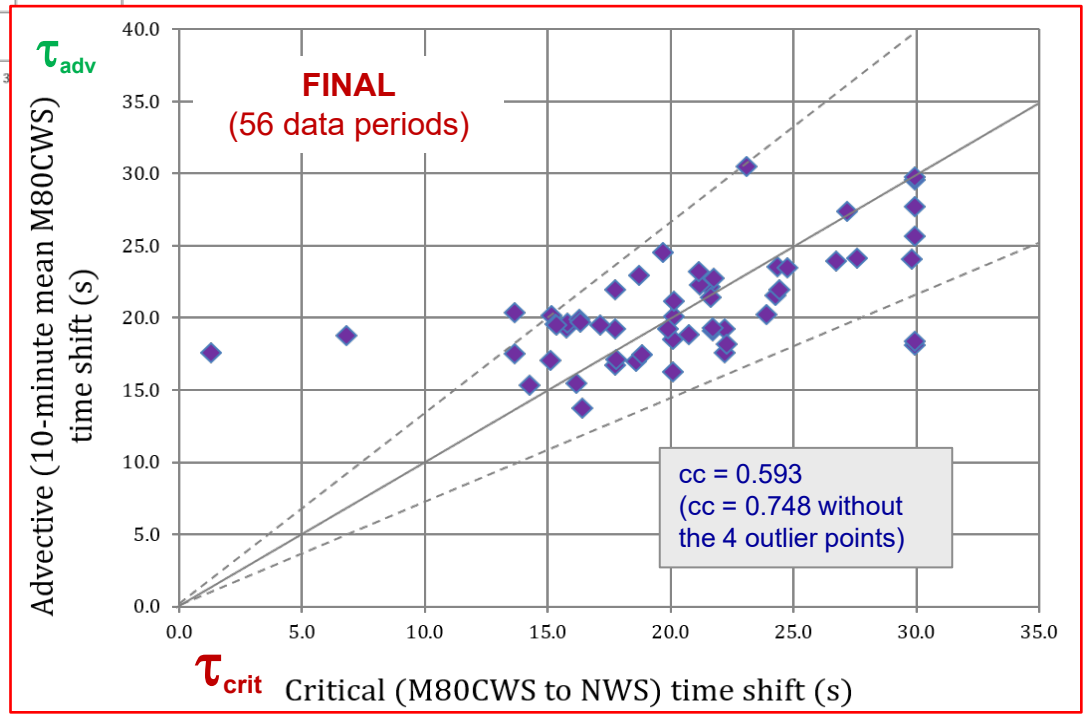




Data Segregation:

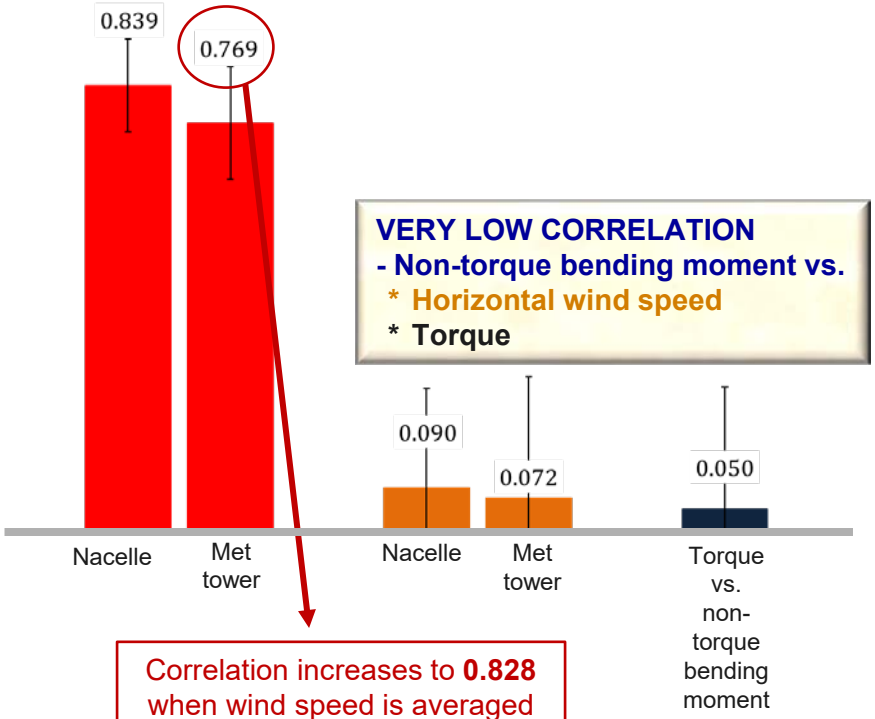
1. Misalignment in wind direction
2. Low wind speed
3. Too many "pitch events"





Key Correlations Quantified

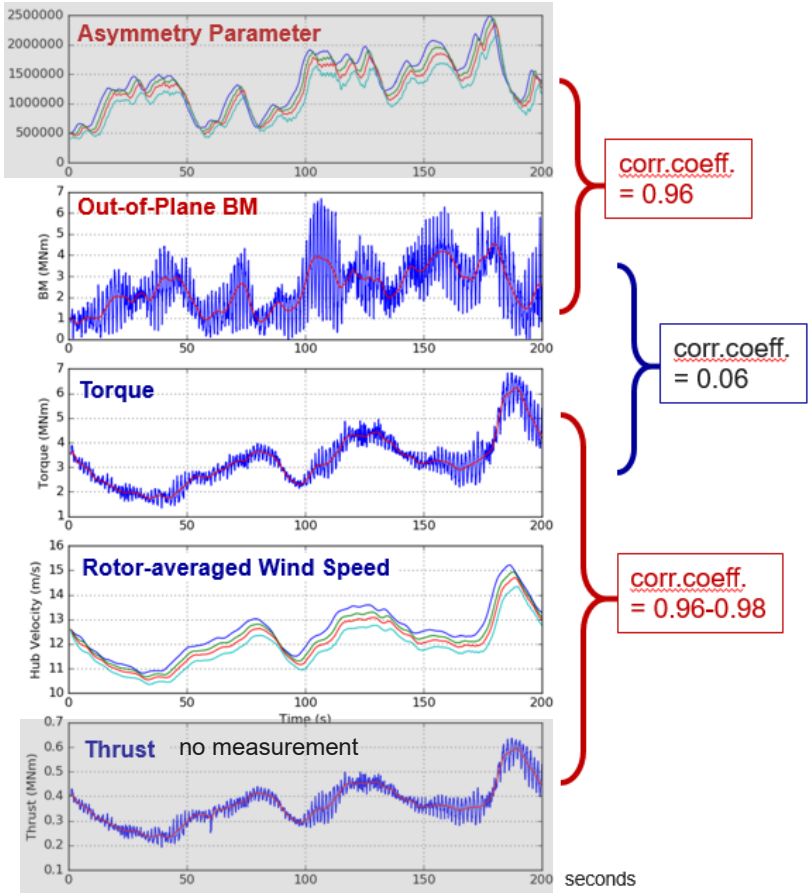
VERY HIGH CORRELATION
- Torque vs.
*** Horizontal wind speed**



VERY LOW CORRELATION
- Non-torque bending moment vs.
*** Horizontal wind speed**
*** Torque**

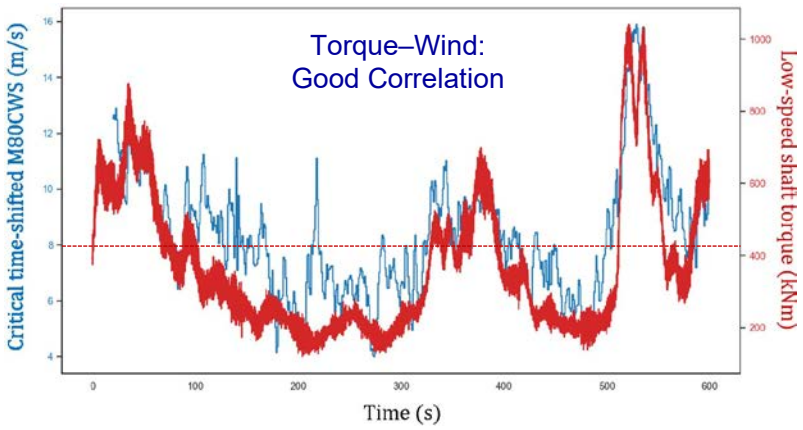
Correlation increases to **0.828** when wind speed is averaged over anemometers covering the rotor, as per Lavely (2017).

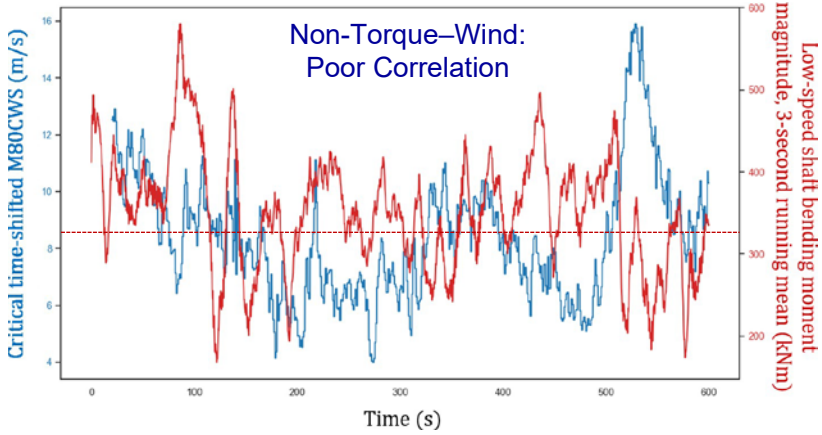
Insufficient data to develop a corresponding experimental "asymmetry parameter."



⇒ Consistent with Lavely/Brasseur result

Other Interesting Results





	Average TORQUE	Average NON-TORQUE	% DIFFERENCE
1.5 MW, 600 s Field Data Mtn Eddies	430 kN·m	325 kN·m	28% difference
5 MW, 200 s LES/ALM Daytime Atmos. Eddies	3,300 kN·m	2,250 kN·m	38% difference

Conclusions:

- The mean of the out-of-plane bending moment is of the same order as the mean of the torque required for power.
- The peak-to-peak variations in the out-of-plane bending moment are higher.

⇒ The moments that force the main bearing are as large (or larger than) the moment that generates power.

Additional correlations between **wind speed** and

- **Blade flap** bending moment: 0.614
- **Blade edge** bending moment : 0.066
- **Tower base** bending moment : 0.736

Conclusions

1. **Lavely/Brasseur analysis of LES with ALM shows that:**
   - Turbulence eddy passages create large fluctuations in all moments.
   - Time changes in **torque correlate strongly with horizontal wind speed variations** within eddies.
   - Time changes in **non-torque bending moments** are uncorrelated with horizontal wind speed fluctuations but **correlate with the asymmetry of horizontal wind fluctuations over the rotor disk.**

   $\Rightarrow$ The mechanisms underlying torque fluctuations (power) and out-of-plane bending moments (forcing main bearing) are fundamentally different.

2. **Identification of 10-minute periods where mountain eddies pass from met tower to NREL/GE 1.5 MW wind turbine:**
   - Removal of data periods with poor alignment and too-low winds
   - Removal of data periods where pitch interferes with load correlations.

Conclusions

3. **Correlations from field data analysis are consistent with LES/ALM:**
   - **High correlation between main shaft torque** and
     - rotor-averaged horizontal wind velocity fluctuations
   - **Low correlation between main shaft torque** and
     - non-torque bending moment fluctuations
     - horizontal wind velocity fluctuations.
4. **Impact of turbulence eddies on non-torque bending moment fluctuations are on the order of the impact on torque fluctuations.**
5. **Same results with the nacelle anemometer (not shown).**

The Combined Simulation and Field Analysis Potential Importance of the Passage of Atmospheric Turbulence Eddies to Main Bearing Function and Failures

Acknowledgments

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