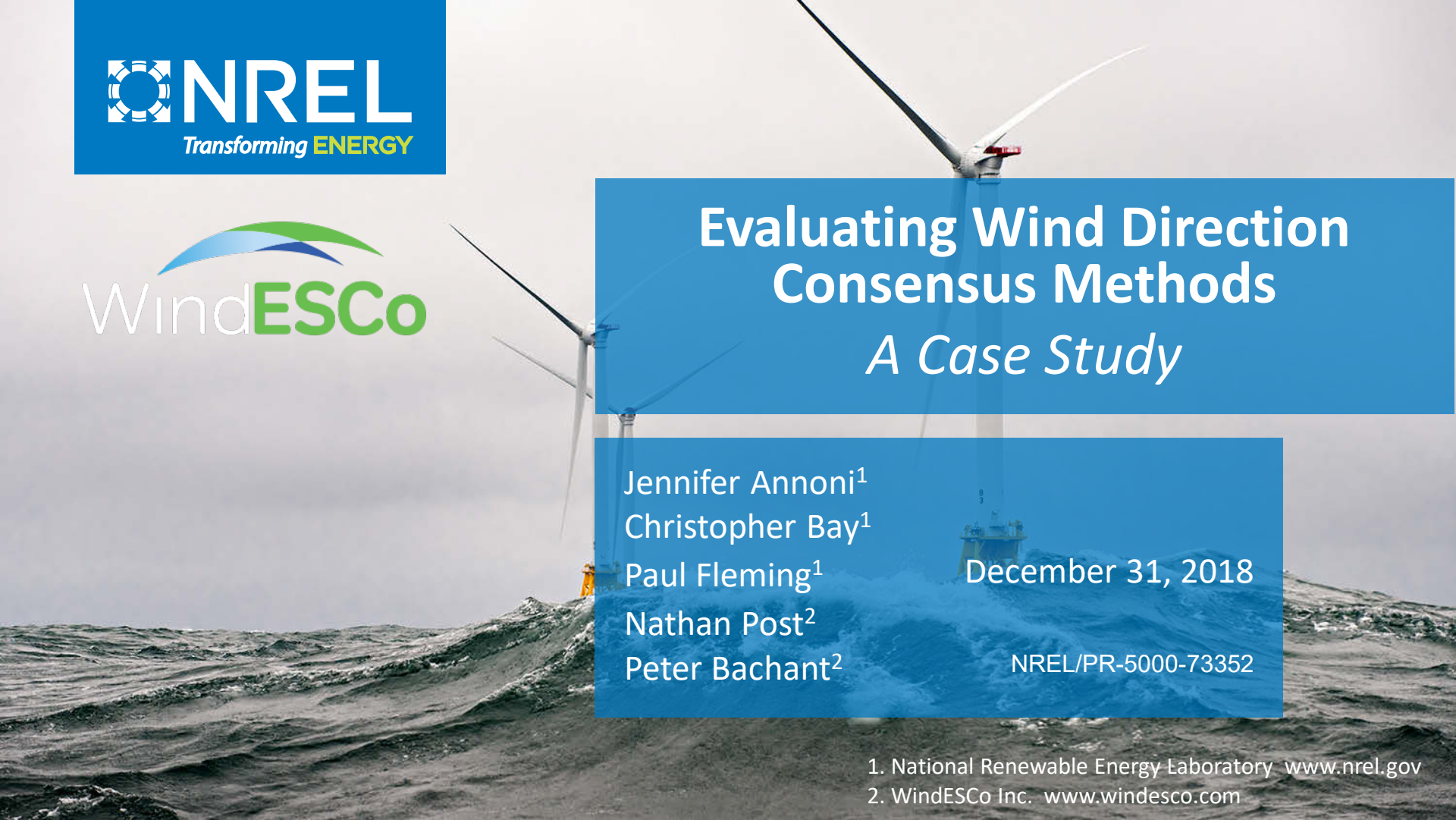

Evaluating Wind Direction Consensus Methods

A Case Study

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Paul Fleming[1]
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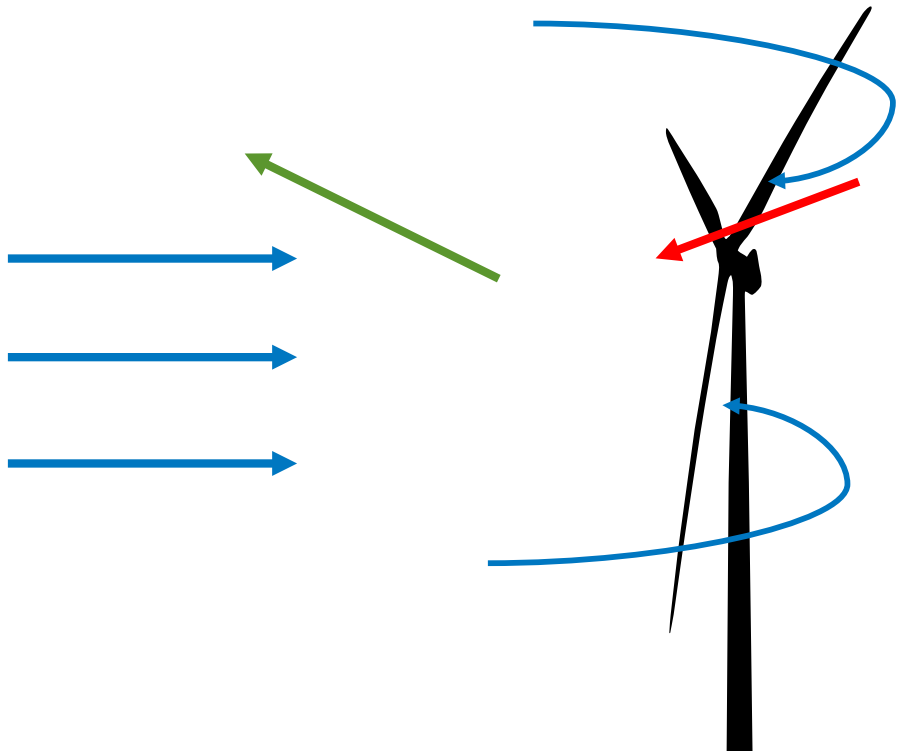
December 31, 2018

NREL/PR-5000-73352

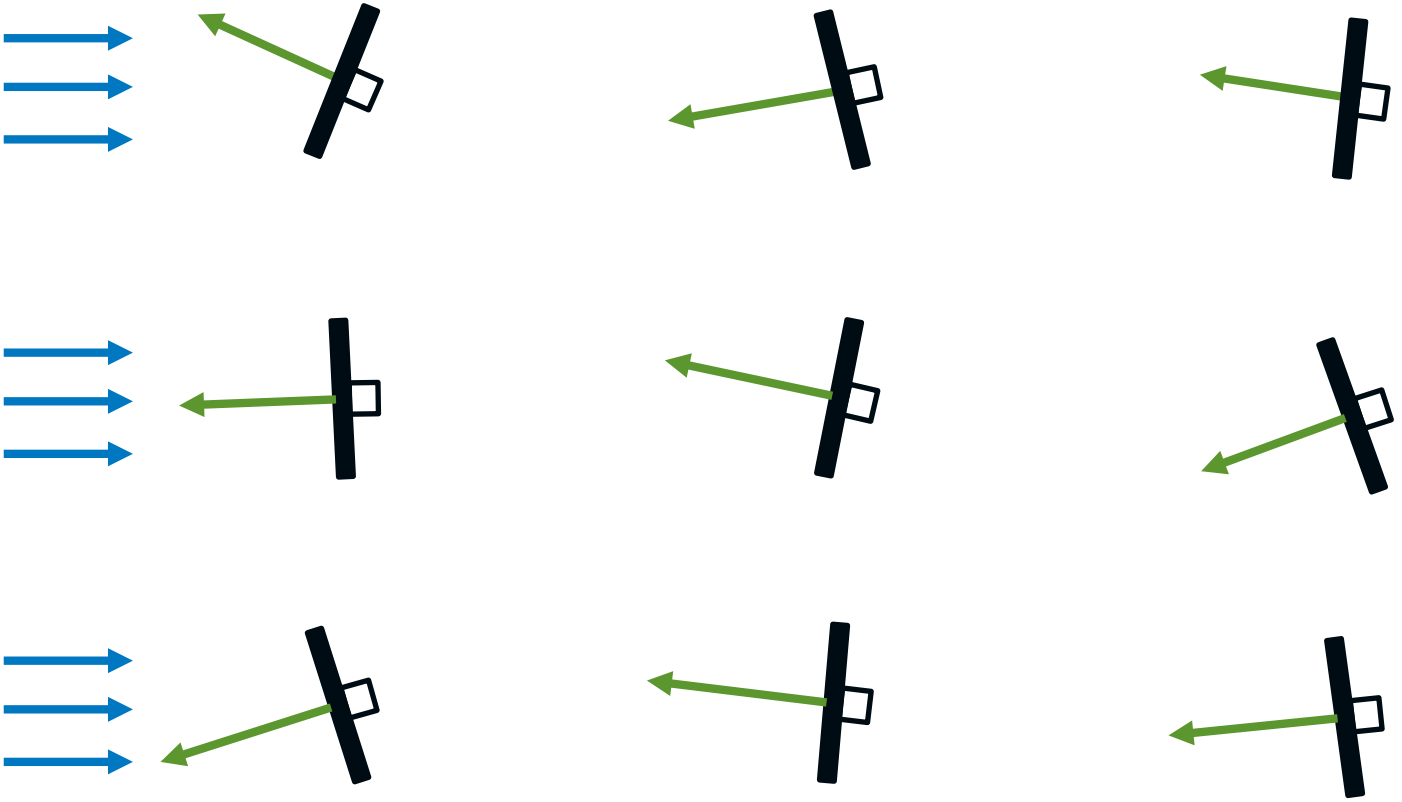
1. National Renewable Energy Laboratory www.nrel.gov
2. WindESCo Inc. www.windesco.com

Typical Wind Turbine Operation

- Turbines operate individually, optimizing their own performance
- Yaw position is determined by a wind direction sensor on the back of the nacelle
- This sensor is often noisy and can lead to yaw misalignment of the turbine.



Misalignment Can Occur Across the Wind Farm



Is there a better way?

Optimizing Nacelle Direction

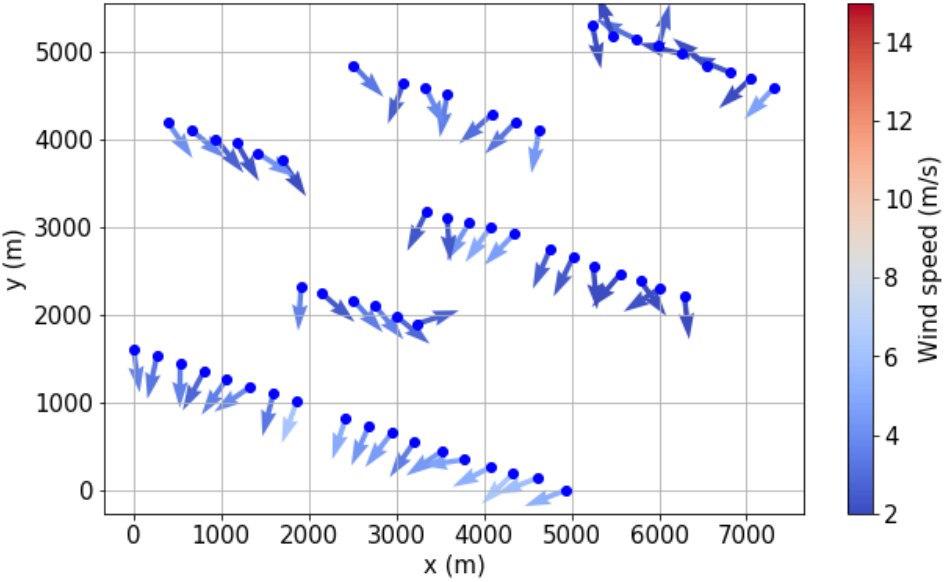
- Objectives:
  - Adjust nacelle direction to **maximize power production**
  - **Minimize wear and tear on yaw drives** by eliminating unnecessary yaw events
  - Explore different data rates to determine optimum filtering and system response time.
- Wind direction consensus theory was developed by the National Renewable Energy Laboratory
  - "A Framework for Autonomous Wind Farms: Wind Direction Consensus", Annoni et al. 2019
- **Case study** using a data set for 58 turbines provided by WindESCo
  - Evaluate the theoretical potential for **improvement in annual energy production (AEP)**
  - **Reduction in yawing** if the approach was implemented at the wind farm.

Collaboration effort funded by the U.S. Department of Energy Small Business Voucher Program

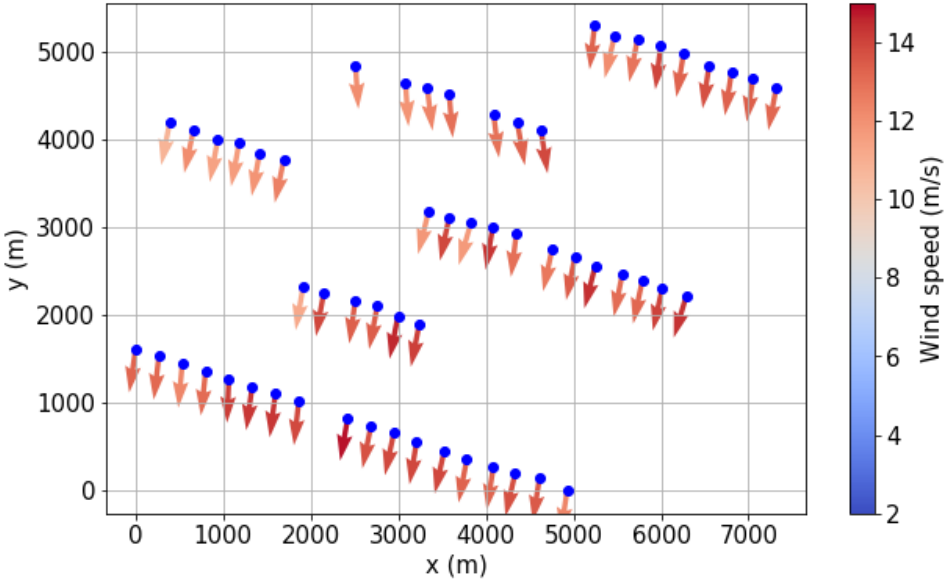
Effects Are Seen in the Field

Actual supervisory and data acquisition (SCADA) data at different wind speeds

Nacelle Direction at Low Wind Speeds



Nacelle Direction at High Wind Speeds

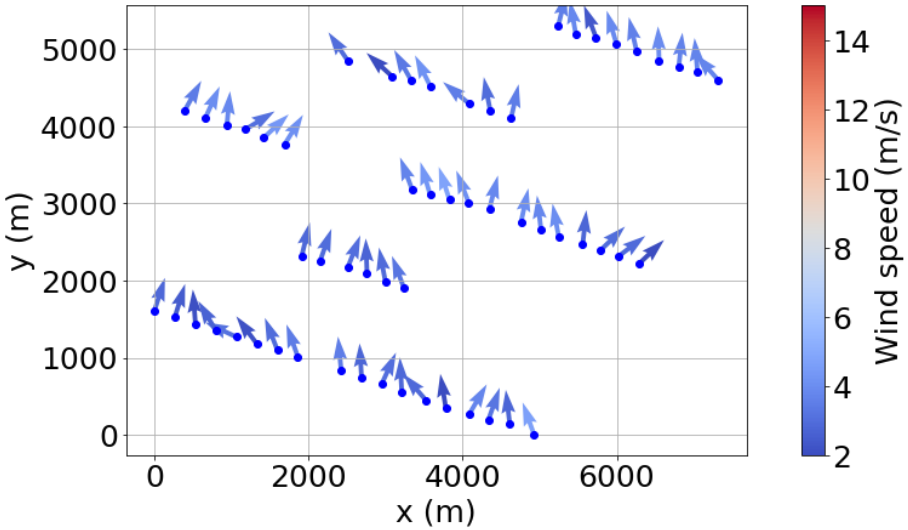


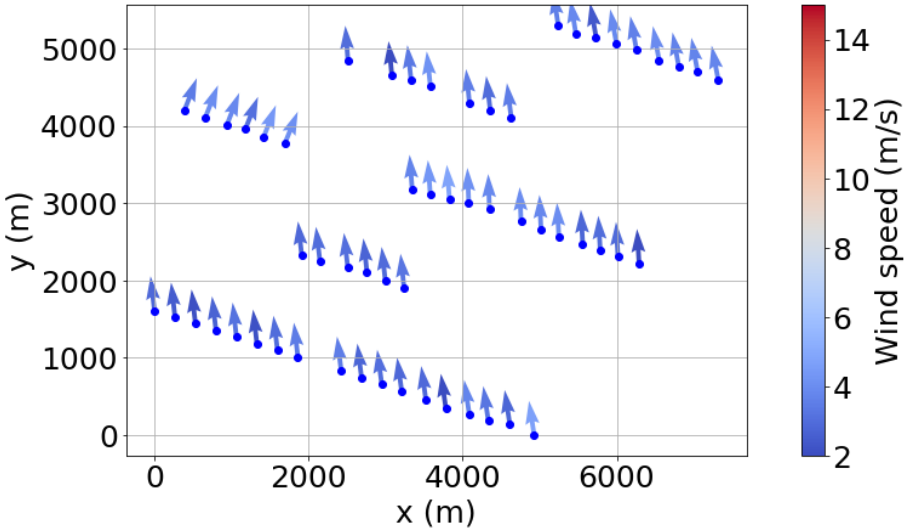
m: meters
m/s: meters per second

- Misalignment of turbines is lost power
- More prominent at below rated wind speeds.

Our Solution Is Increased Communication

Actual SCADA Data → Estimated Wind Direction





- Through communication, turbines can reach consensus on the wind direction
- Corrects for faulty/noisy sensors.

Wind Direction Change Seen in the Field

Actual SCADA Data

Consensus Algorithm Output

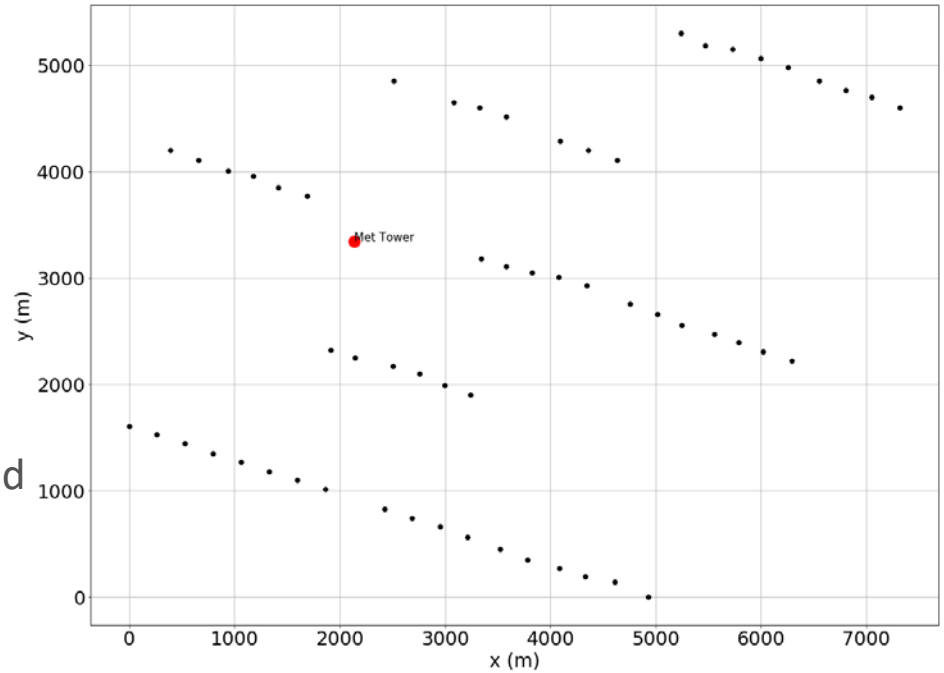
Turbine Sensors Can Fail/Be Wrong

Actual SCADA Data

Consensus Algorithm Output

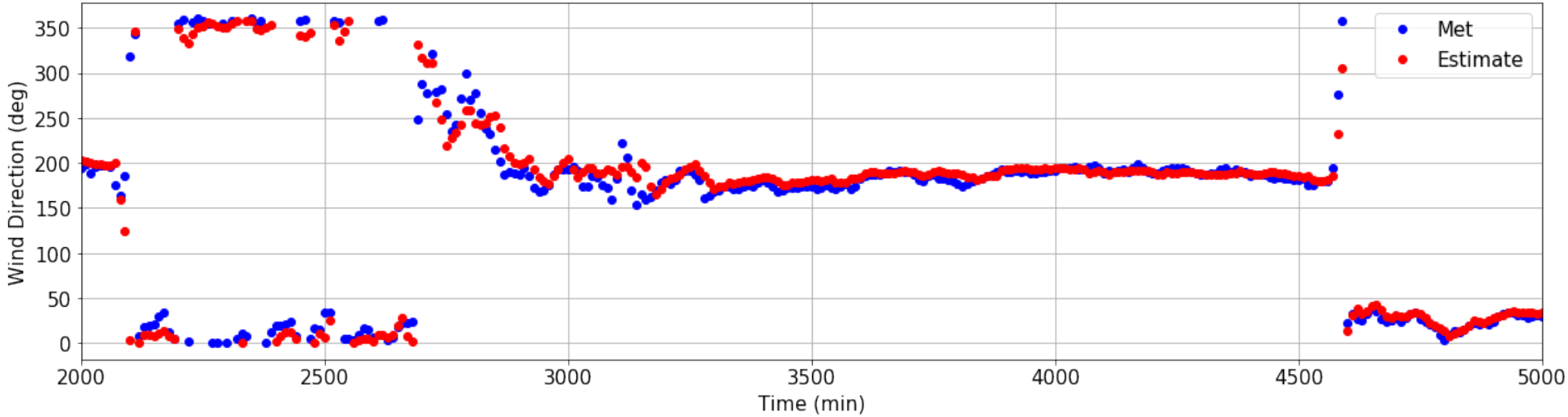
Example Data Set

- Large wind farm with 2.5-megawatt (MW) turbines
- SCADA data collected by WindESCo with 1-hertz time resolution:
  - Nacelle direction
  - Power
  - Yaw error
  - Wind speed
  - Pitch
- SCADA 10 seconds (s), 30 s, 1 m, 5 m, 7 m and 10 m statistics calculated
- Eight months of high-speed data
- Ten-minute meteorological (met) tower data
  - Wind speed
  - Wind direction.



Met Tower Comparison

Validation of consensus wind direction estimate compared to met tower measurements

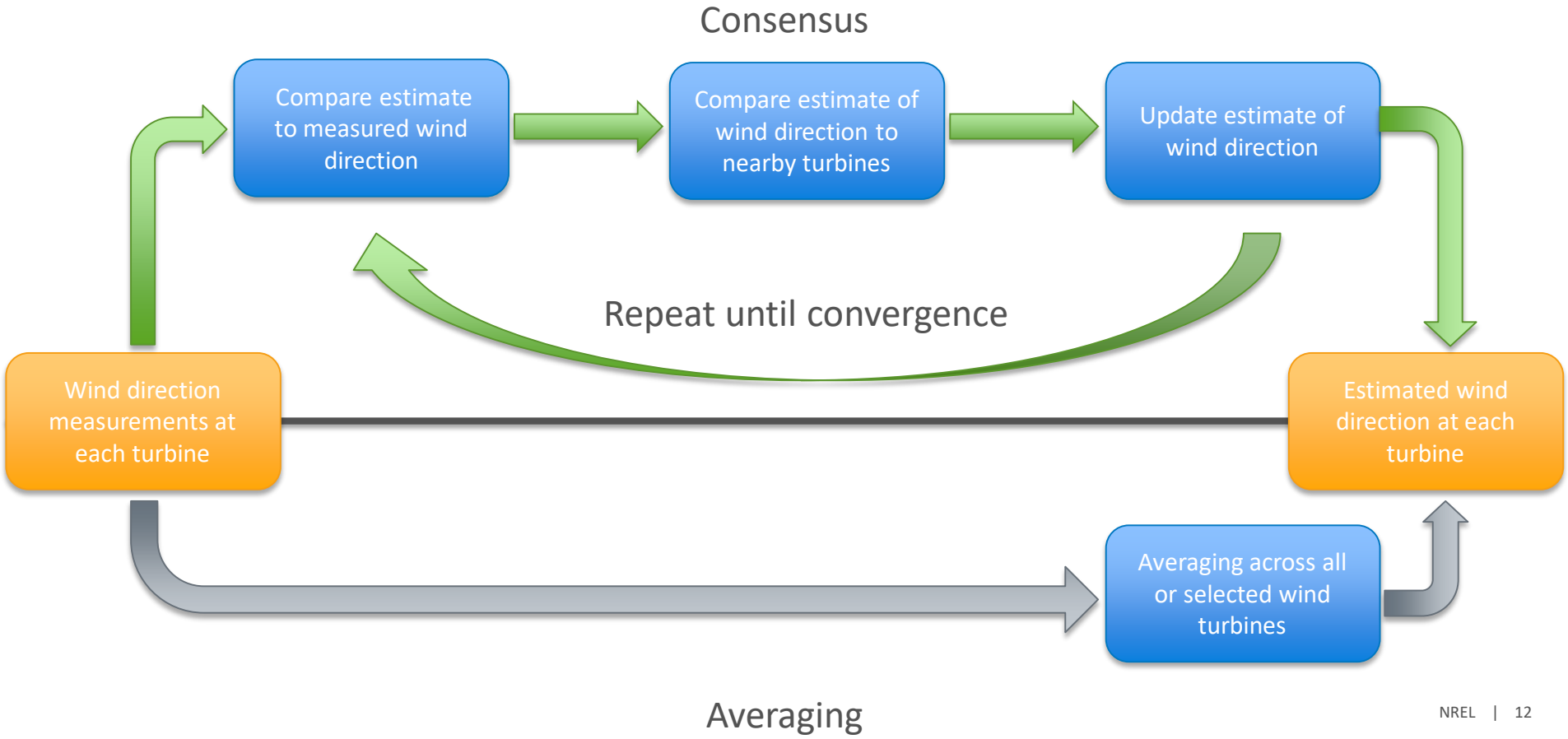


Alternative Approaches

- The consensus method is relatively complex to implement
- Some simpler approaches to consider:
  - Averaging
  - Weighted averaging
  - Clustered weighted averaging

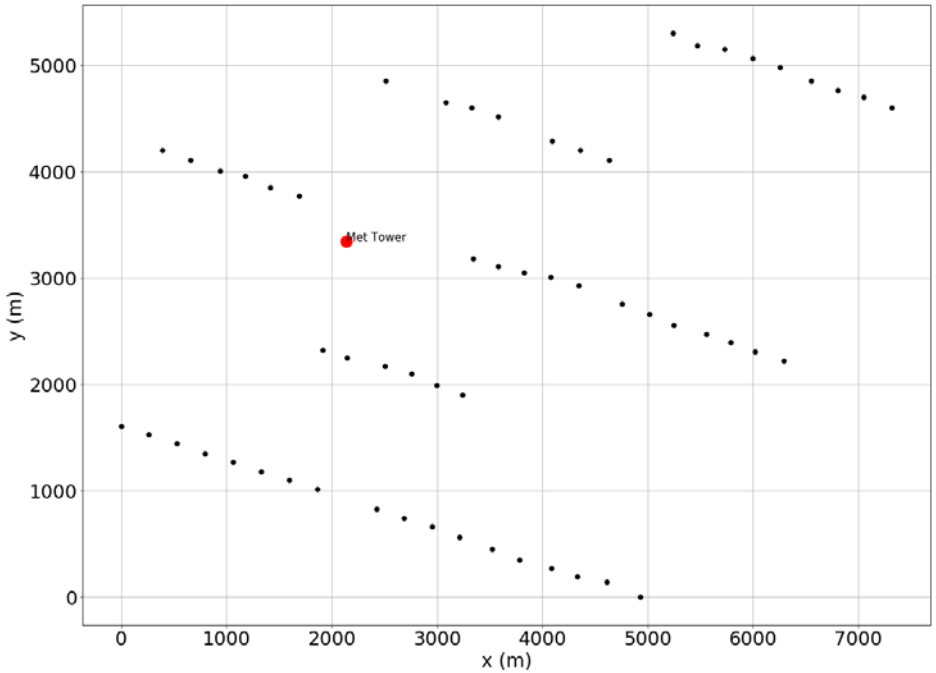
- Results are then compared to the consensus method.

Consensus Versus Averaging



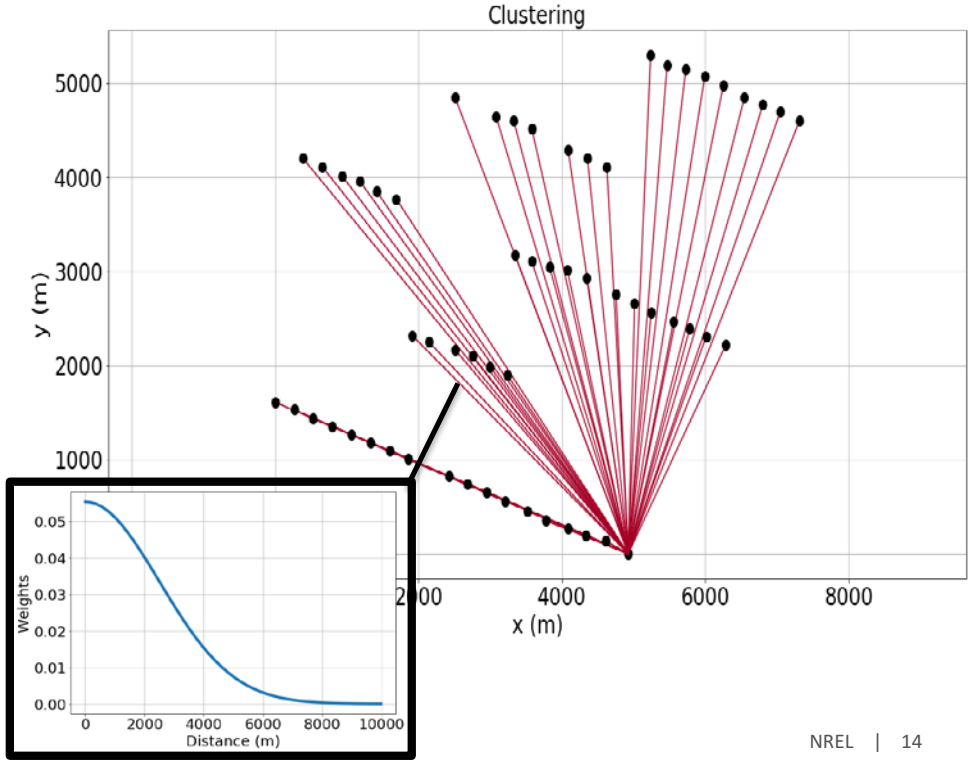
Averaging Wind Direction

- Circular average of wind direction measurements from all turbines in the wind farm
- Pros
  - Computationally efficient (< 0.01 s)
- Cons
  - Does not take into account local terrain
  - Equally take into account turbines far away
  - Difficult to catch outliers/faults.



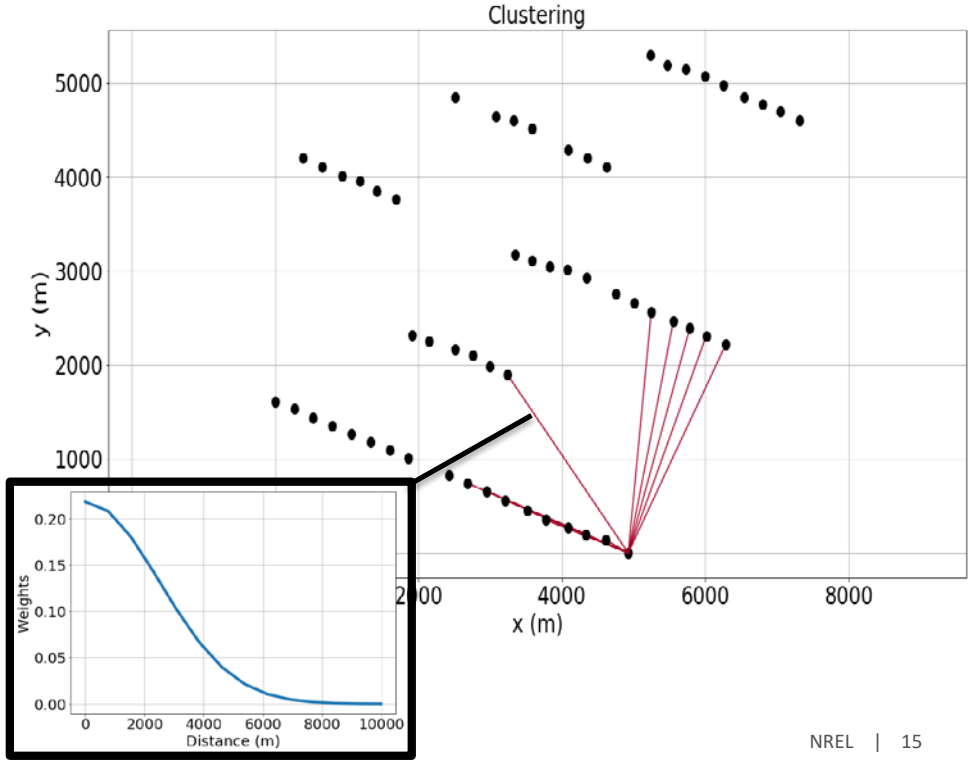
Weighted Averaging Wind Direction

- Weight each turbine wind direction by a function of distance from the turbine of interest
- Pros
  - Computationally efficient
  - Heavily weights turbine information that is closer
    - Normally distributed
- Cons
  - Difficult to catch outliers/faults.



Clustering Weighted Averaging Wind Direction

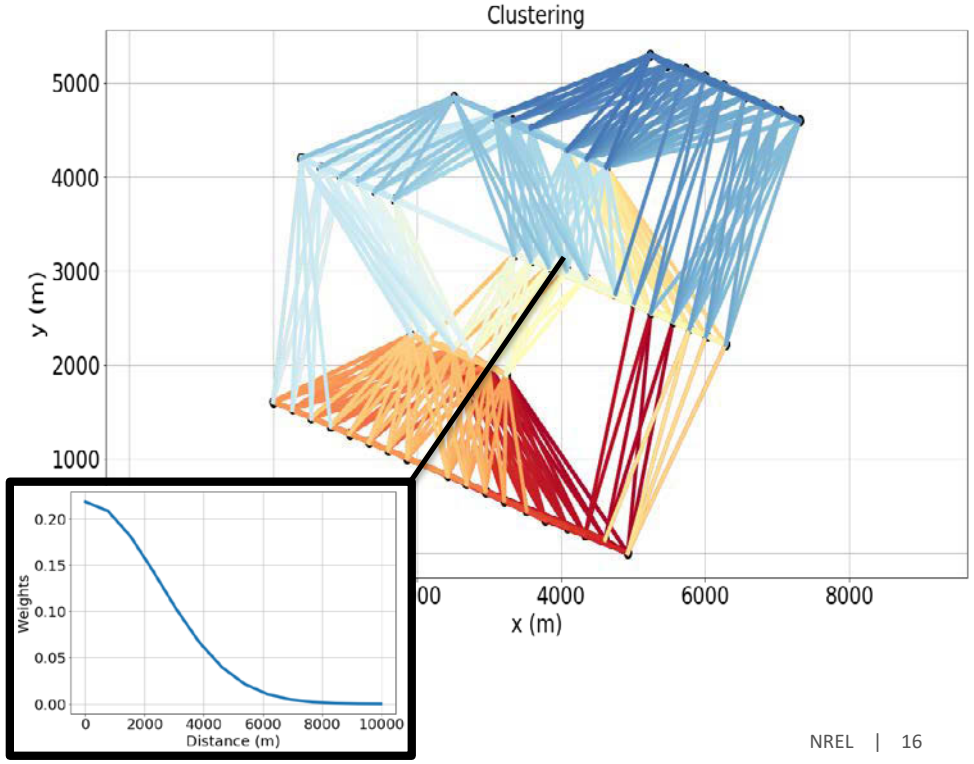
- Select only turbines within a certain distance and include these in a weighted average (turbines closer to the turbine are weighted more)
- Pros
  - Computationally efficient
  - Heavily weights turbine information that is closer
    - Normally distributed
- Cons
  - Difficult to catch outliers/faults
  - Not enough turbines to average out these faulty sensors.



Wind Direction Consensus

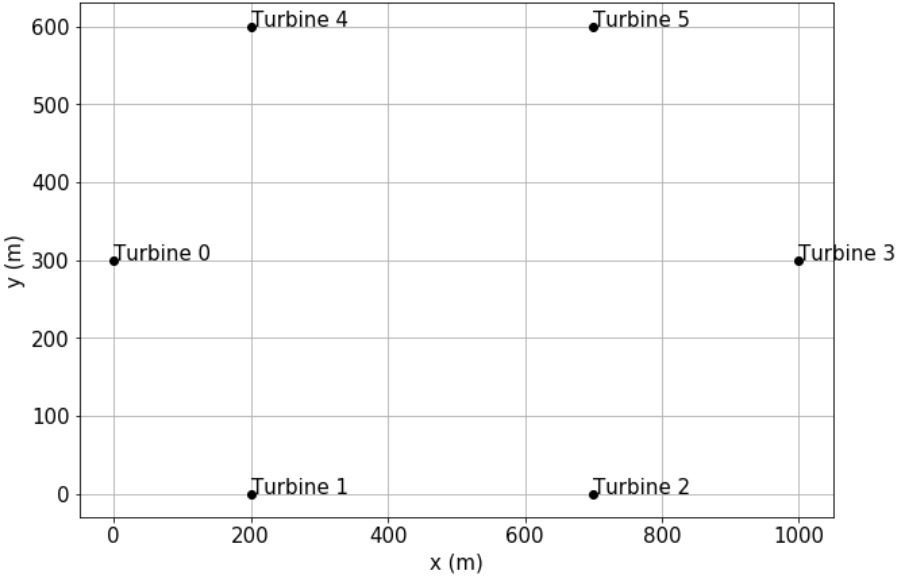
Cluster Averaging with Feedback

- Pros
  - Iterative approach
  - Acknowledges local effects
    - Change in direction across the farm
  - Catch outliers
  - “Tug-o-war” to come to agreement on wind direction
- Cons
  - More difficult to implement
  - Slower than the other methods (0.5 s to compute versus 0.01 s).

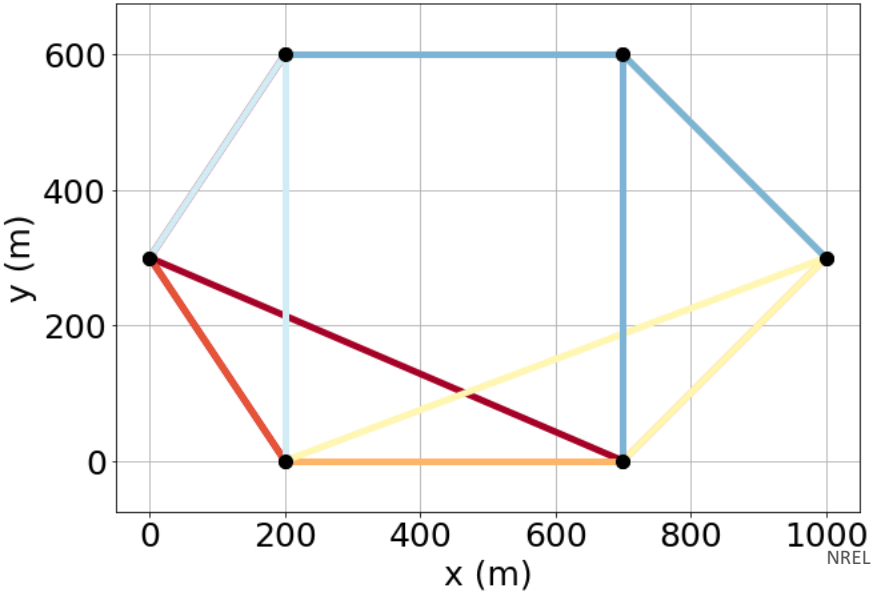


Example Wind Farm To Demonstrate Differences

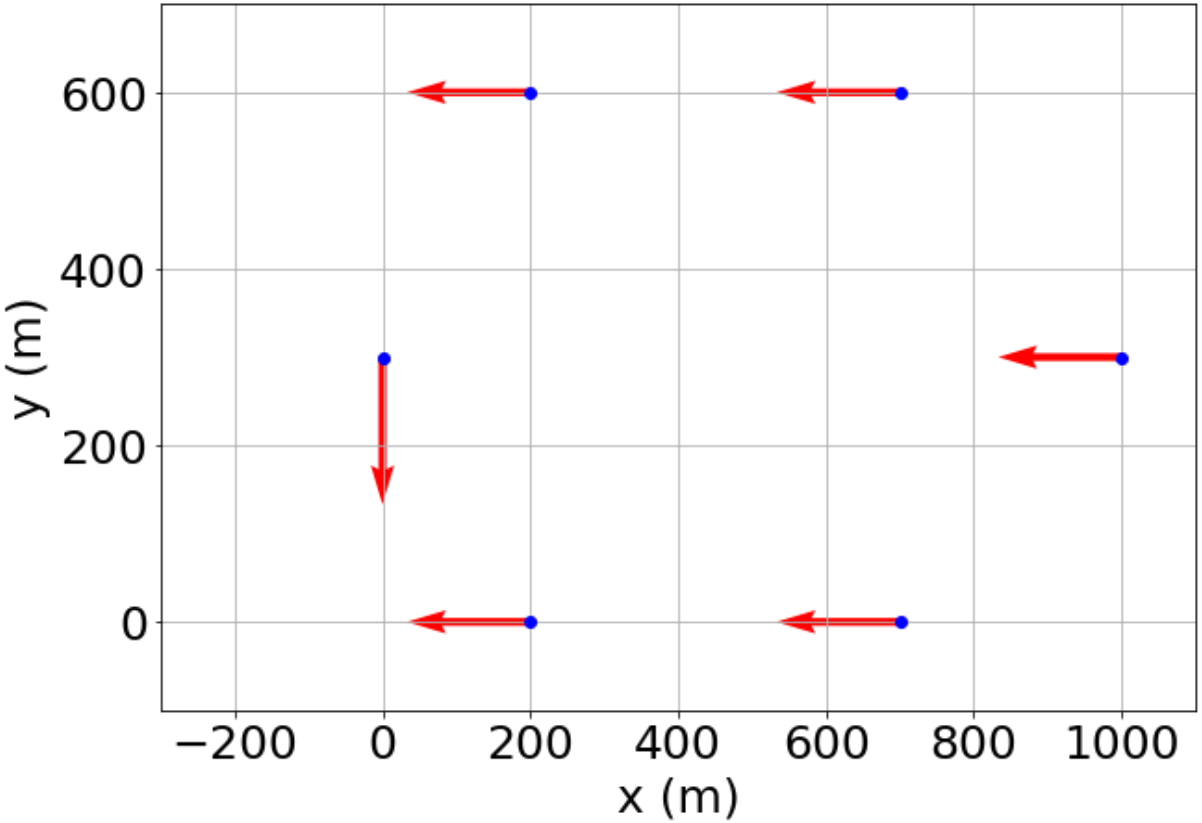
We use a small example of six turbines to demonstrate the conditions that the consensus method can overcome.



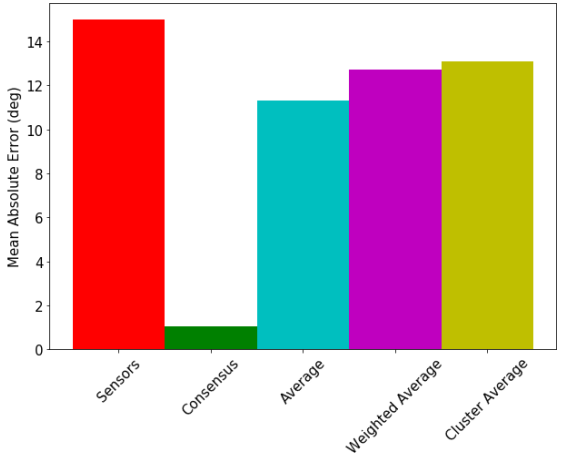
Determine what turbines should talk to each other

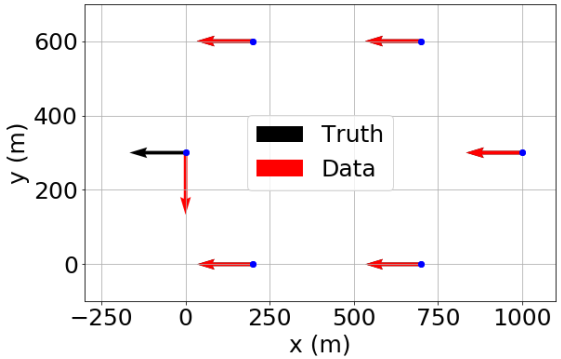


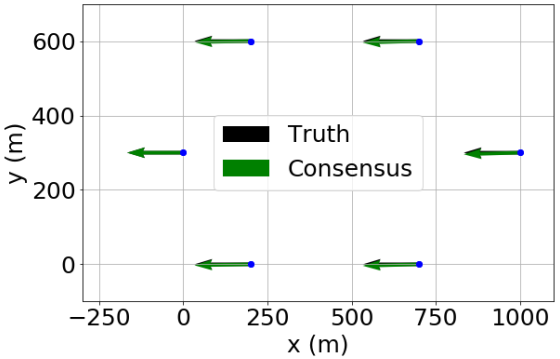
Faulty Signal on Turbine 0



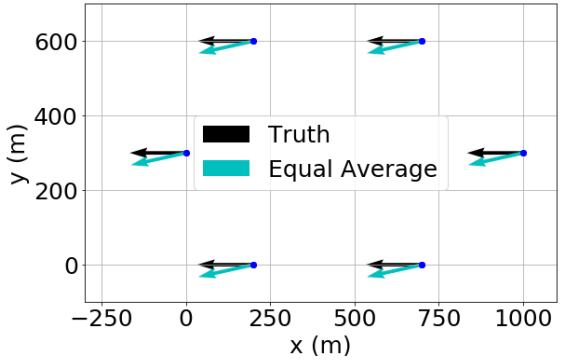
Faulty Signal Results

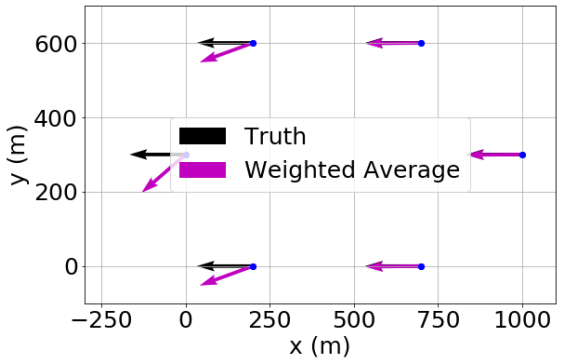


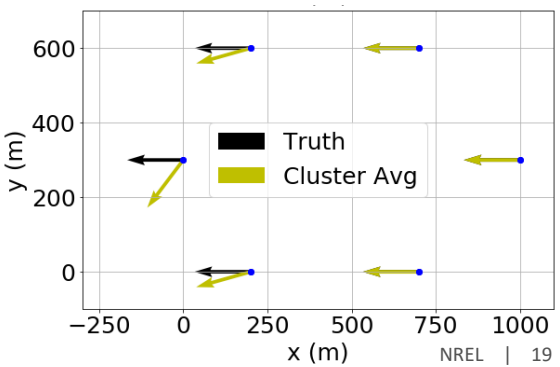




Note: Error spreads to other turbines







Determine the Effects for Realistic Data

Perform the same process on a realistic synthetic data set.

Note: we need to generate a set of true wind directions because we do not know the wind direction exactly at each turbine in the measured data set. **This synthetic data is then used for demonstration purposes**.

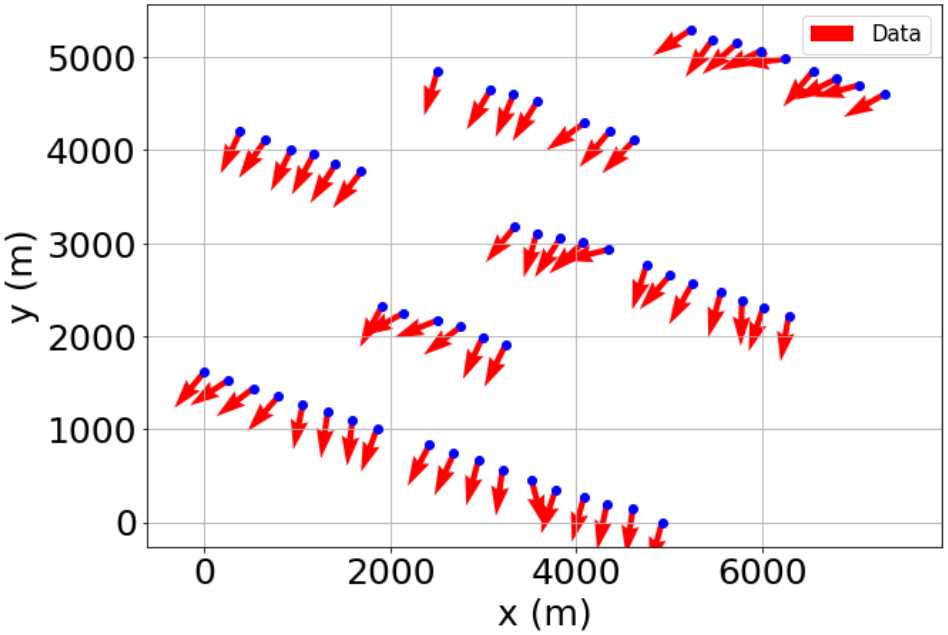
Steps:

1. Determine the amount the wind direction changes across the wind farm
2. Determine the average “noise” seen across the wind farm
3. Simulate set of turbine wind direction measurements with these same parameters

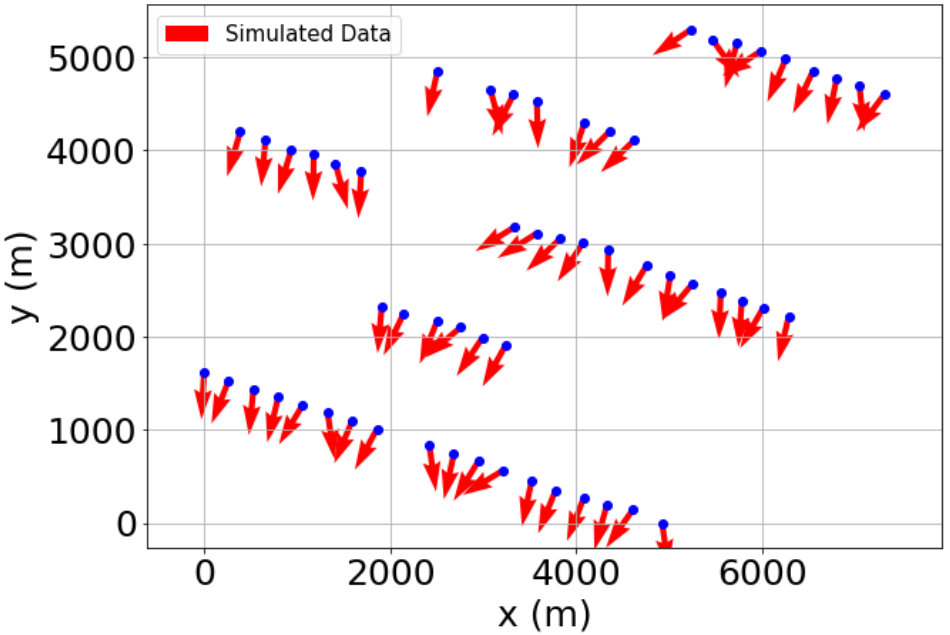
- Approximate change in directions across the wind farm = 10 degrees (deg)
- Approximate noise (i.e., variation in wind direction, across the wind farm = 20 deg).

Example Based on SCADA Data

Actual – SCADA Data

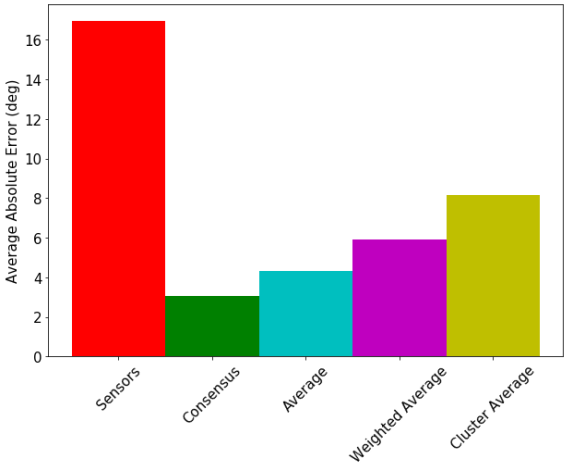


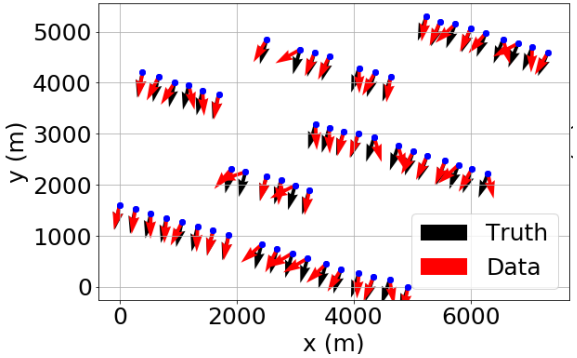
Simulated Noisy Data

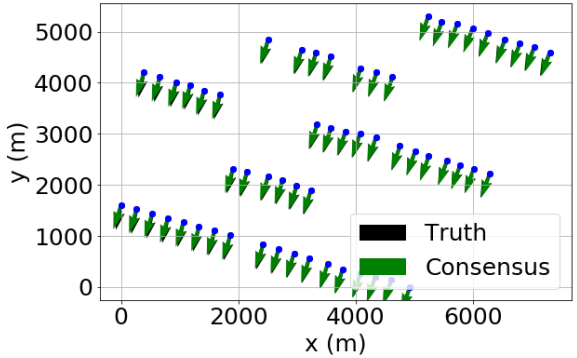


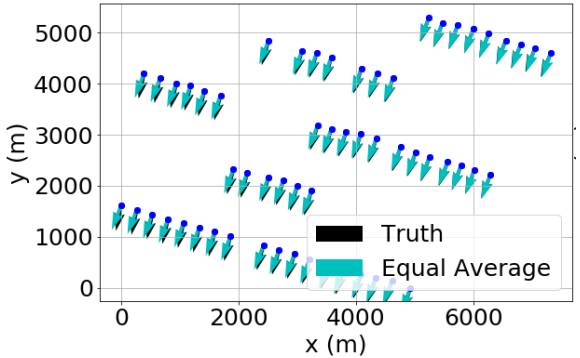
Note: Visually, the two snapshots look similar in terms of amount of variance.

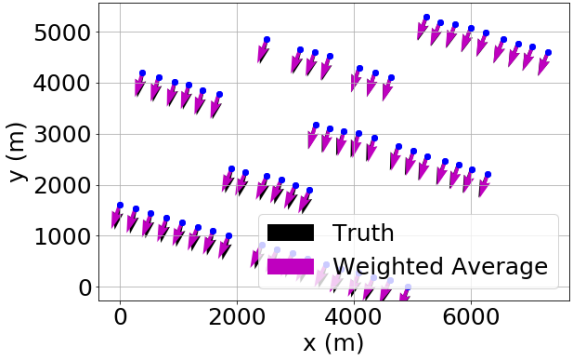
Results – Typical Yaw Error

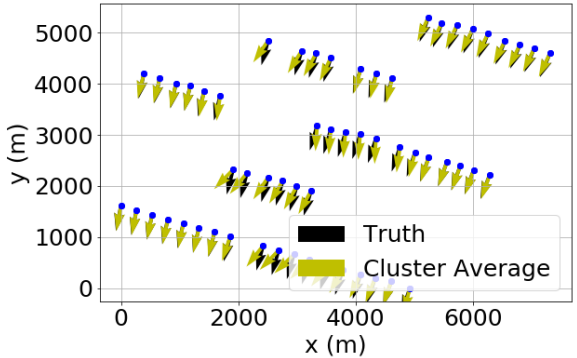




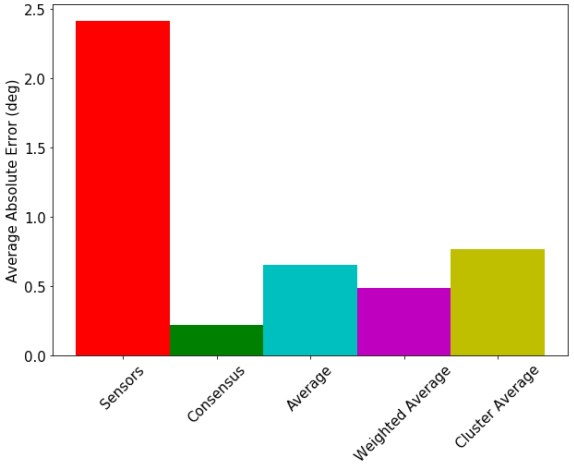


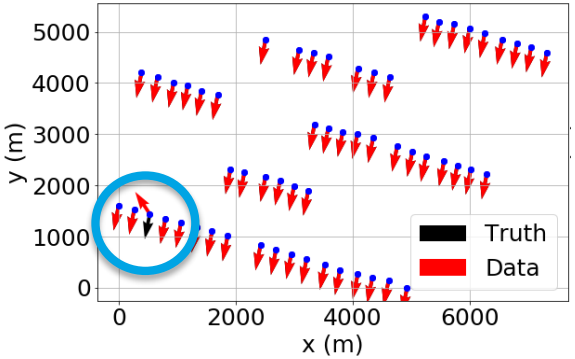


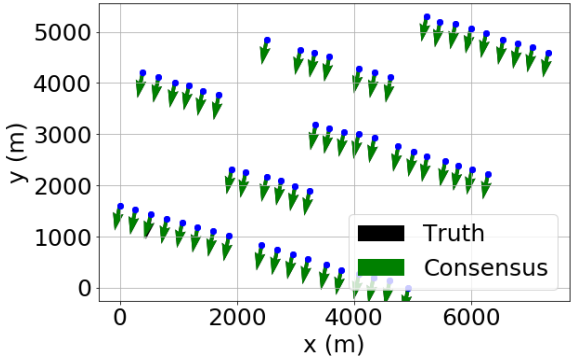


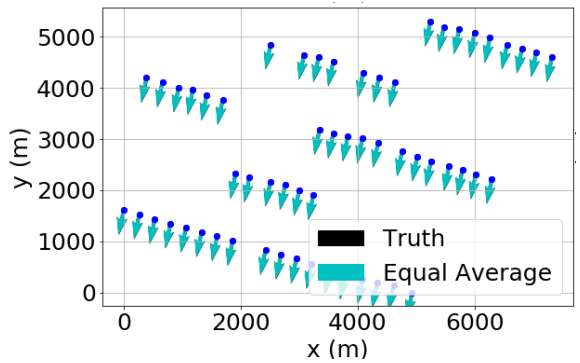


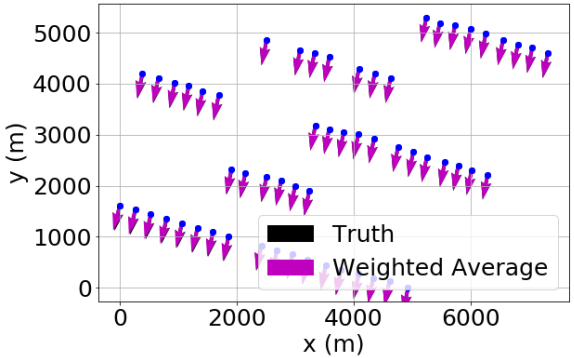
Faulty Signal

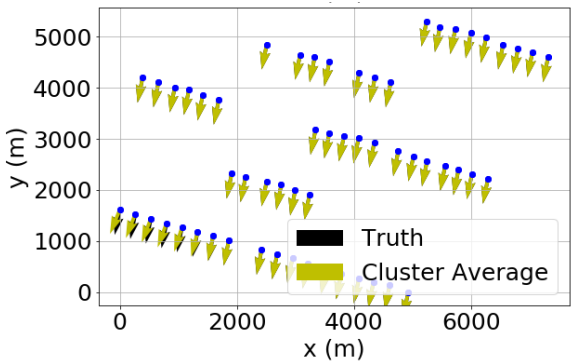




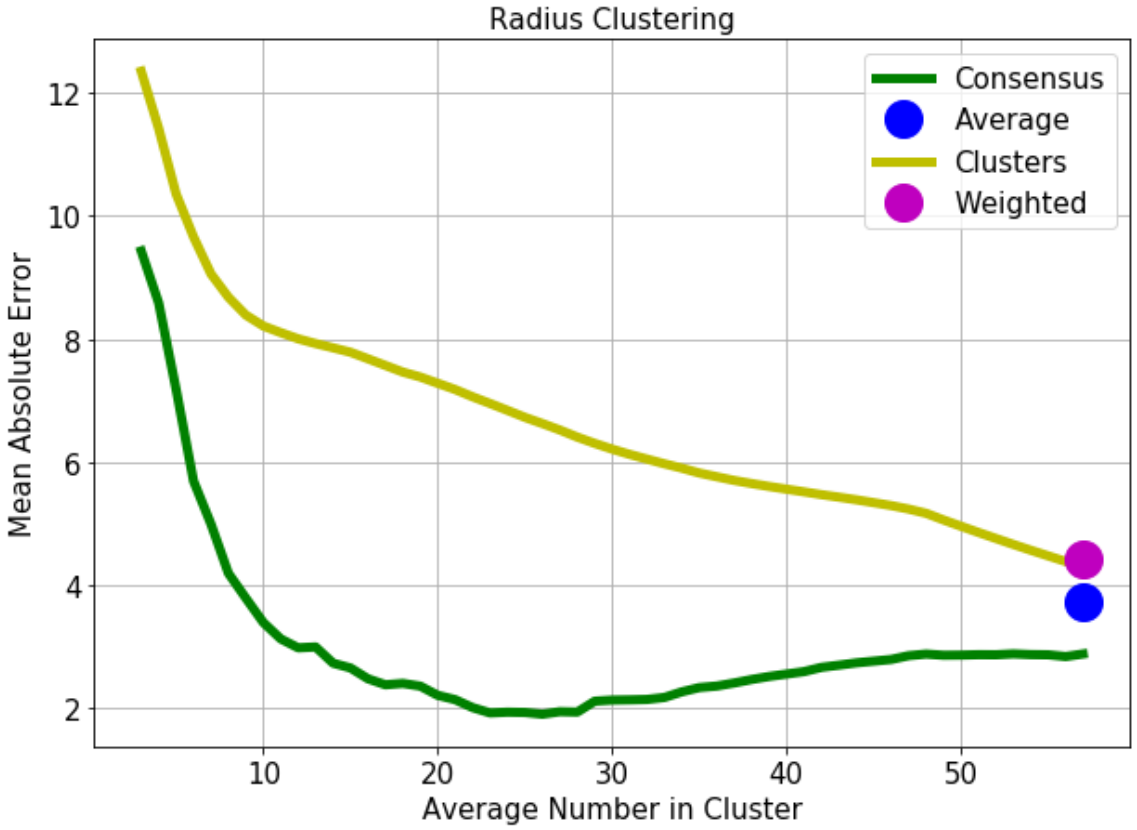






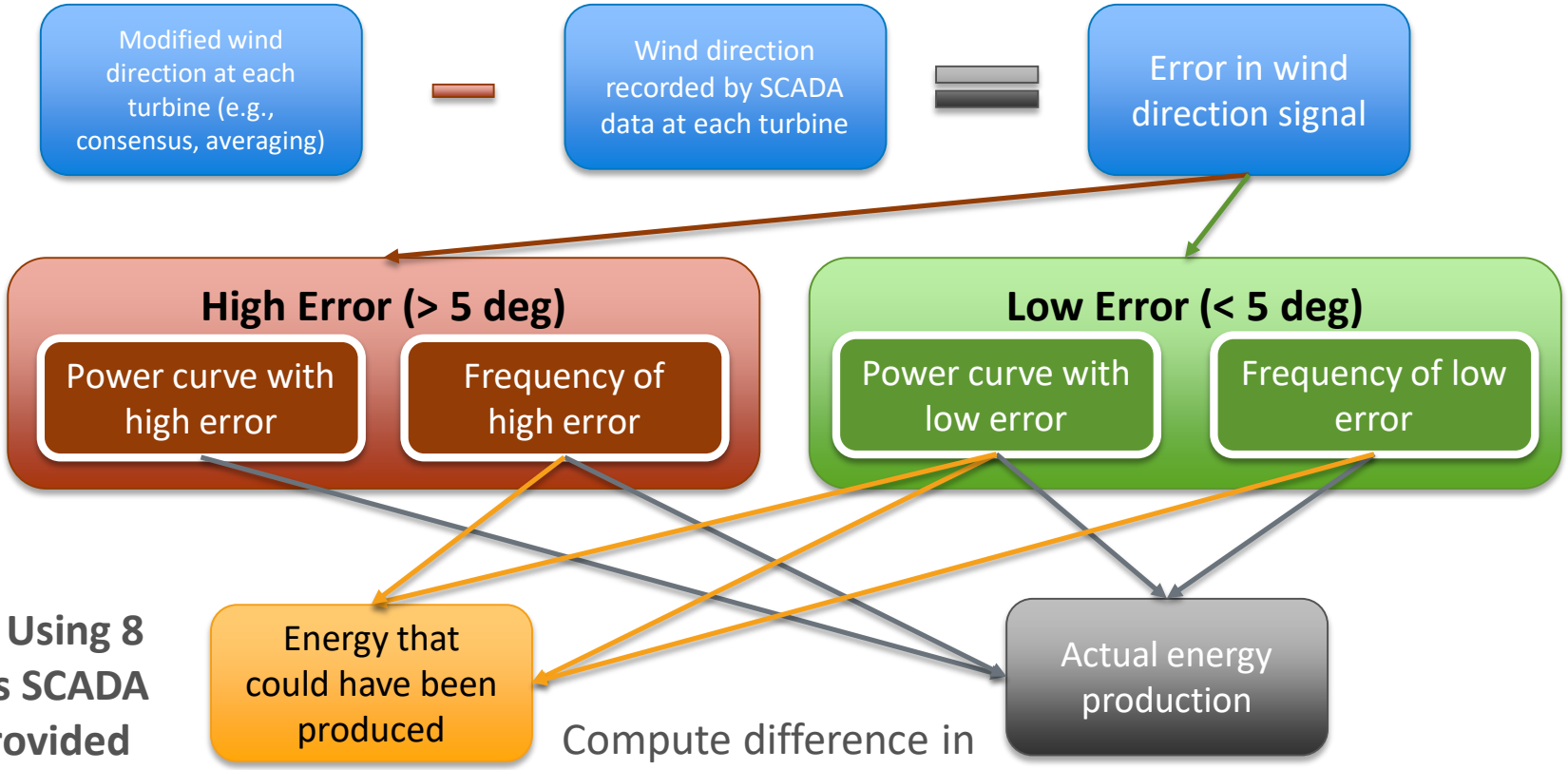


Number of Turbines To Include in Analysis



Consensus approach provides significant advantages for smaller wind farms compared to other methods. Results are similar for a large wind farm.

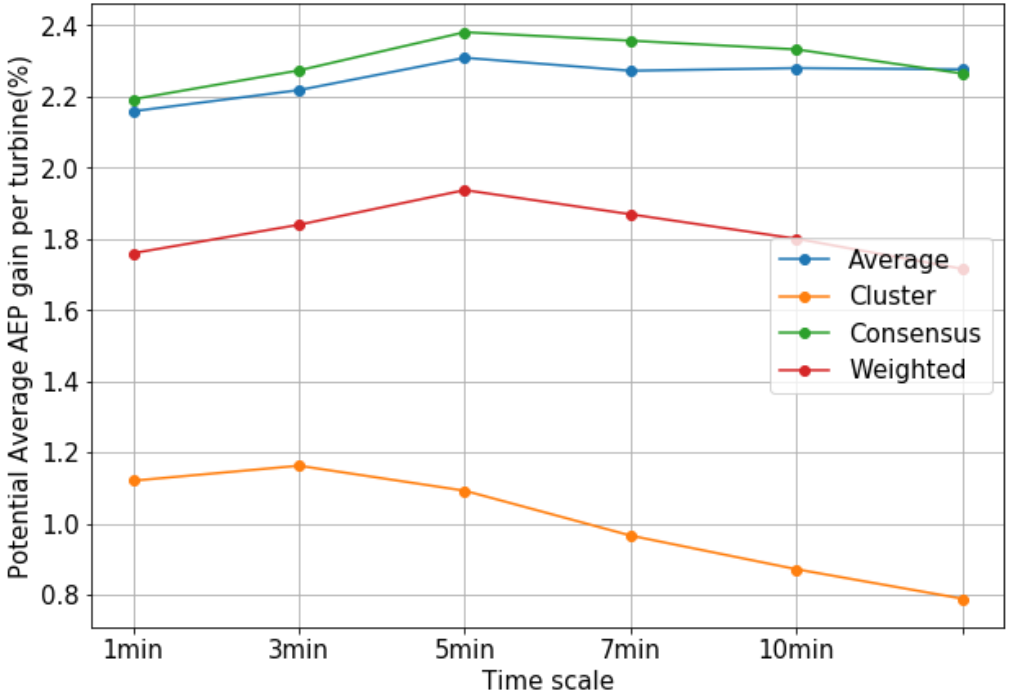
Calculating AEP Gain



***Note: Using 8 months SCADA data provided by WindESCo**

Performance of Different Methods

Using 8 months SCADA data provided by WindESCo



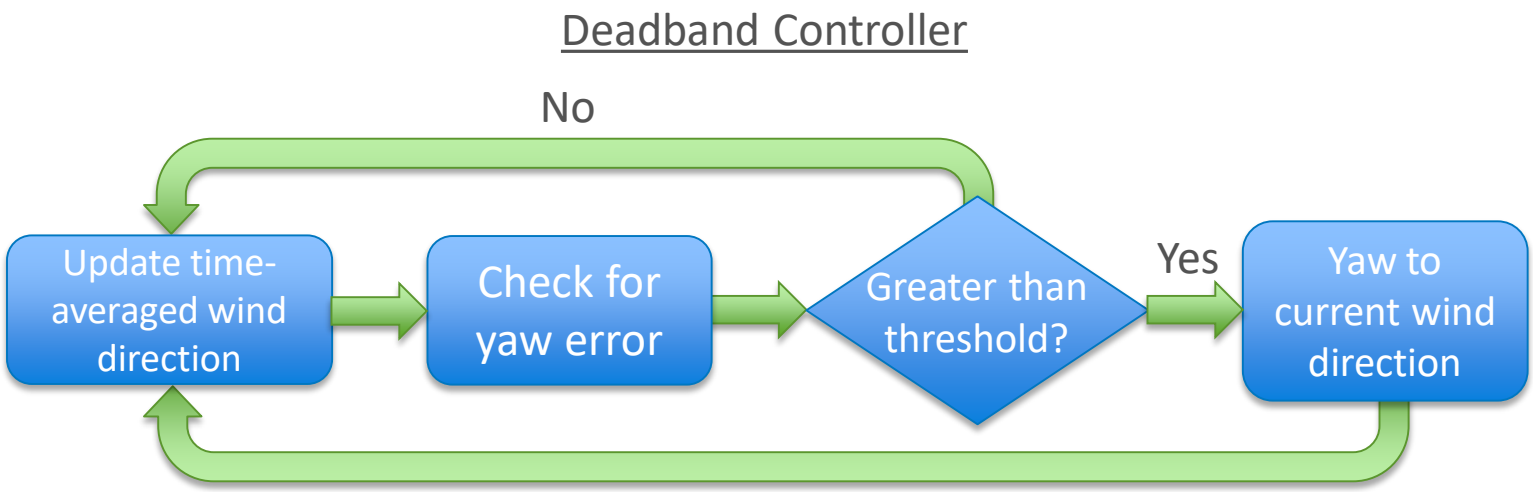
Results discussion:

1. Averaging appears to be the next best method
   - Minimal bias/errors in turbines
   - Flat terrain
   - Weighted average is second best

2. Consensus also detects 2%+ AEP gain is possible, and is more robust to faults (as shown in earlier slides)

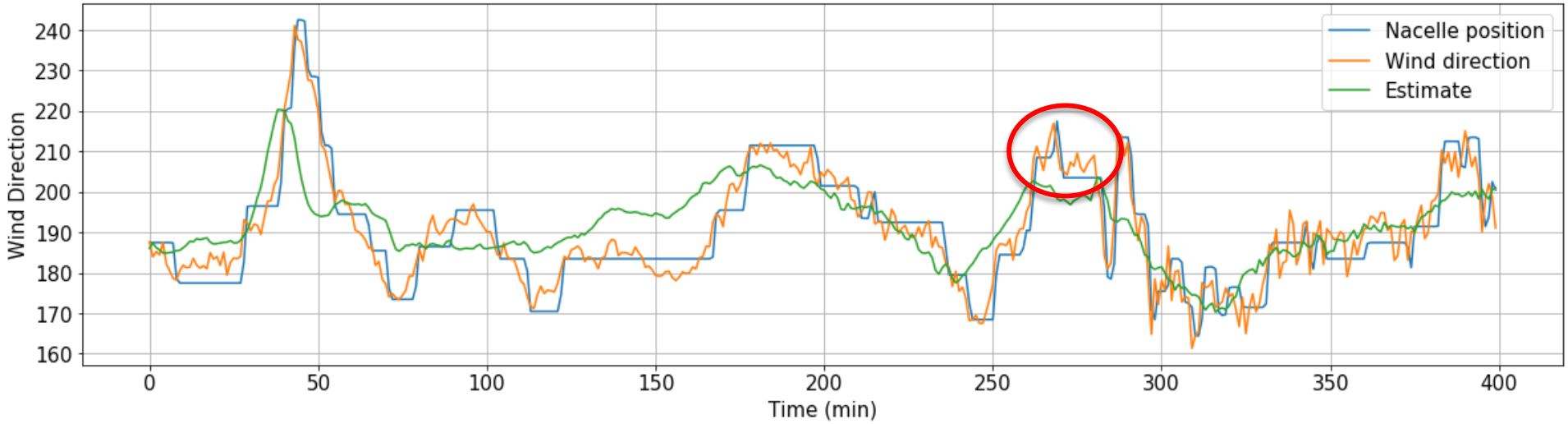
3. One-minute updates would be sufficient.

Simulating Yaw Controller Response



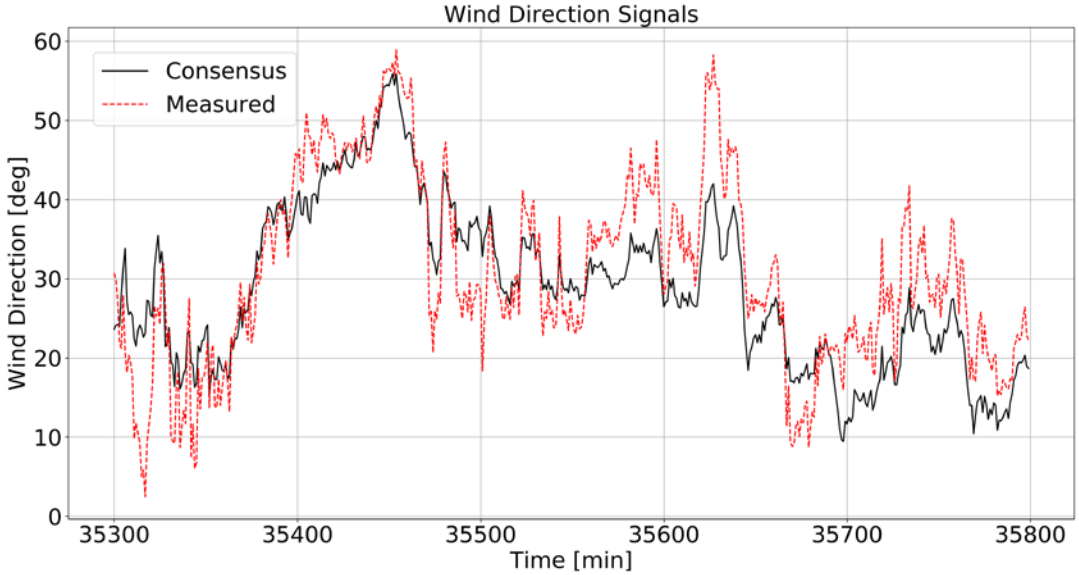
- A deadband yaw controller was simulated in the manner shown above
- The average wind direction was computed from the previous 10 minutes
- The threshold for yaw error was set to 10 deg.

Wind Direction Signal



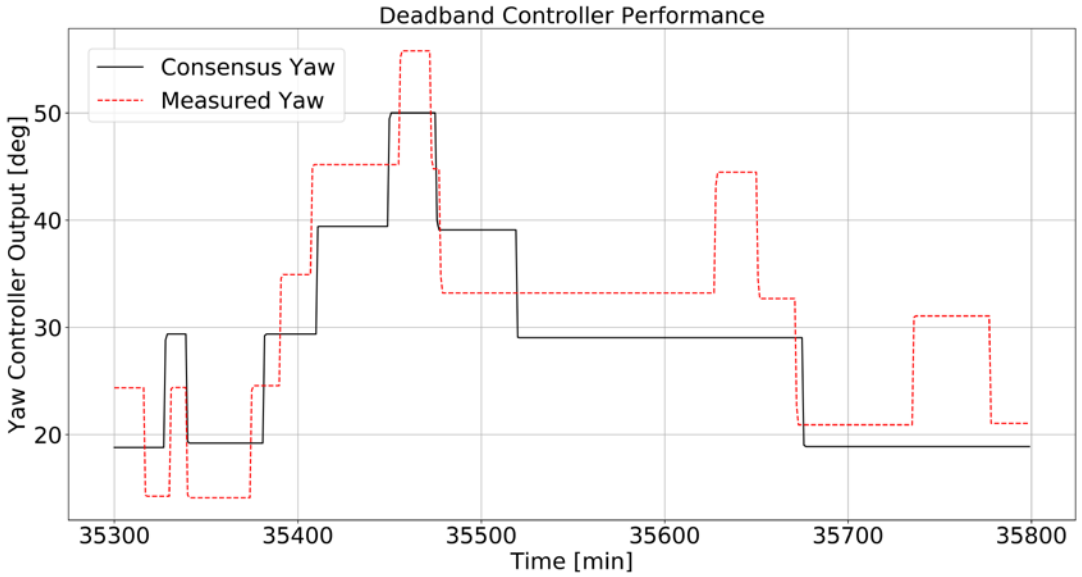
The estimated wind direction from the consensus algorithm has less variance than the measured wind direction, thus it is proposed that yaw actions chasing the wind, like the one highlighted in red, can be avoided.

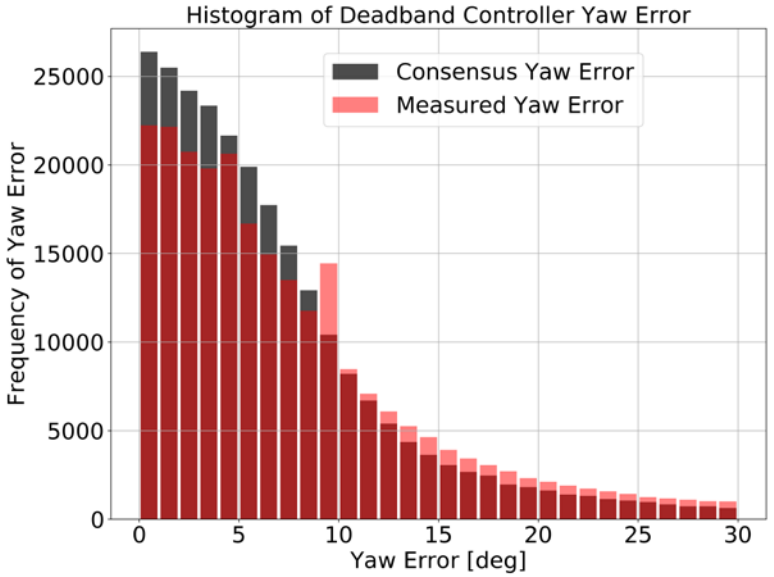
Input to Yaw Controller



- With the consensus approach, there is less variance in the wind direction signal, thereby leading to less yaw action by the yaw controller.

Output of Deadband Yaw Controller





- With the consensus approach, yaw movements are reduced (shown on left)
- Using the consensus estimated wind direction, the yaw controller is more accurate (shown on right)
- The reason for the spike observed near 10 deg is unclear; this could be sensor related and seems to be turbine-dependent.

Reduced Amount of Yawing

- Yaw travel was calculated for each turbine across the farm
- At a 1-minute time step for the controller, the degrees travelled across the farm were reduced by approximately 31%.

Degrees Traveled across Farm

Wind Direction	Degrees Travelled
Measured	1.510E+07
Consensus	1.048E+07

> 31% reduction

Conclusions

- Validation analysis of the consensus control method was performed using SCADA data from a large wind farm
- Significant AEP lost because of yaw misalignment resulting from local wind direction measurement errors at each turbine
- Simulated analysis indicates **AEP increase > 2% is possible**
  - Need field tests to verify
- Yaw analysis indicates that there would a **31% reduction** in yaw travel for the simulated controller.

Thank you

www.nrel.gov

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Nathan Post: nathan@windesco.com

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