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Progress On SCADA Data Based Wake Analysis

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Sandia SCADA based wake analysis efforts

- Sandia completed a wake analysis and visualization of the wind flow based on SCADA data in two Mid-West wind farms of different layouts
- The analysis shows wake deficits as expected, but has also revealed new speed-up effects associated with upstream turbines
- These new effects appear to have a positive upside on power production while at the same time also reducing power variability
- Indicative results show that these lower variability situations also are associated with lower tower vibrations
- The analysis methods can potentially impact the way we:
  - Design wind farms
  - Operate and analyze under-performance
  - Quantify reliability issues and life time fatigue

Vision and objectives

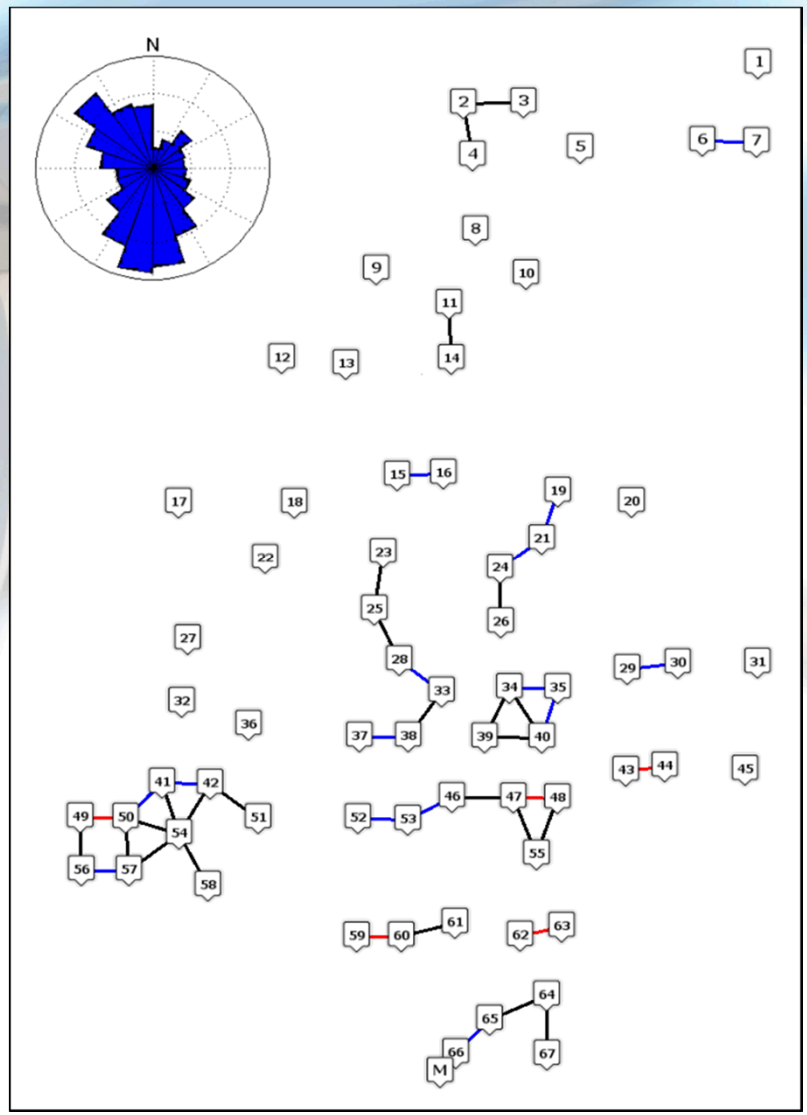
- **Short term:** Explore and develop analysis methods for performance visualization in order to identify opportunities for wind farm level improvements relating to wakes and wind farm flow in general

- **Mid term:** Explore and develop correlation between reliability metrics and performance observations in wind farm flows. Progress analysis to complex terrain.

- **Long term:** Explore and develop time based and spatial structure based methods for continuous monitoring and improvement methods, taking advantage of new wake related discoveries

Performance from SCADA Data

- 1.5 year of SCADA data collected from 67 mid-west MW-class turbines
- Met-mast south of farm {M}
- Flat terrain surrounded by clusters of threes, farm houses and other wind farms
- Data is reduced from 2 sec. resolution to 10 min. value
- Wind rose: NW and S
- Red, blue & black lines show <5D, 5-6D and 6-7D spacing



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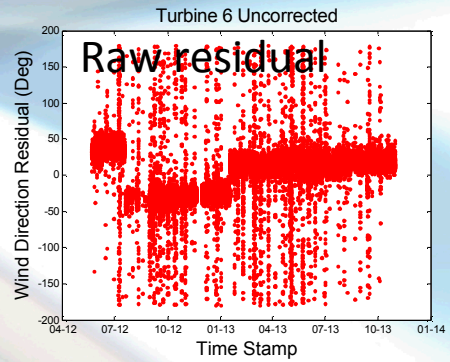
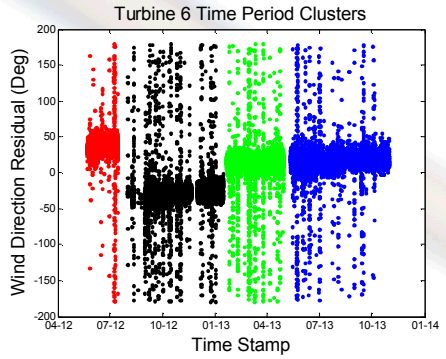
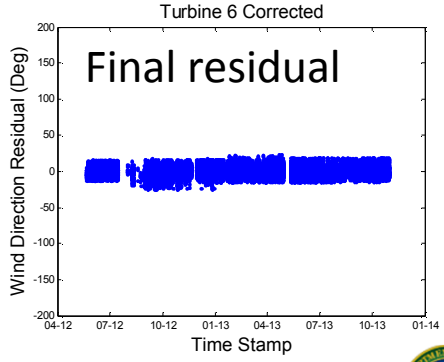
Correcting nacelle position and initial data cleaning

- Only operational data are used for the analysis
- Initial data is 61,000 10 min values per turbines, keeping only data from 4 m/s to 20 m/s, 46,000 10 min values per turbine remain, which agrees with the annual wind speed distribution for the site
- The nacelle position generally serves only little purpose for the turbine control, so often the sensor is un-calibrated and associated with drift and/or offset
- Steps for correction of nacelle position:
  1. Define residual as deviation from average of met-mast and two neighbor turbines
  2. Identify and remove periods with discrete off-set
  3. Remove outliers larger than one std. dev.
- The remaining data is ~34,000 10 min values per turbine







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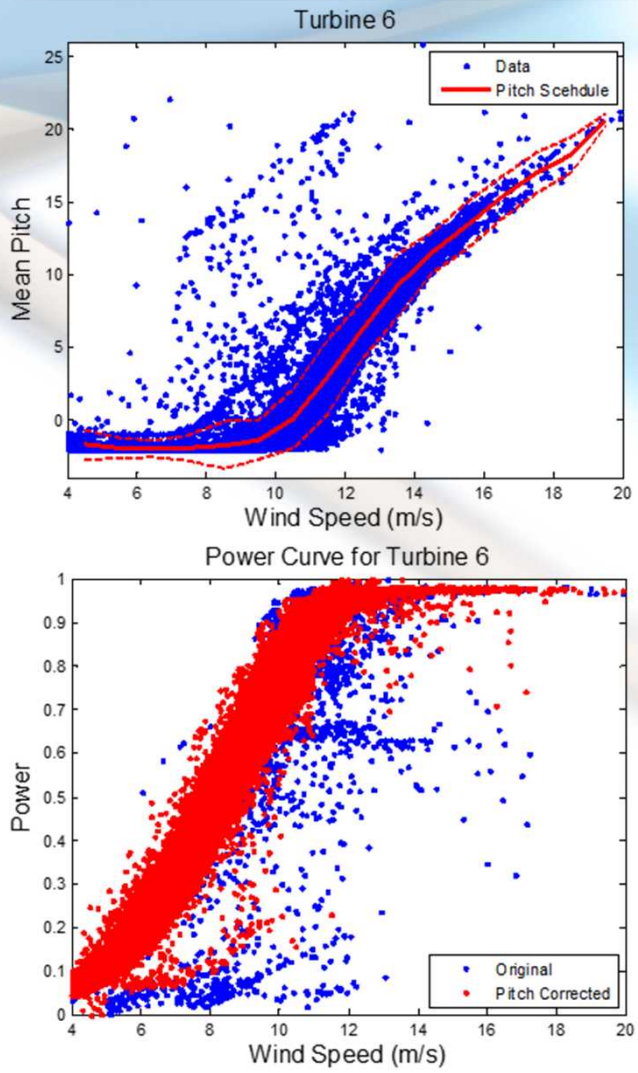
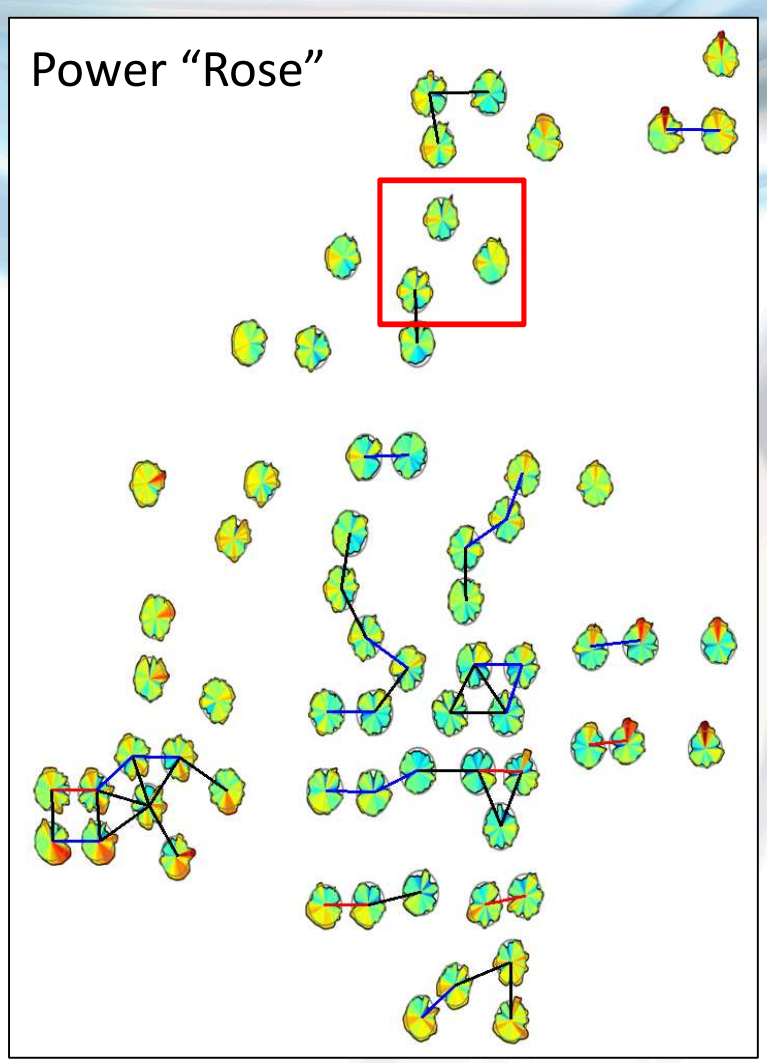
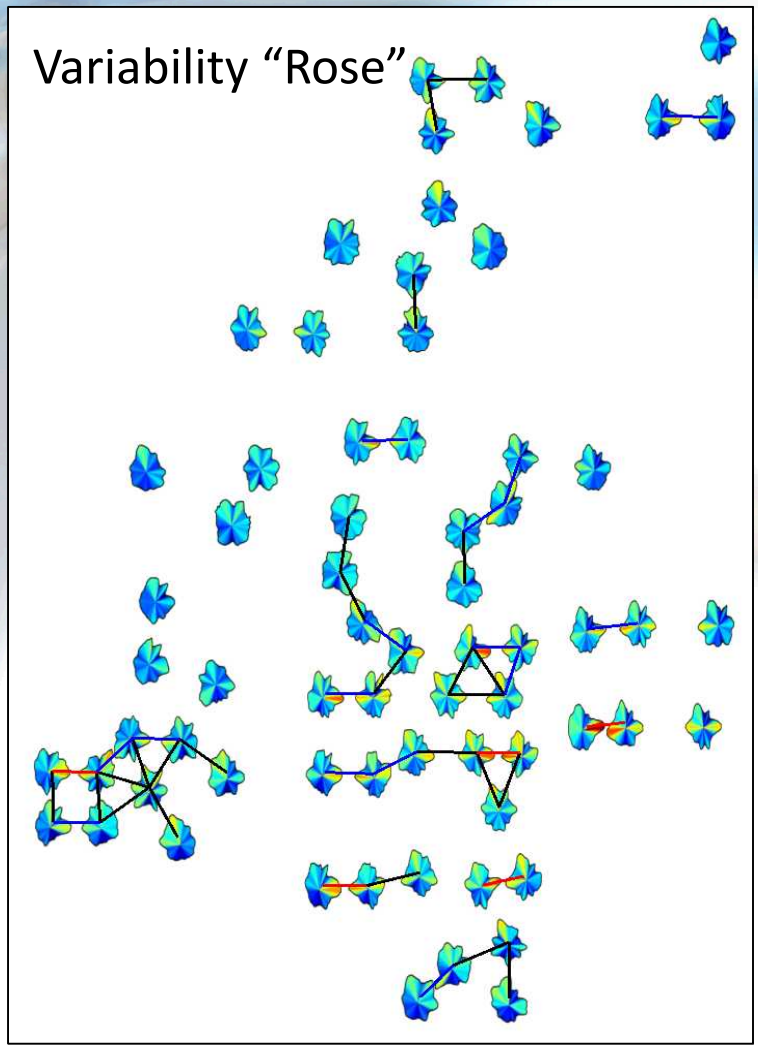
Cleaning power curves

- With the wind range and nacelle position corrected, turbine pitch as a function of nacelle wind is used to filter abnormal power mode operations
- Steps for correction of power curve:
  1. Compute 1 m/s binned pitch curve
  2. Remove outliers larger than one std. dev.
- The method removes:
  - Most severe outliers
  - De-rated power modes
  - Most low wind outliers
- Final number of data available is 32,000 10 min values per turbine or ~ 222 days of operation



Directional analysis of SCADA data





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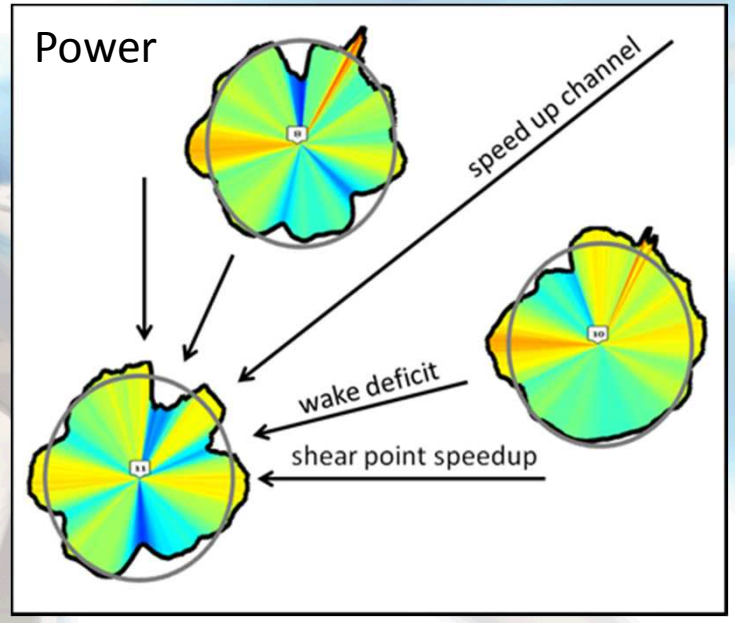
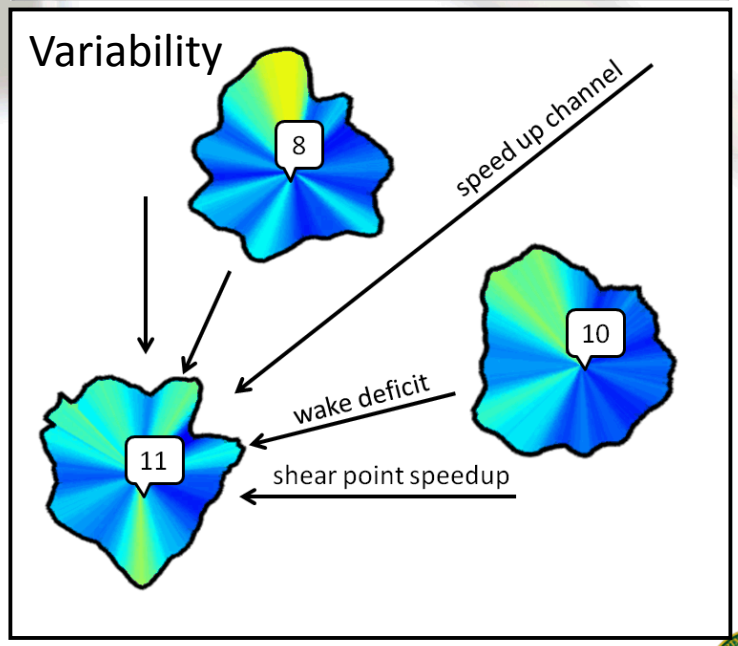
Operational quantification

- Observation: High power extraction relative to average performance occur with low variance
- If low variance equal low rates of fatigue and wear, then low rates of failure should be observed as a function of direction
- Working hypothesis: Direction plays a major role and is a simple way to quantify power and reliability
- Can we link data-mining of SCADA and apply a simple metric for reliability ?





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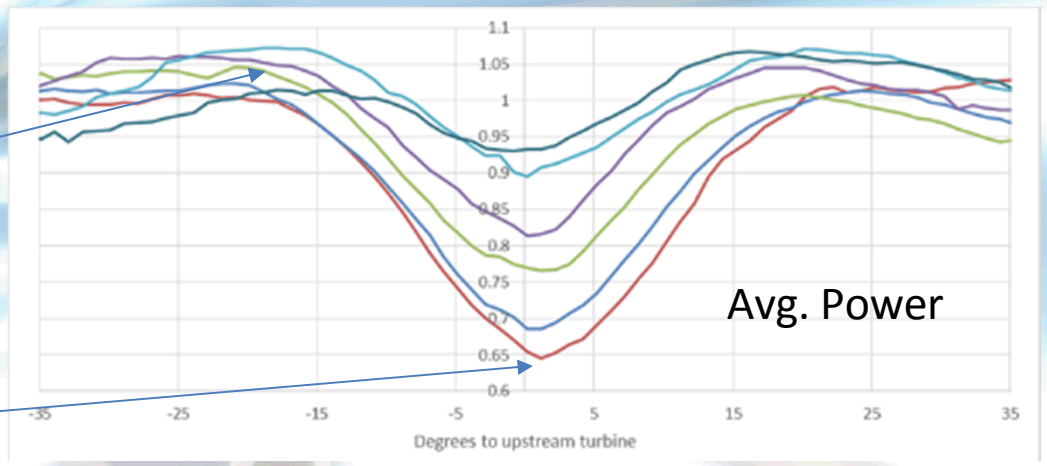
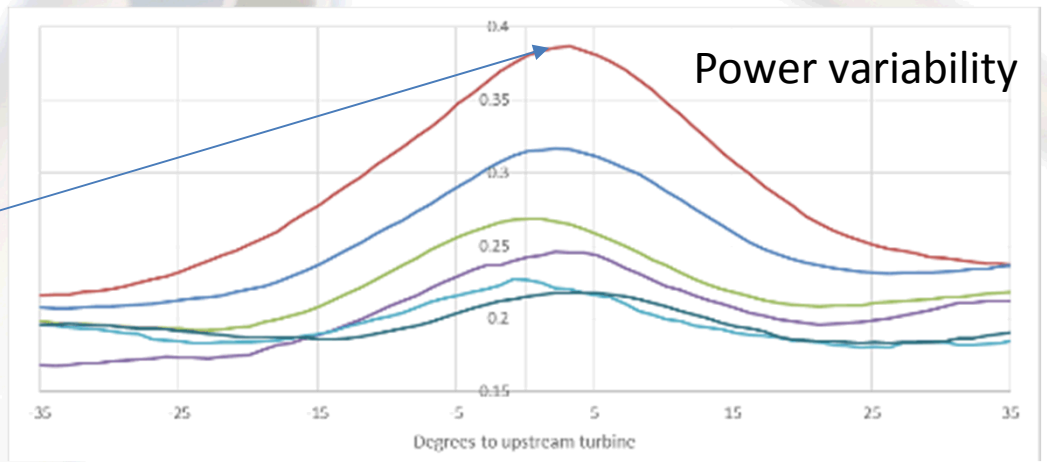
Average wake behavior

Speed-up outside
From 7.5 to 11.5 D
Power up to 7%
Wind up to 2%

Max deficit has
reasonable agreement
with Jensen to 3rd power

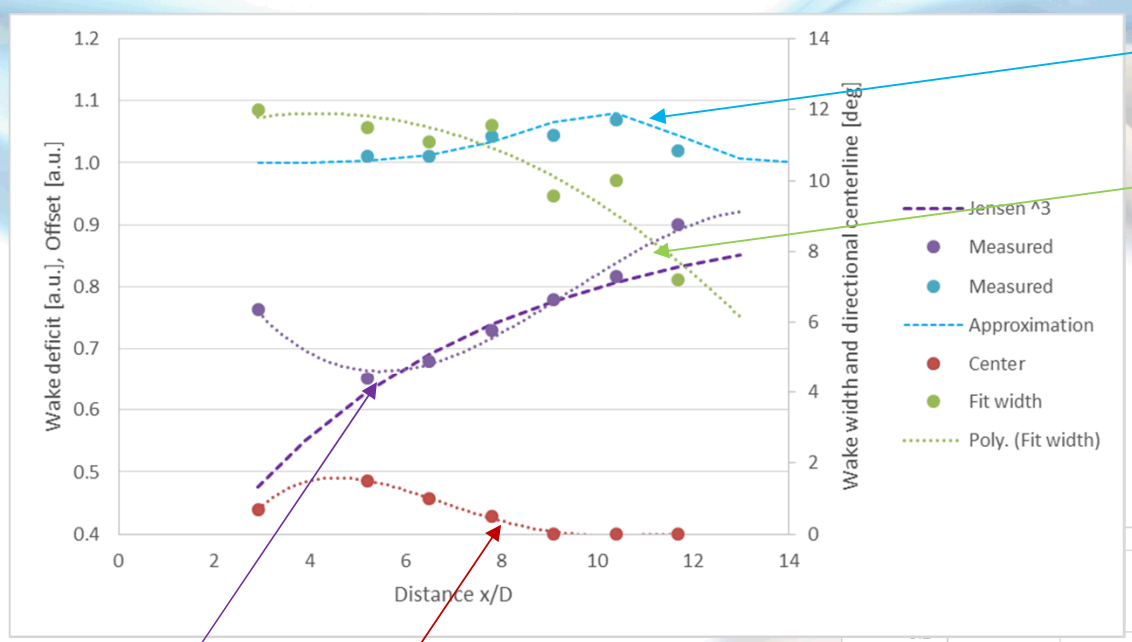


Max deficit/ peak
variability of wakes is not
a straight line !



Curves are from 5 to 11.5 D

Parameters



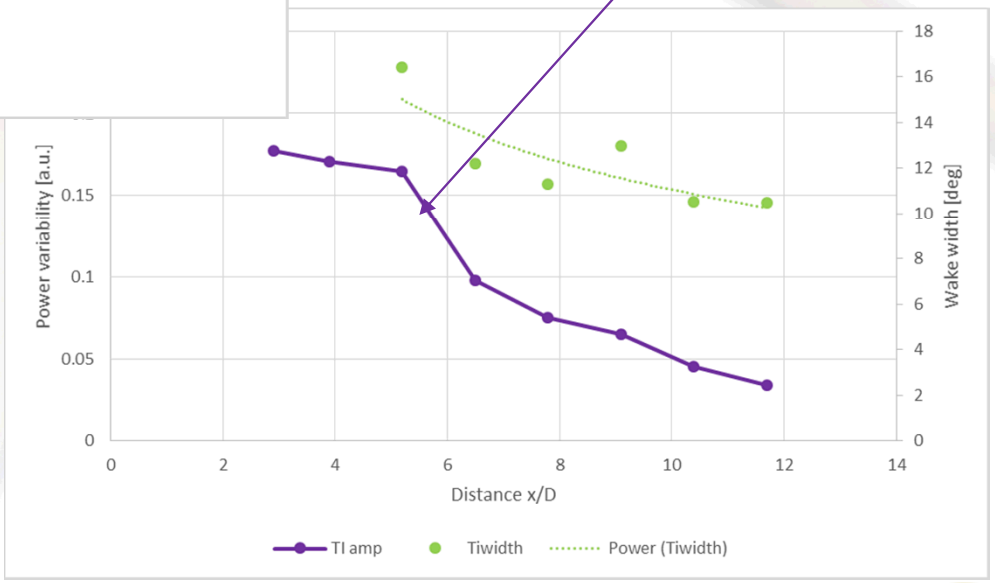
Speed-up

Width

Variation

Deficit

Centerline offset



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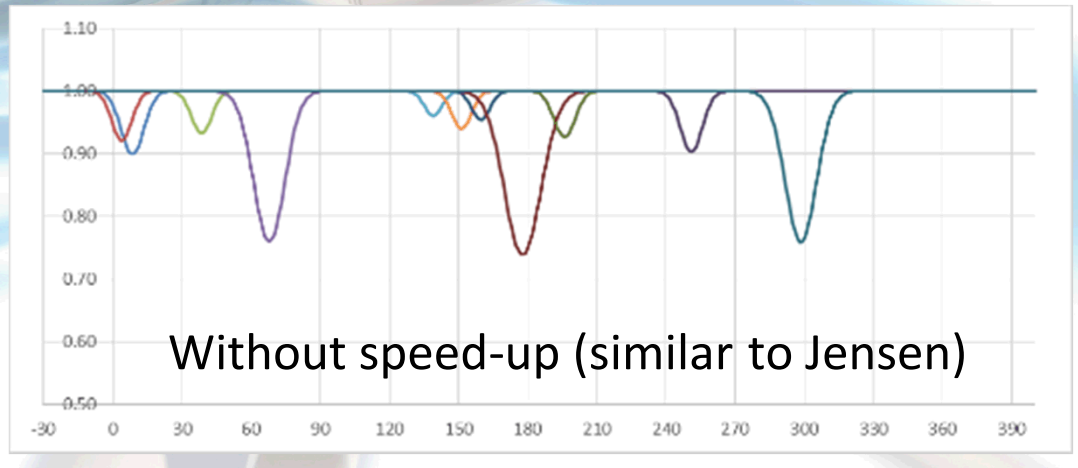
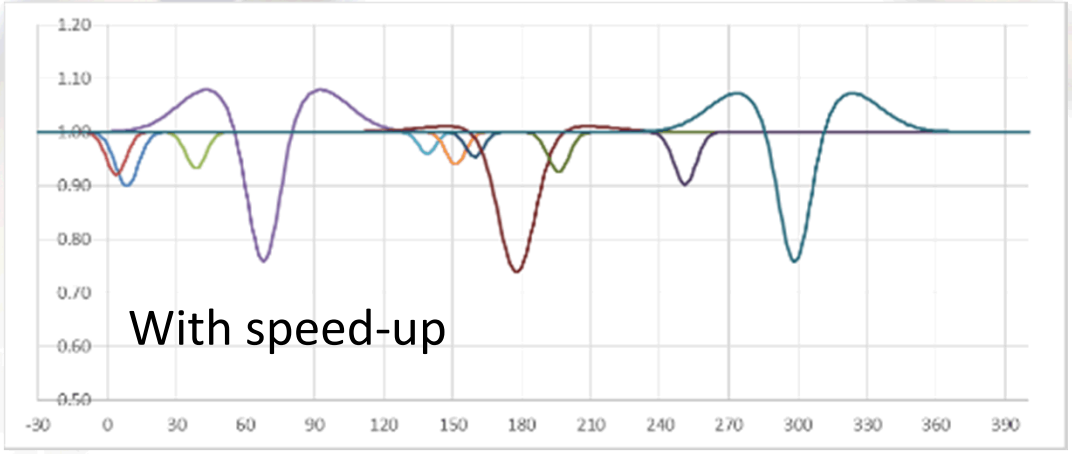
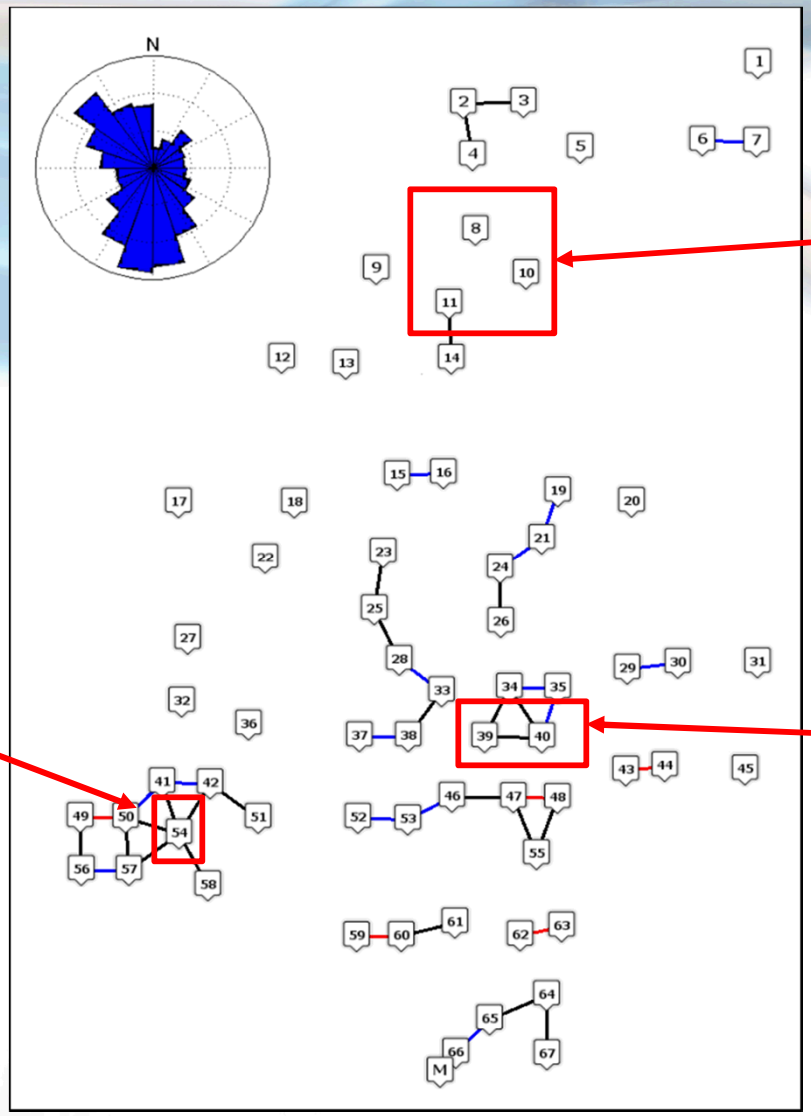
New model – in development

- Sum wakes from neighboring turbines in polar coordinates





Two examples

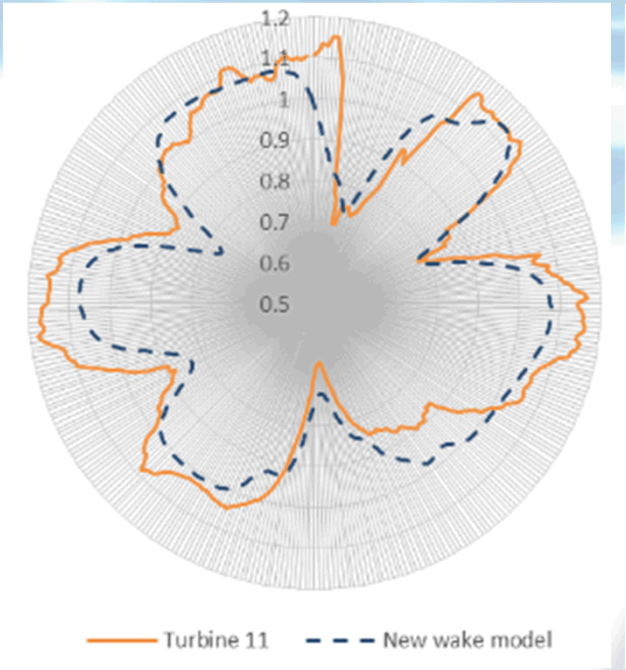


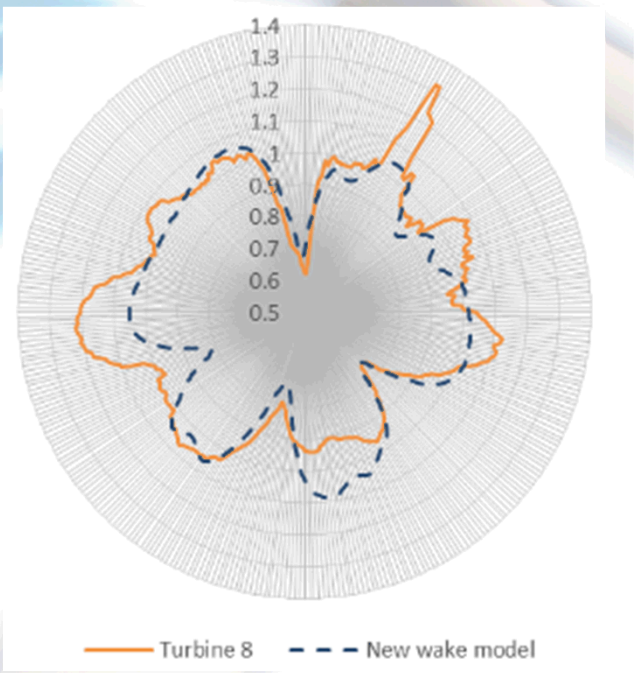
Sparsely waked

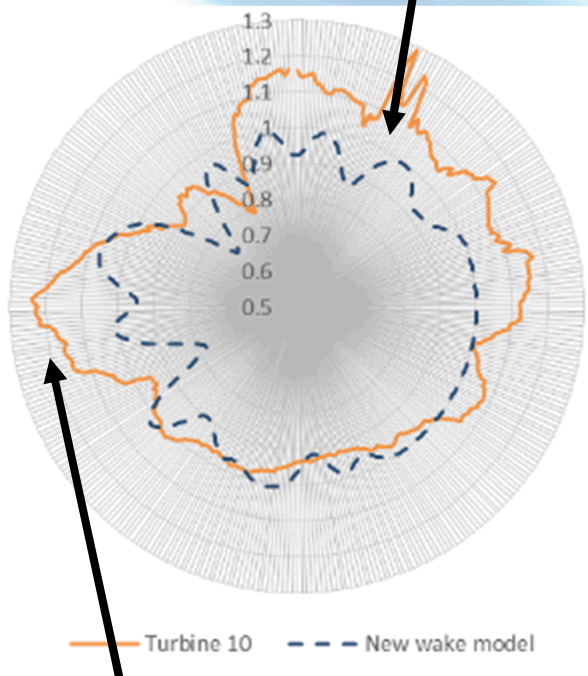
Closely waked

Heavily waked

Example: Sparsely waked



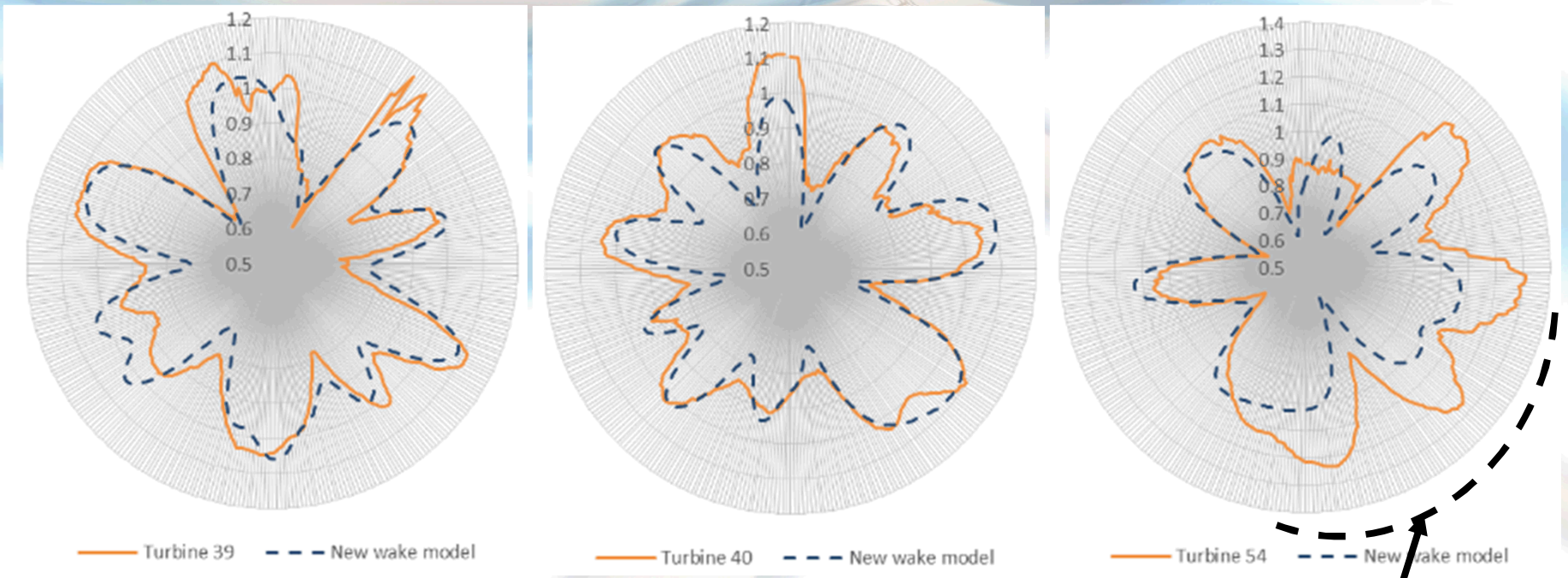




Tree cluster,
Farm building
Small hills

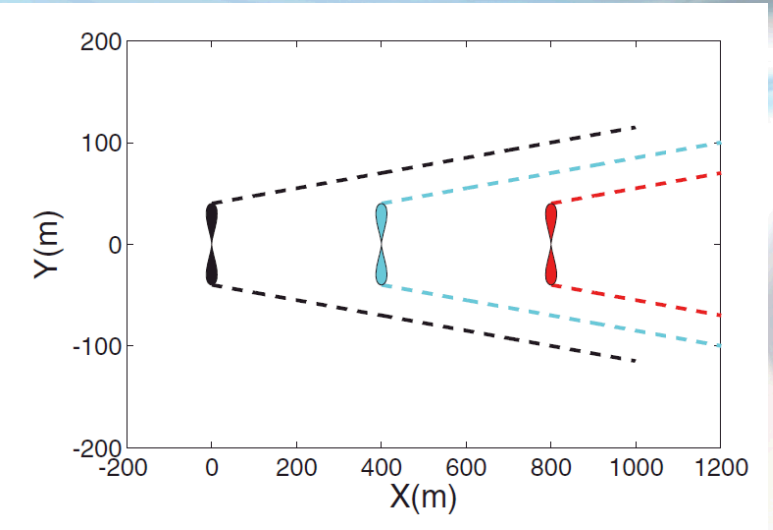
Multi-row of turbines
Other wind farm

Example: Heavily and closely waked



High speed-up seen at neighbor turbines, probably from the upstream wind farm

Wakes reduction, greedy versus collaborative control



- Needs of cause to be convoluted with actual wind distributions

	Gain by deferred wake loss - greedy versus balanced induction	
Name	Potential	Direction
Windfarm 1	16.1%	295
Windfarm 2	9.1%	99
Windfarm 3	5.2%	120
Windfarm 4	7.1%	96
Windfarm 5	24.7%	249
Windfarm 6	8.1%	22
Windfarm 7	3.9%	281
Windfarm 8	8.7%	268
Windfarm 9	5.5%	291
Windfarm 10	4.5%	307
Windfarm 11	10.9%	90
Windfarm 12	17.4%	92
Windfarm 13	10.7%	90
Windfarm 14	10.0%	272
Windfarm 15	4.4%	276
Windfarm 16	5.6%	266
Windfarm 17	18.8%	208
Windfarm 18	11.3%	88
Windfarm 19	9.0%	271
Windfarm 20	1.2%	267
Windfarm 21	9.8%	340
Windfarm 22	3.6%	0
Windfarm 23	0.9%	179
Windfarm 24	1.6%	292
Windfarm 25	17.1%	347
Windfarm 26	24.0%	159
Windfarm 27	13.5%	169

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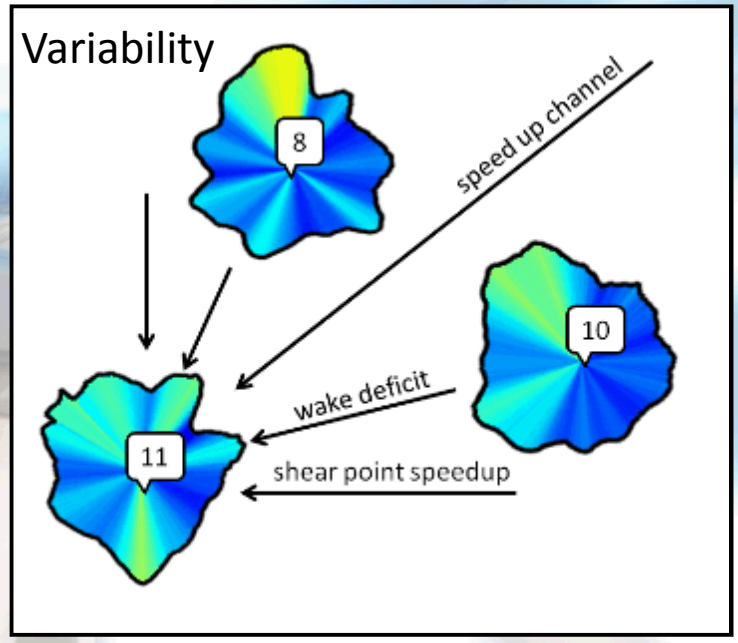
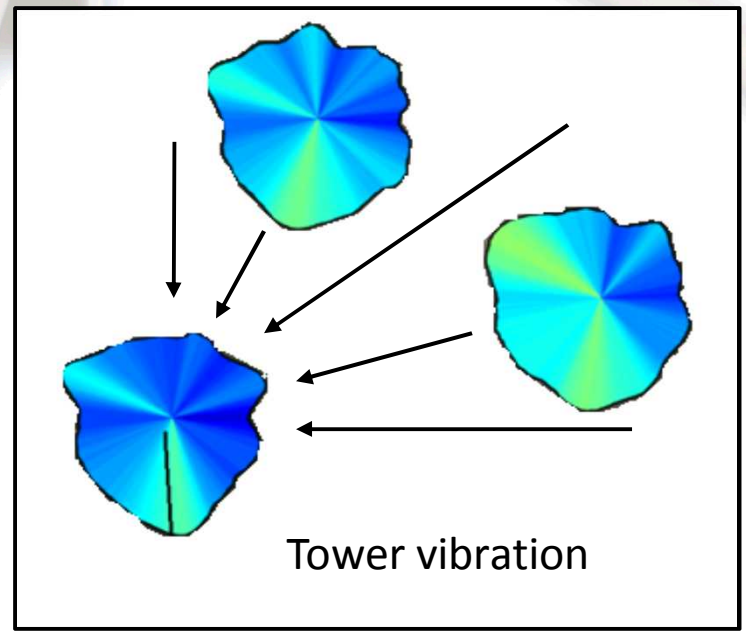
Tower vibration (exploratory)

- Similar effects in tower vibration and power variation is observed
- In-direct wind effects
- Next step – refine methods and identify correlations and validate on multiple wind farms





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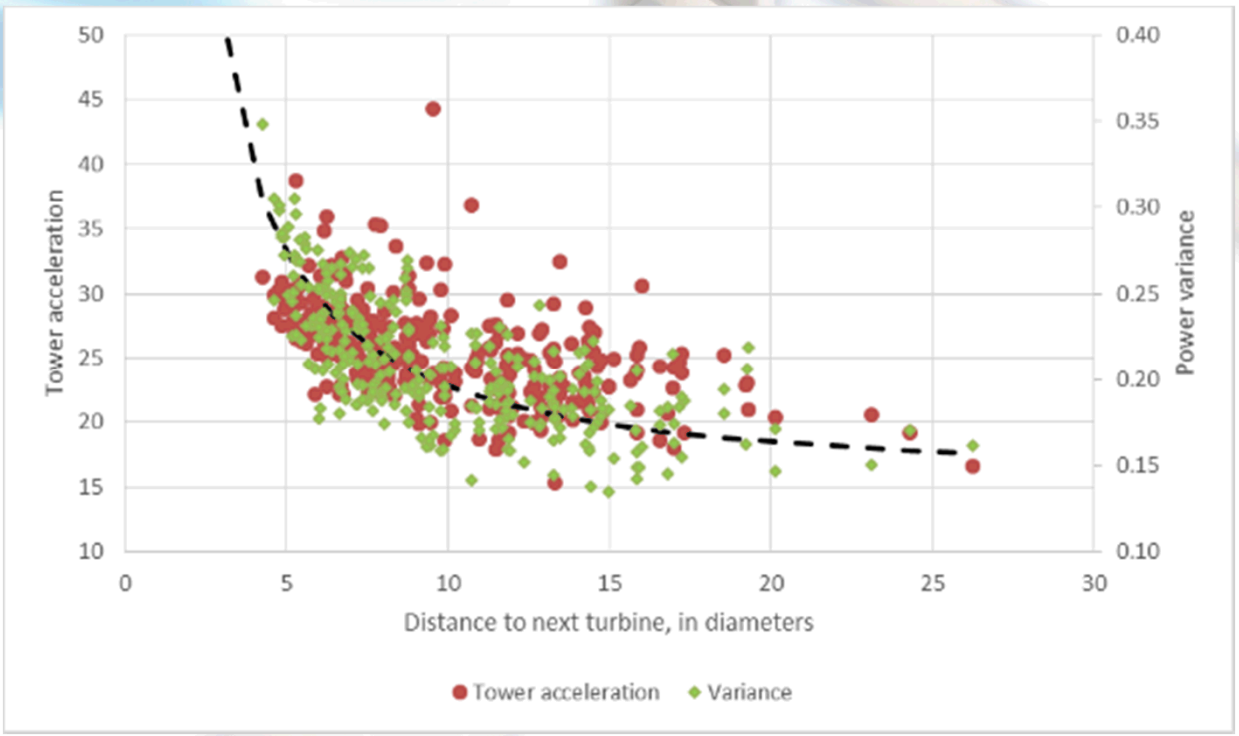
Tower vibration in wakes (exploratory)

- The power variance and tower vibration are well aligned in wakes



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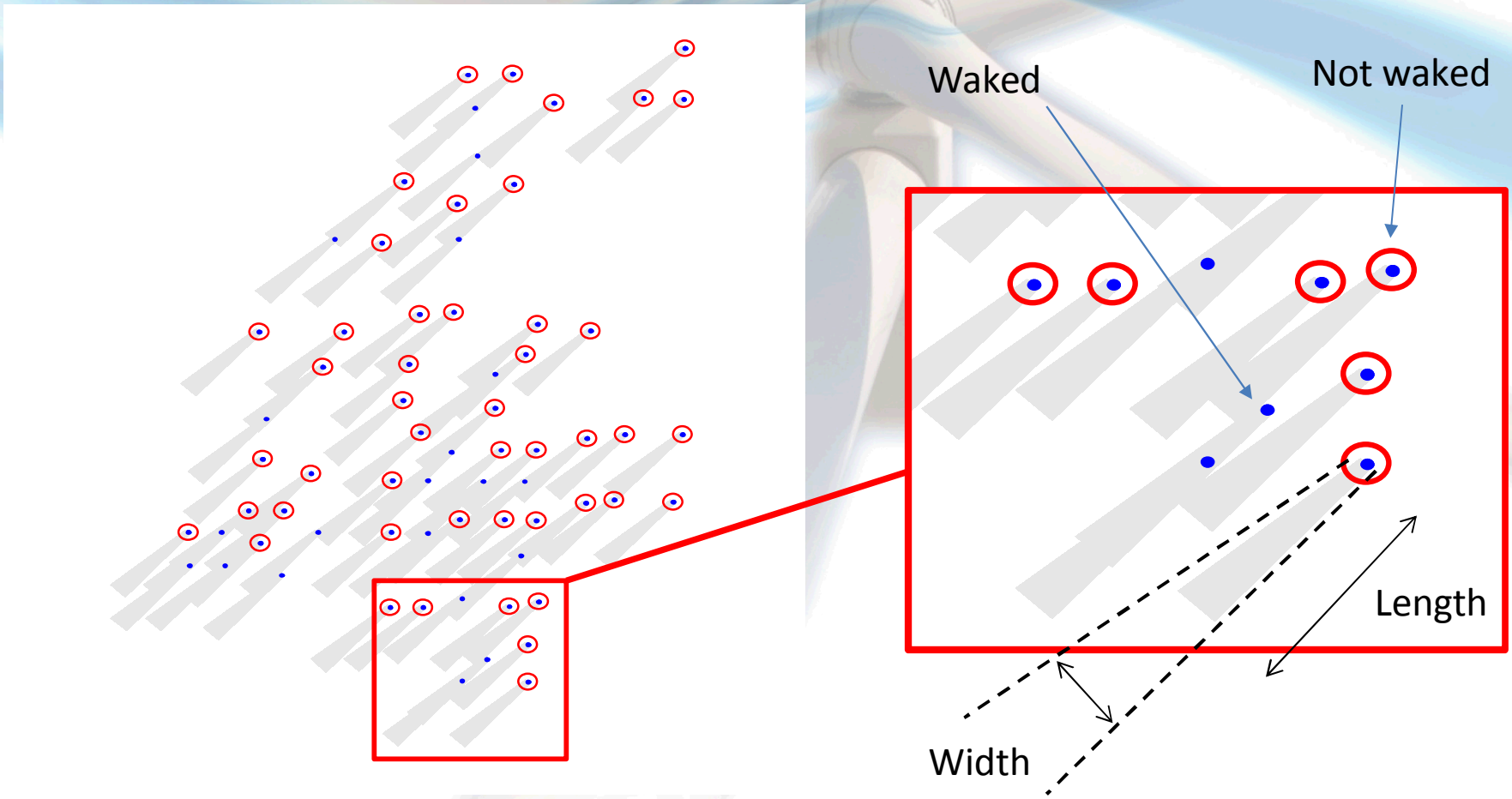
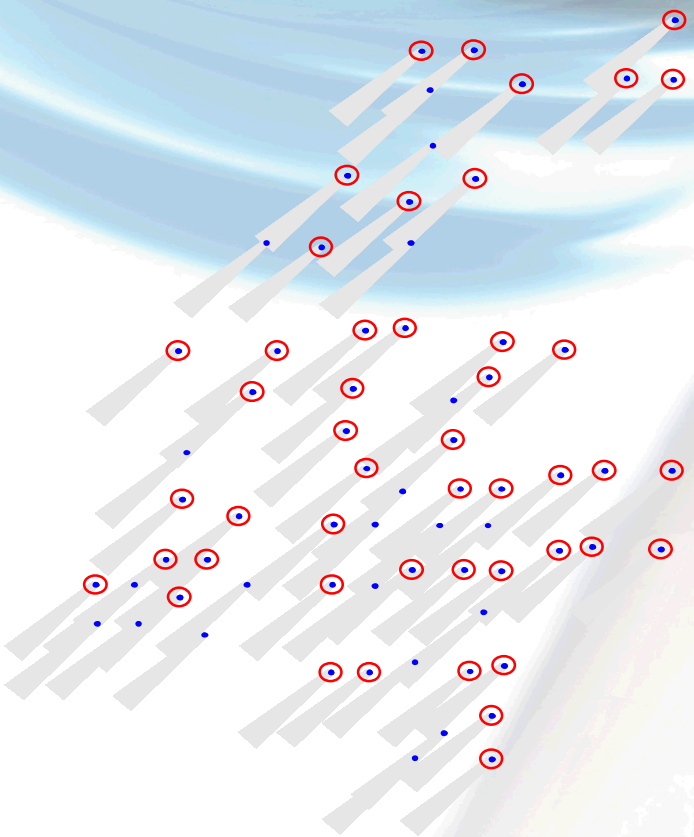
Error flags (exploratory)

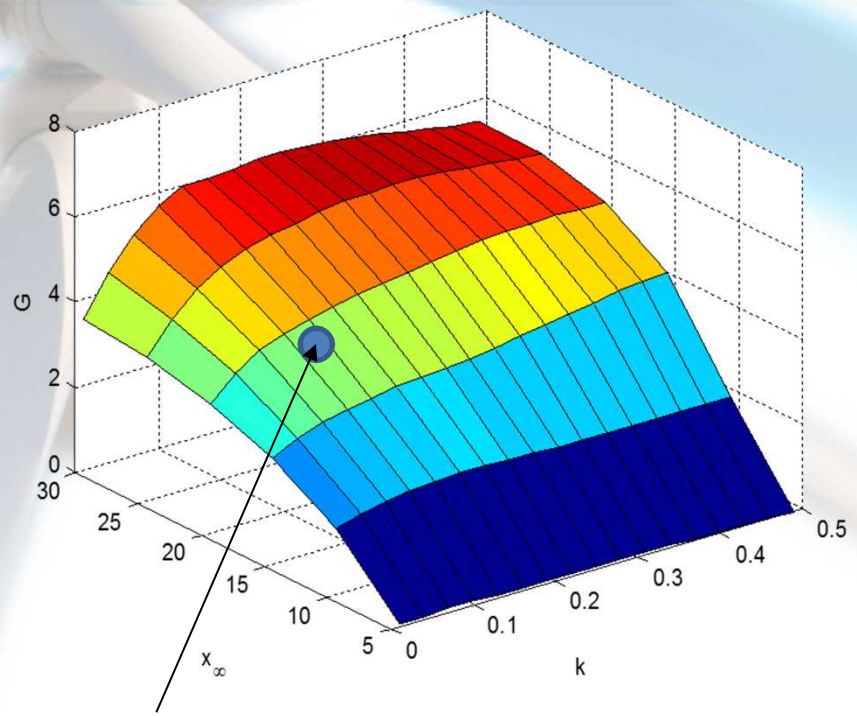
- Simple error count tend to align with main wind direct, although there is great individual variation across the wind farm
- Challenge is to catch the count and relevance of error leading up to the event

Determination of waked / not waked



Wake loss as function of assumed wake shape





Standard model parameters,
Sum of loss and gains is about 3% loss

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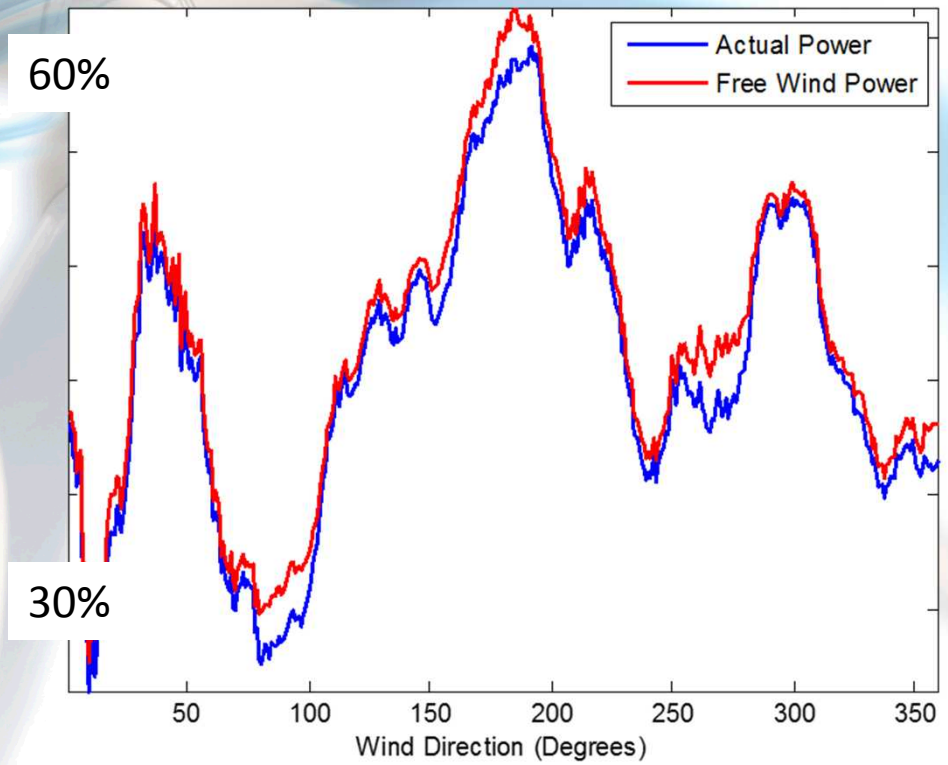
Free versus actual wind power

- This wind farm is “randomly” layout, so difference between free front row wind power and overall wind power is small
- In other wind farms, these can be much more significant



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Conclusion and outlook

- The novel directional analysis applied has proven effective in mapping wake deficit in a complex wind farm layout
- New speed-up effects have been documents and a simple model is proposed
- Performance related use of the new wake effects/model could be:
  - Impact on wind farm layout modeling
  - Use as “mask” for under performance detection
  - Use for rapid projection of forecasting based on direction
  - Fleet-wide (or nation wide) performance mapping
  - Use as mask for wind farm controllers
- Reliability related use could be:
  - High power associated with the speed-up effects is counter-intuitively associated with low power variability and lower vibrations
  - Simple correlation with machine performance could be established
  - Convolute performance with fault analysis could provide insight
  - Analysis could enhance the relationships and give accurate lifetime performance (power and reliability) estimates

They have figured it out !