

Wind-farm power production diagnostic tools with applications to wake steering

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(acknowledgement to J. Lundquist and M. Rhodes for wind cube data)

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National Renewable Energy Laboratory
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ISU Wind Science Research Facilities

- ❖ **Research field site in a homogeneous agricultural landscape**
 - ❖ Flat terrain
 - ❖ Homogeneous agroecosystem
 - ❖ Corn and soybeans during growing season
 - ❖ Bare soil outside the growing season
- ❖ **Identical twin 120-m meteorological towers**
 - ❖ One inside a utility scale wind farm
 - ❖ One at the windward edge of the same wind farm
 - ❖ 22 km apart
 - ❖ Instrumented at 6 levels for mean flow and turbulence research
- ❖ **Surface flux stations**
 - ❖ Crop-atmosphere interactions
 - ❖ Turbine impacts on crops
- ❖ **Diagnostic and modeling tools**
 - ❖ WRF model improved for stably stratified boundary layer
 - ❖ Wake diagnostic tools



SCADA Diagnostic Tools

❖ Data

- ❖ SCADA data from three wind farms with utility-scale turbines

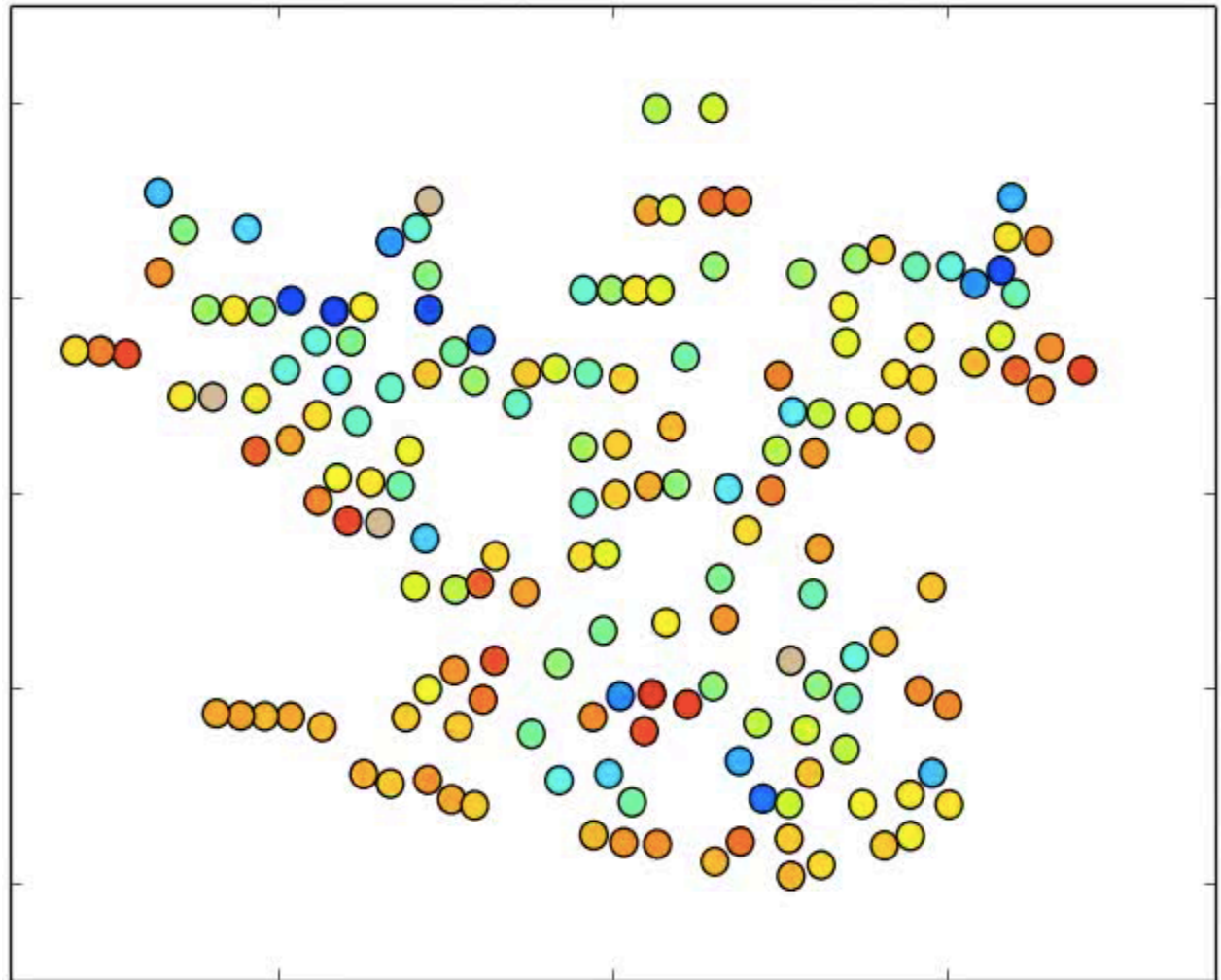
❖ Capabilities

- ❖ Work-arounds for irregular data-reporting time stamps
- ❖ Yaw correction for uncalibrated yaw in SCADA data
- ❖ Wind Plant Power Production Visualization
- ❖ Farm-wide power curve, yaw monitor, pitch monitor
- ❖ Wind Plant Power Production Animation
- ❖ Turbine Wake Power Reduction Diagnostic
- ❖ Wind Farm Power Production Directional Tool (categorized by stability and day vs night)
- ❖ Estimated seasonal value of wake steering for individual turbines in a wind farm
- ❖ On-the-fly power curve, farm yaw monitor, pitch monitor



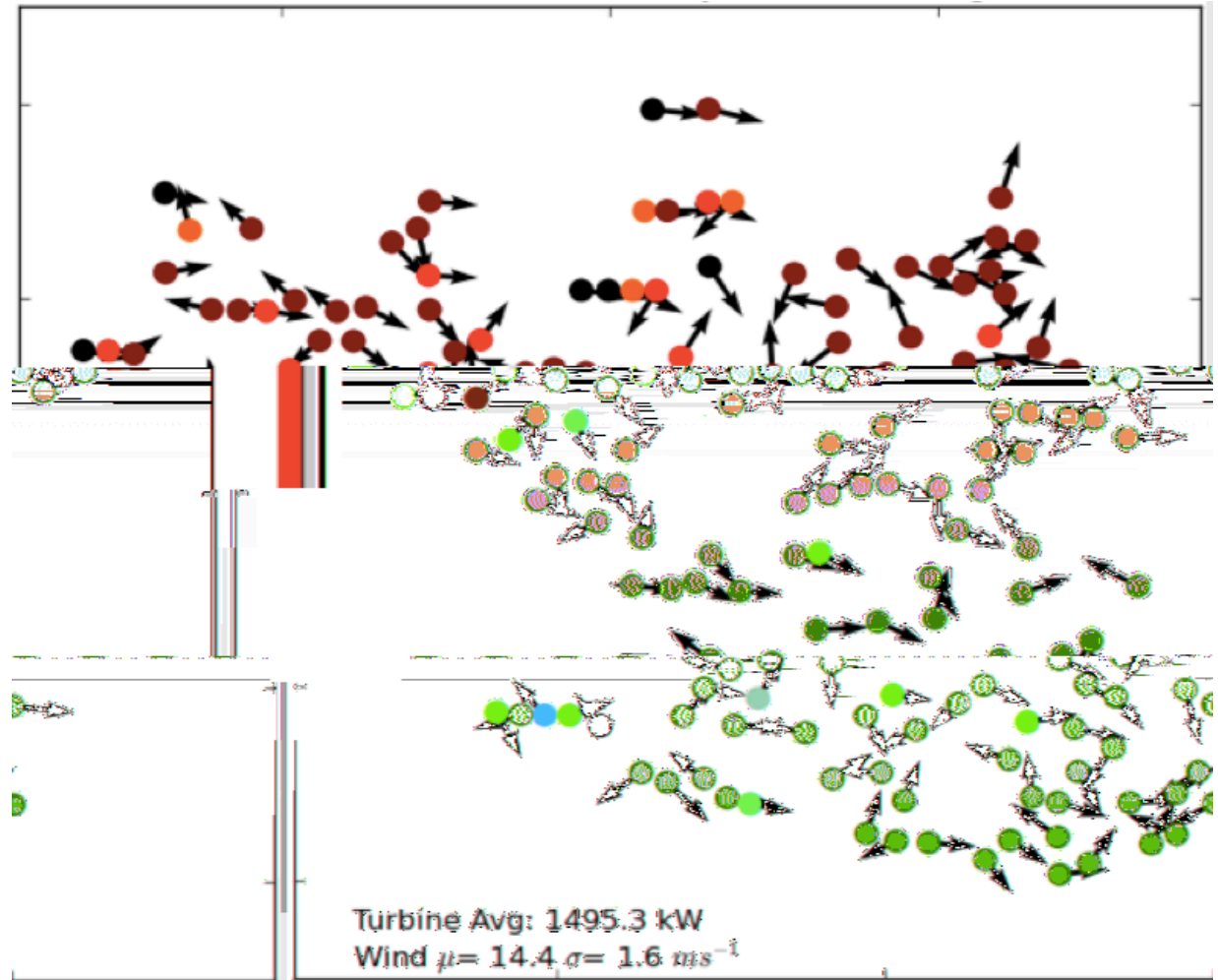
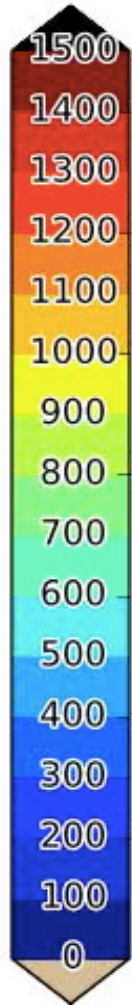
SCADA Diagnostic Tools:

Power visualization



SCADA Diagnostic Tools:

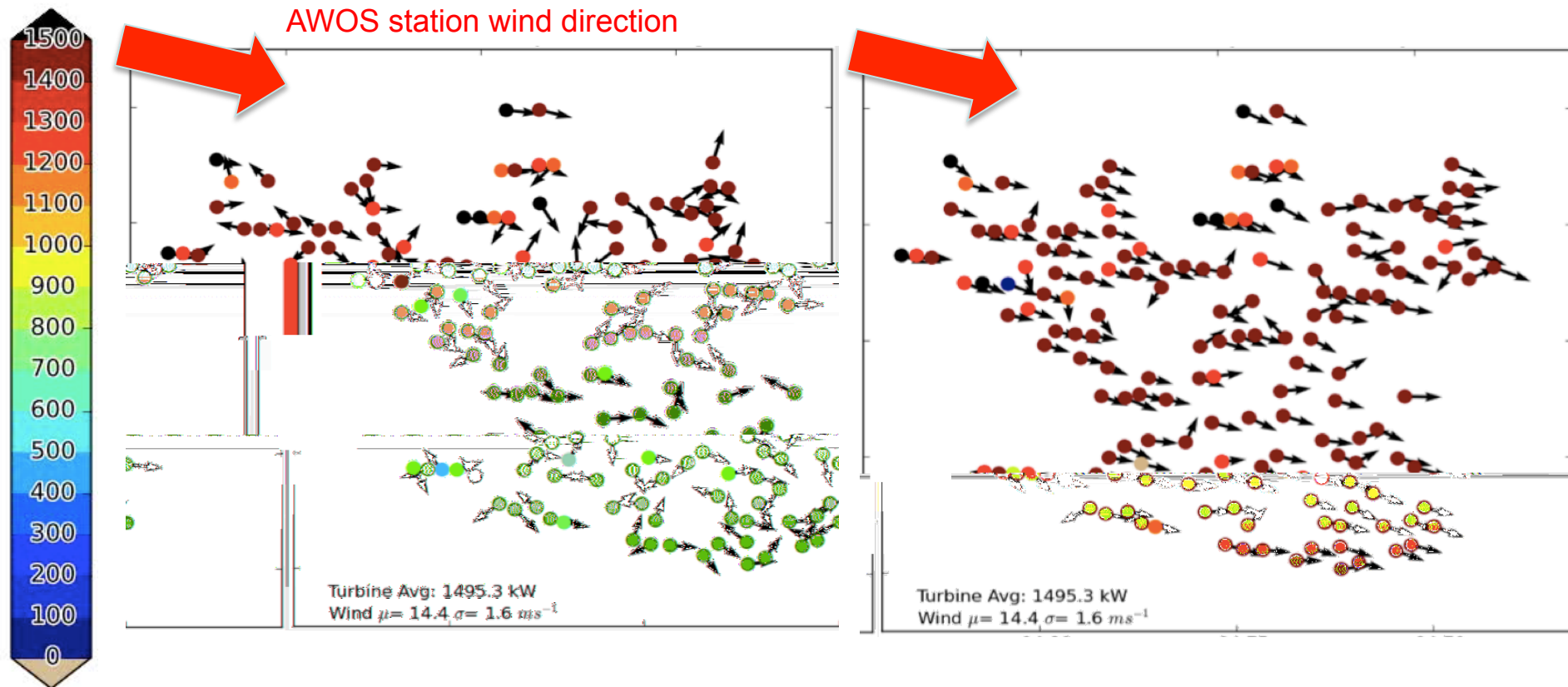
Power visualization



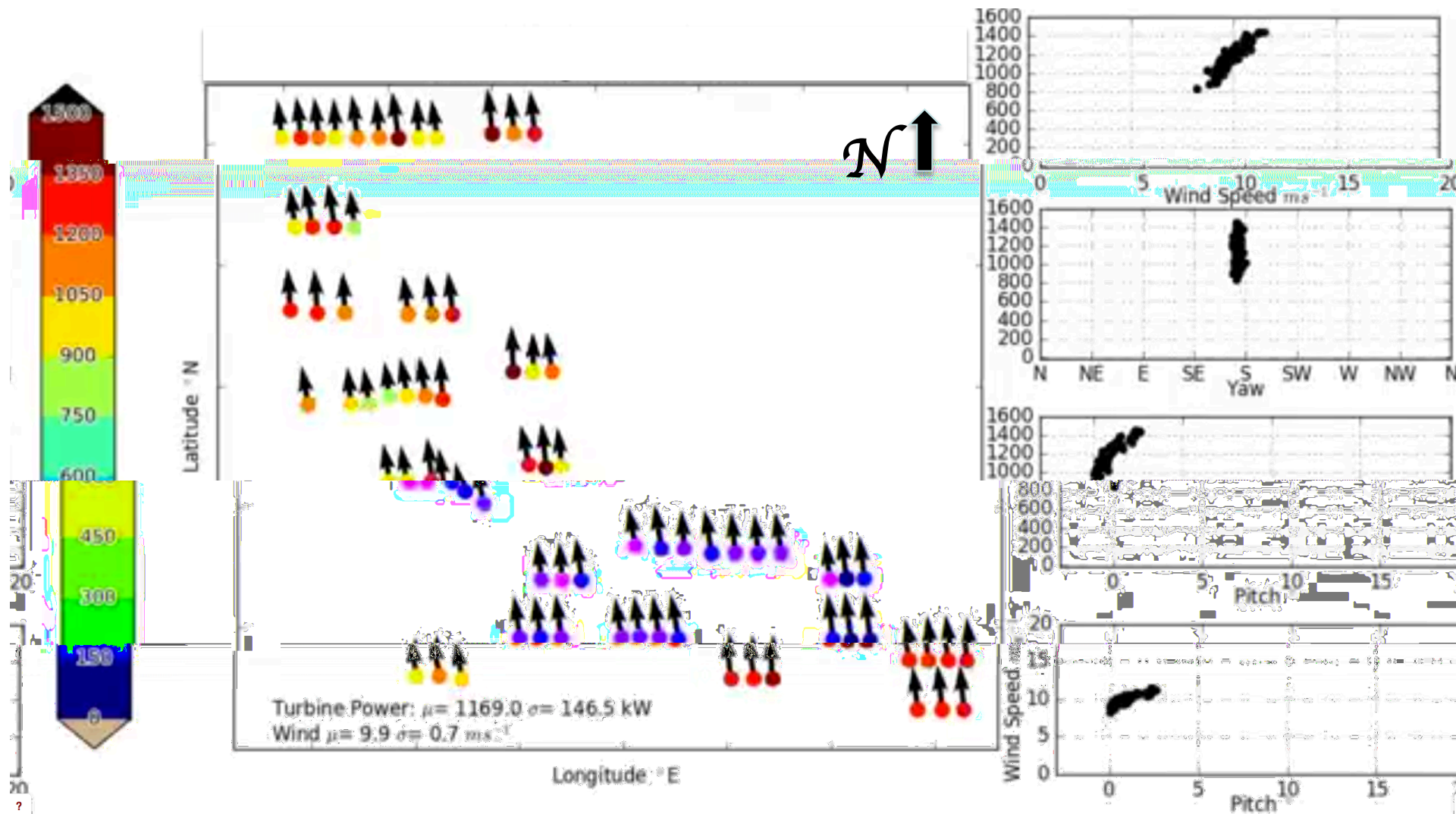
SCADA Diagnostic Tools: Power visualization

Before

After

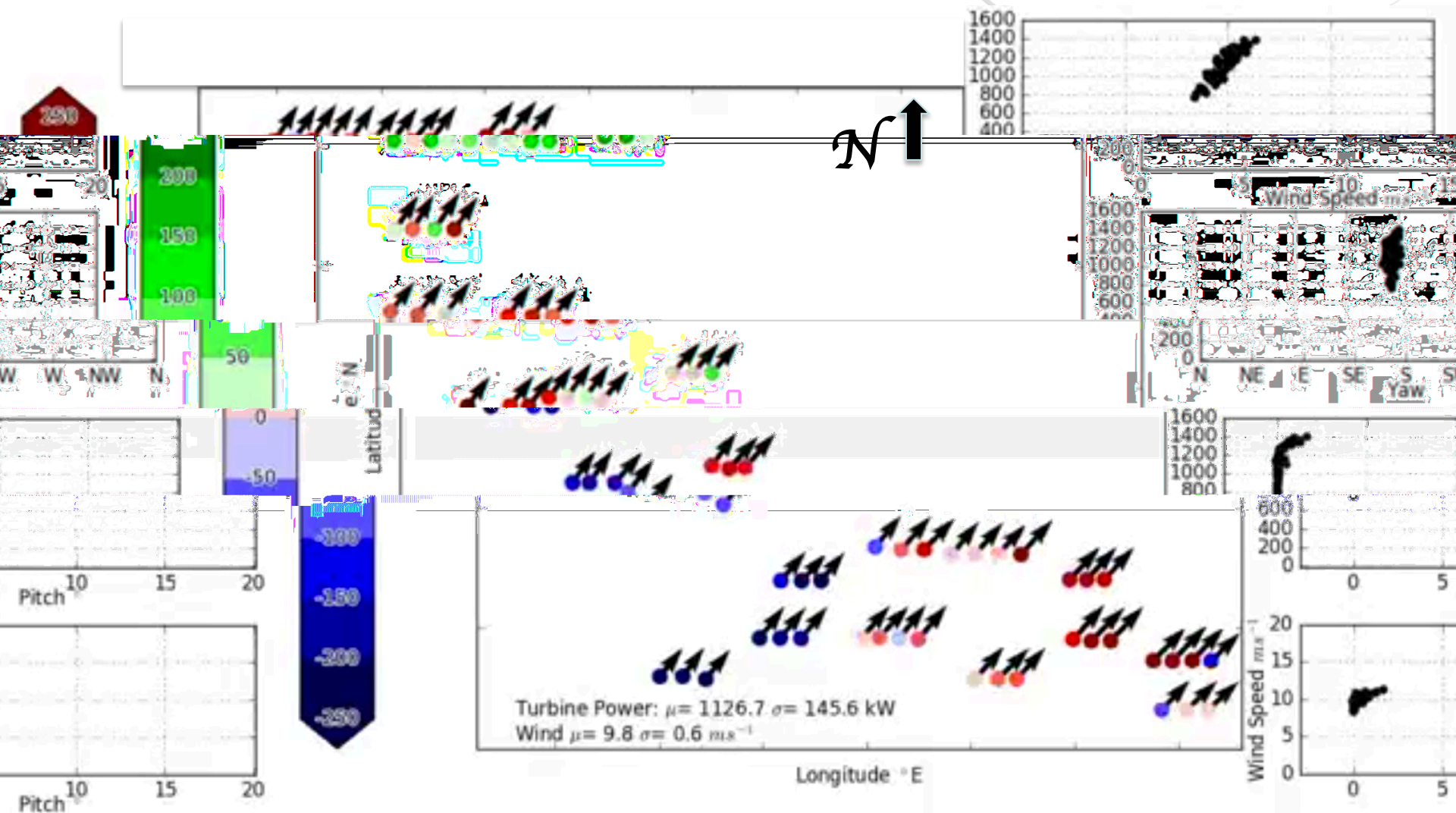


SCADA Diagnostic Tools: Power visualization



SCADA Diagnostic Tools:

Wind-Plant Turbine Power-Differential Tool

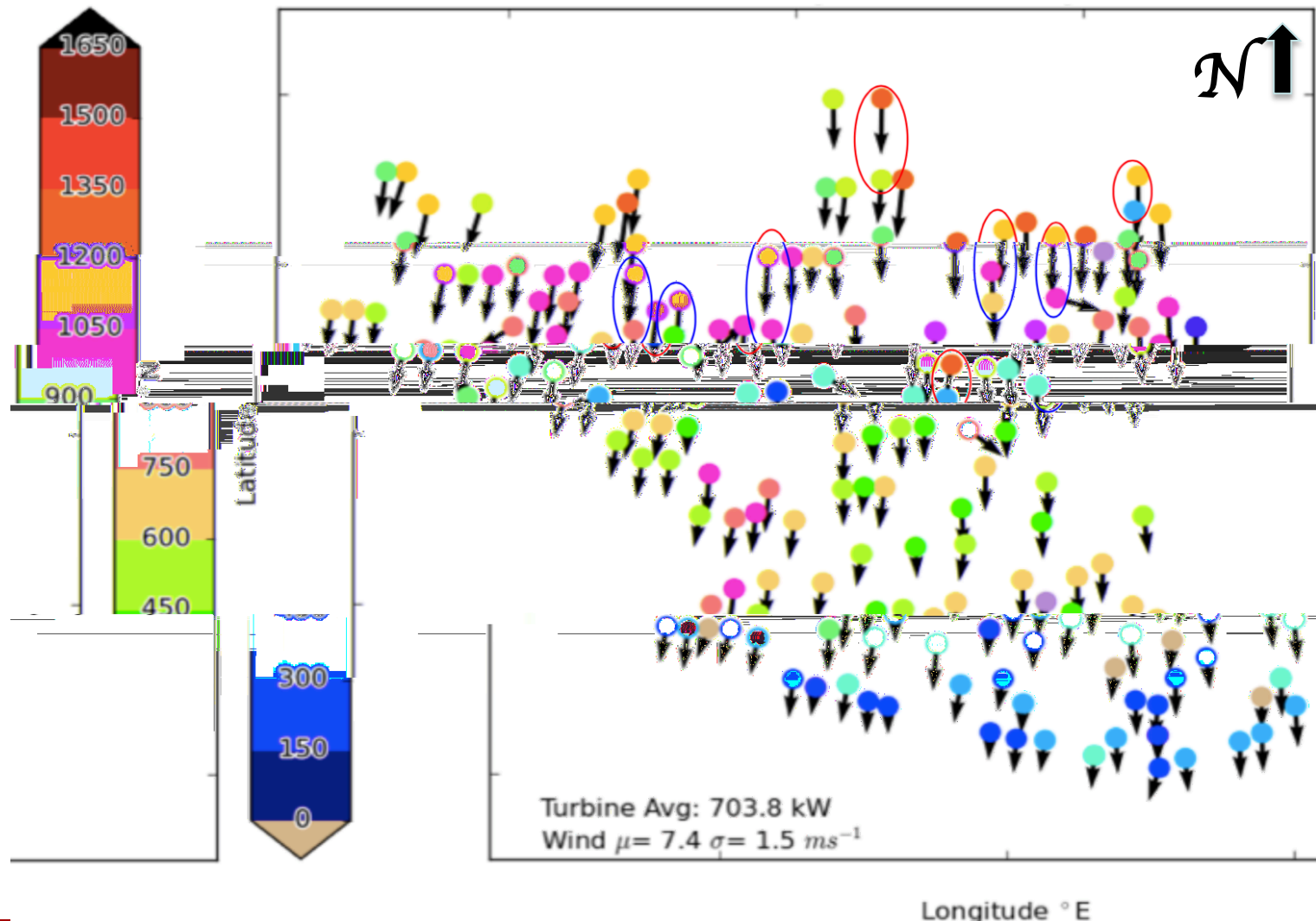


SCADA Diagnostic Tools: **Power visualization**

Animation 1

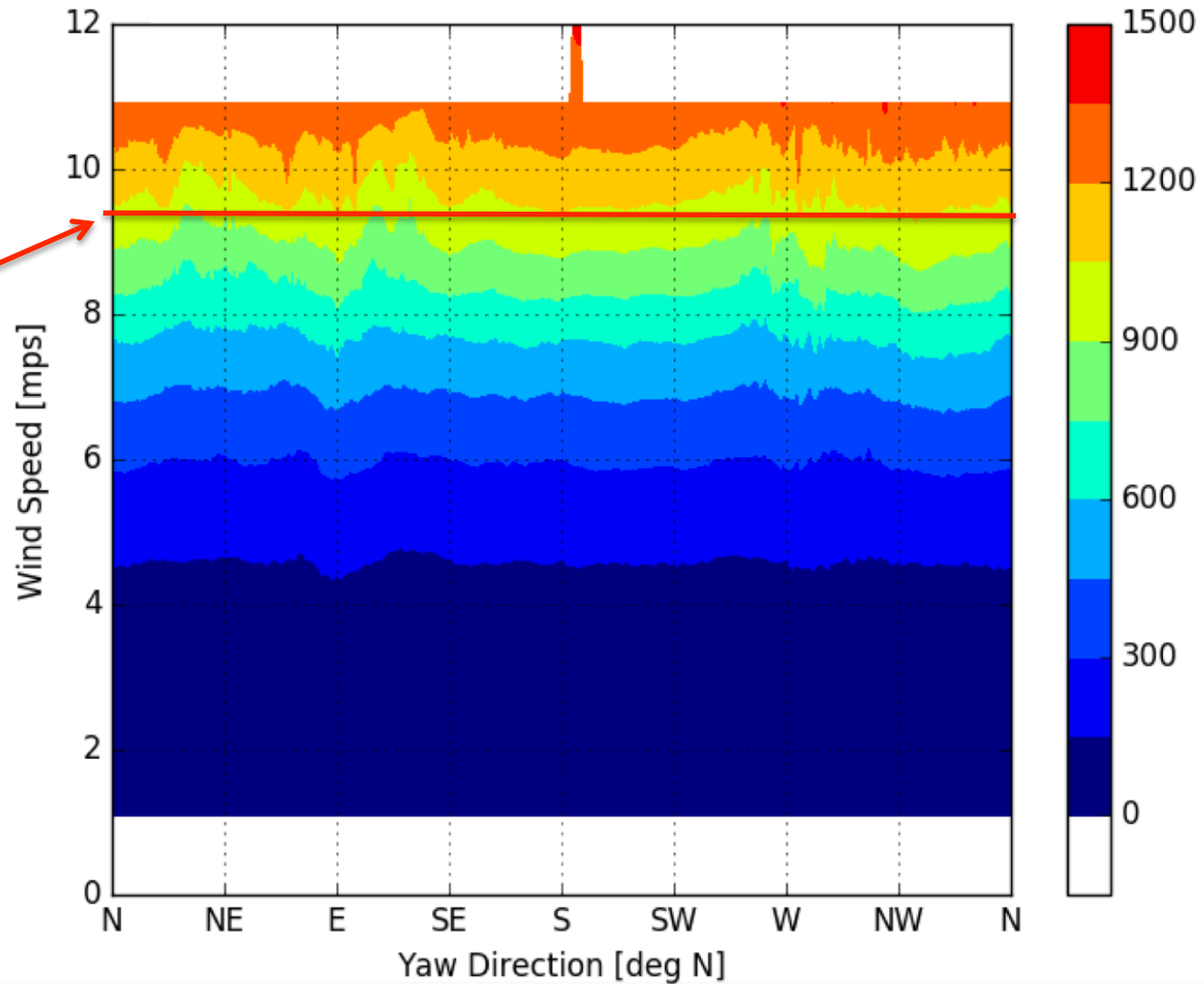
SCADA Diagnostic Tools:

Power visualization



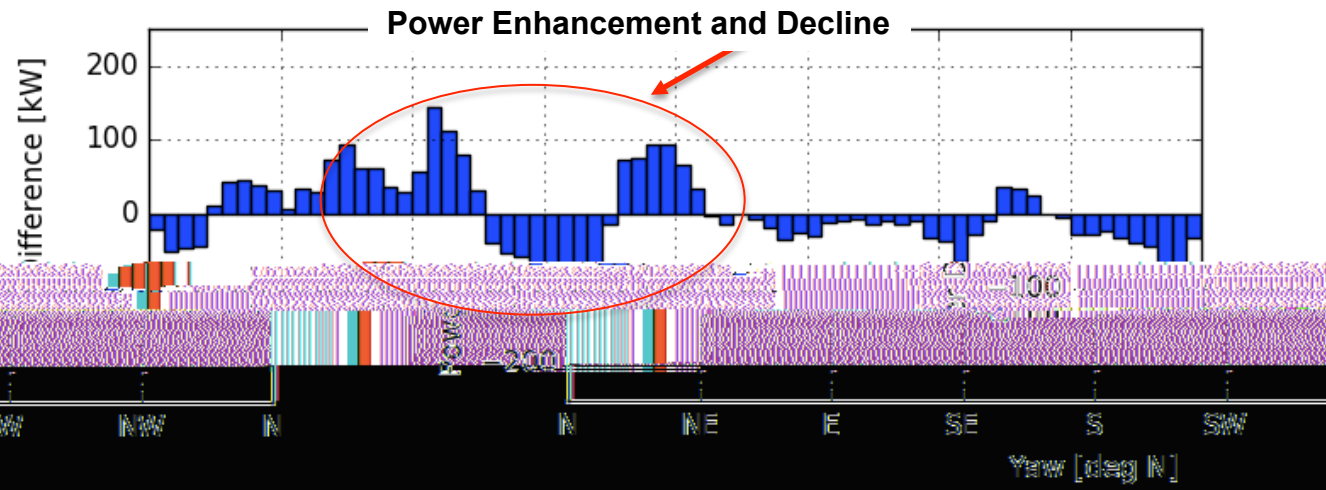
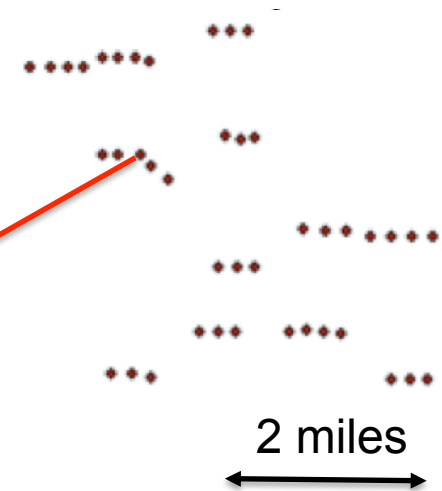
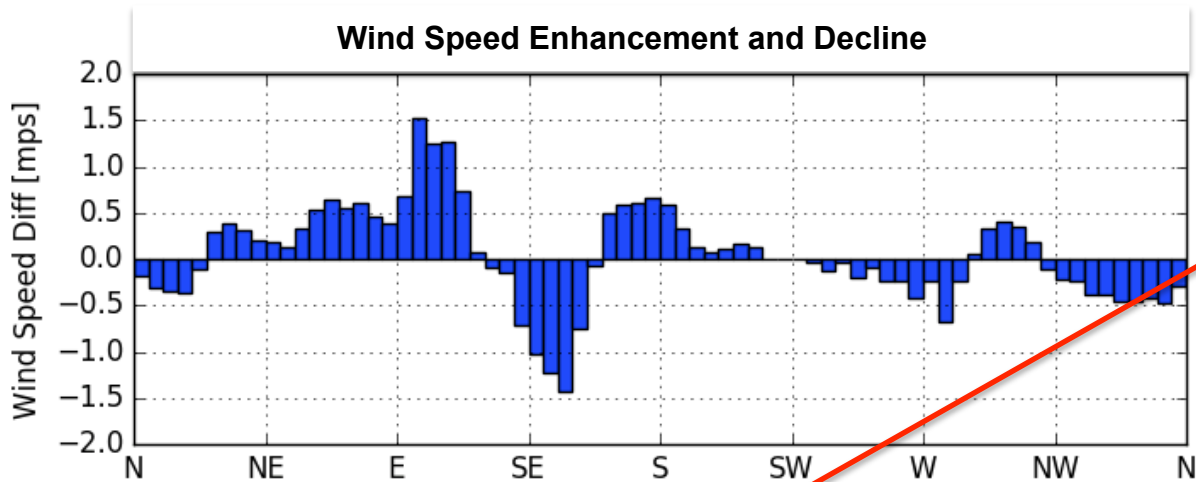
SCADA Diagnostic Tools:

Directional Power visualization



For a given wind speed the wind farm power can vary by ~ 15% depending on wind direction due mostly to wake interaction

SCADA Diagnostic Tools: Directional power evaluation

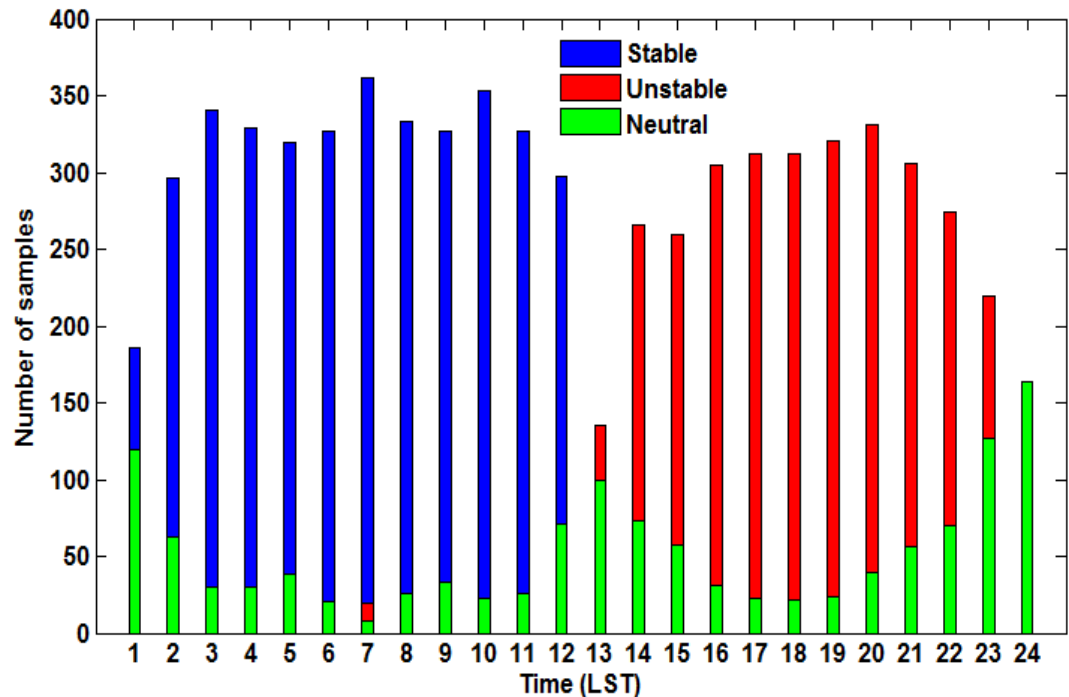


Stability and directional variability

Stability classification

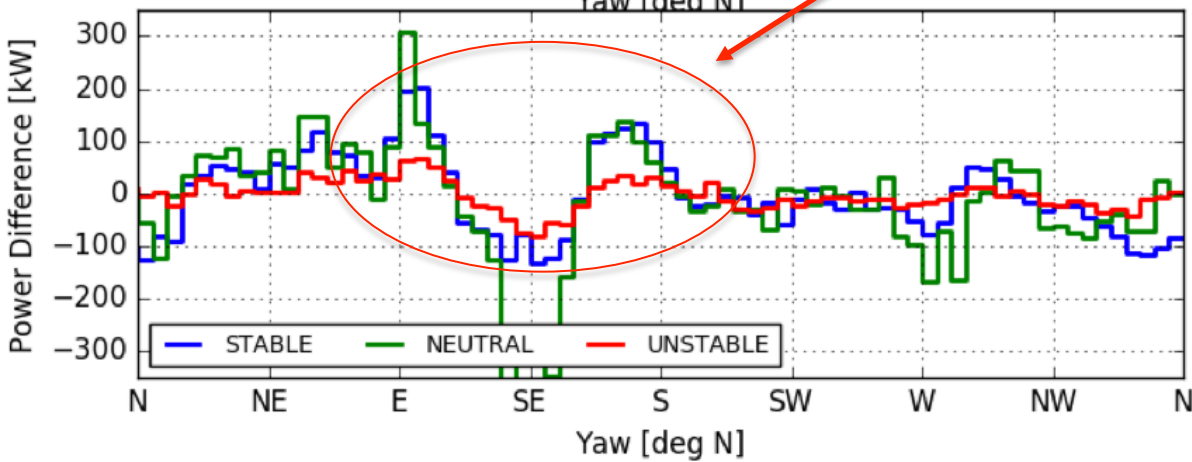
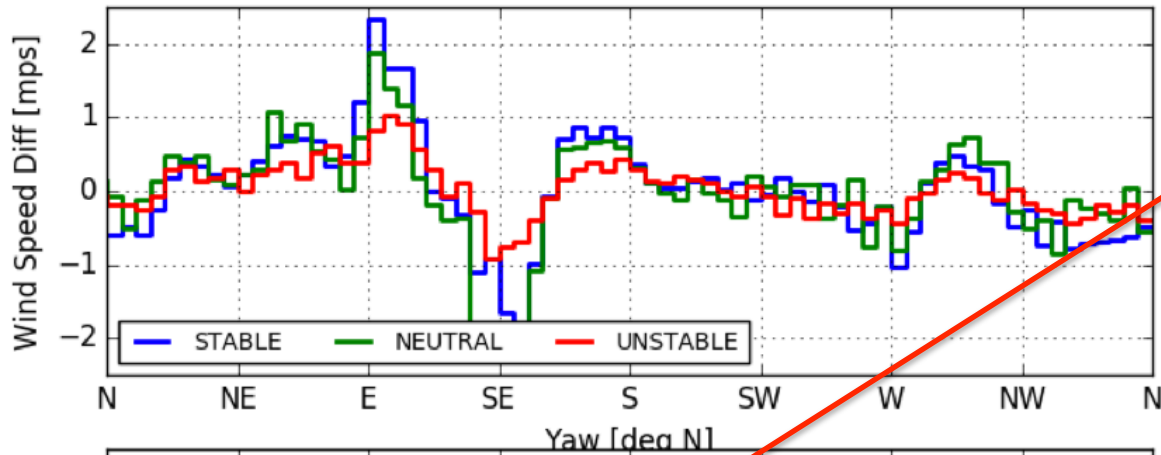
- ❖ Determine Obukhov length (L) from reference surface flux station **ISU 2** (south of P_0)
- ❖ Stability categories
 - **STABLE** $0 \text{ m} < L < 200 \text{ m}$
 - **UNSTABLE** $0 \text{ m} > L > -200 \text{ m}$
 - **NEUTRAL** $|L| \geq 200 \text{ m}$

Diurnal distribution of stability



Non-waked wind directions at CU 1 LiDAR from 145° to 255°

SCADA Diagnostic Tools: Directional power evaluation



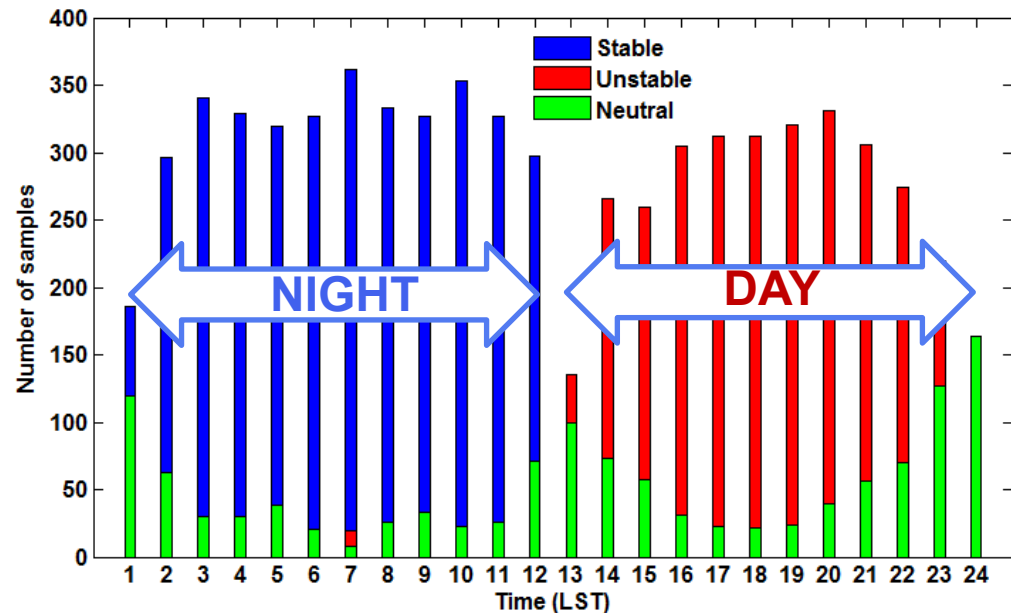
Stability and directional variability

Wake Concept Tool

Stability classification

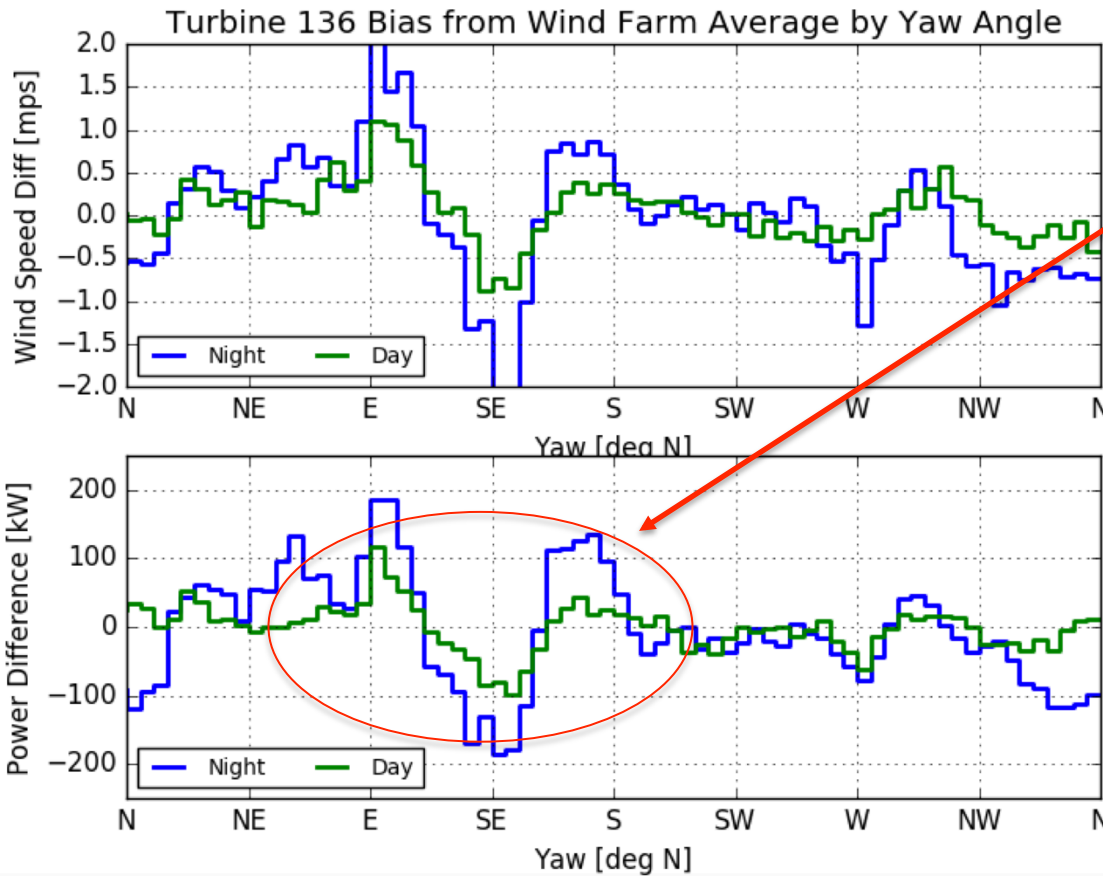
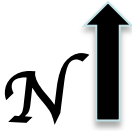
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- ❖ Stability categories
 - **NIGHT**
 - **DAY**

Diurnal distribution of stability
(summer case)

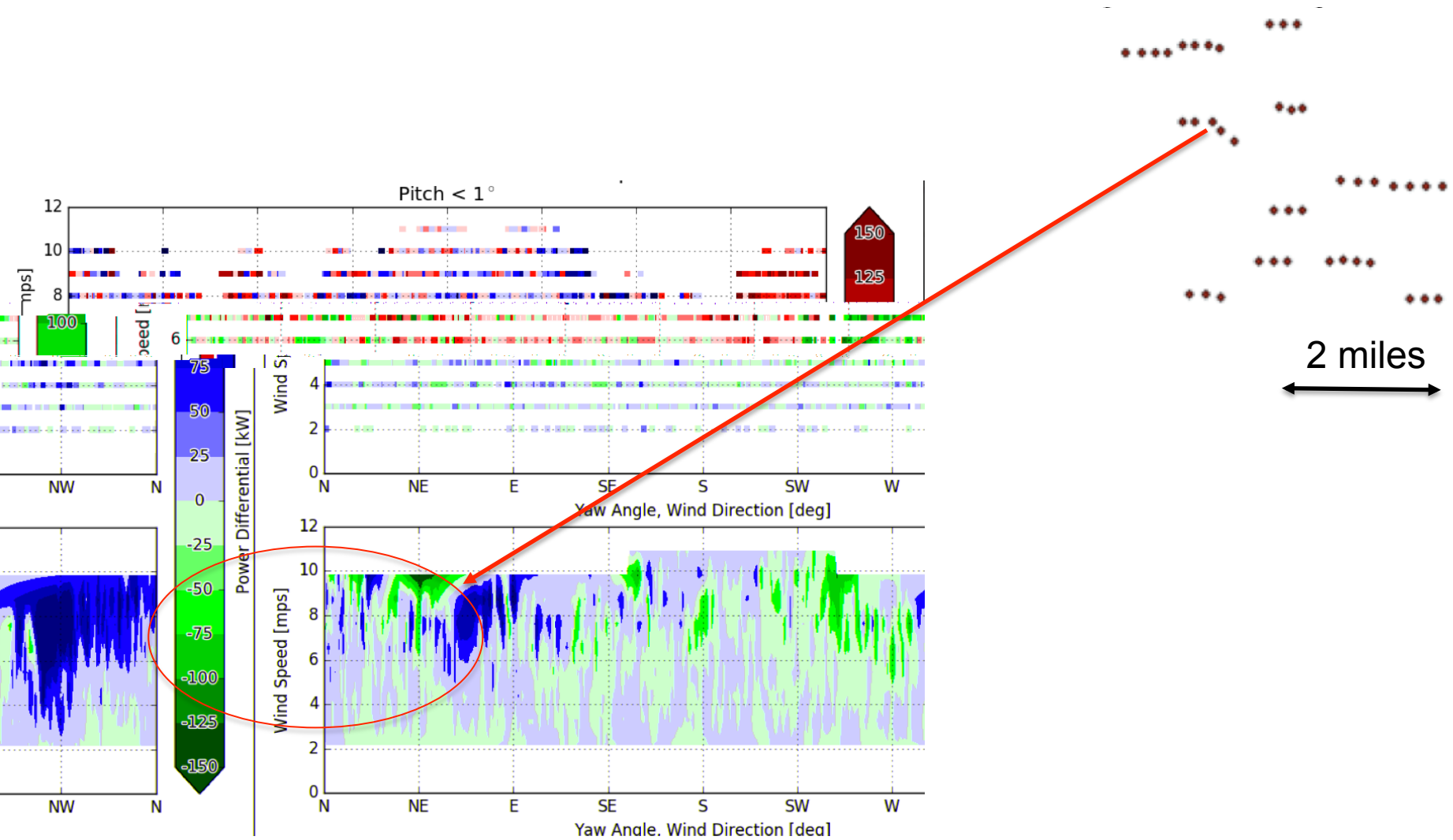


Non-waked wind directions at CU 1 LiDAR from 145° to 255°

SCADA Diagnostic Tools: Directional power evaluation



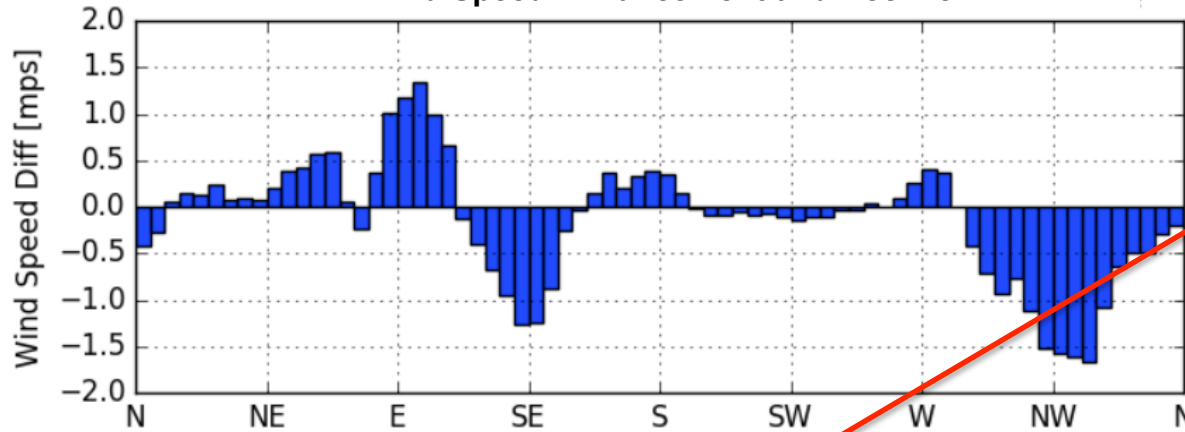
SCADA Diagnostic Tools: Directional power evaluation



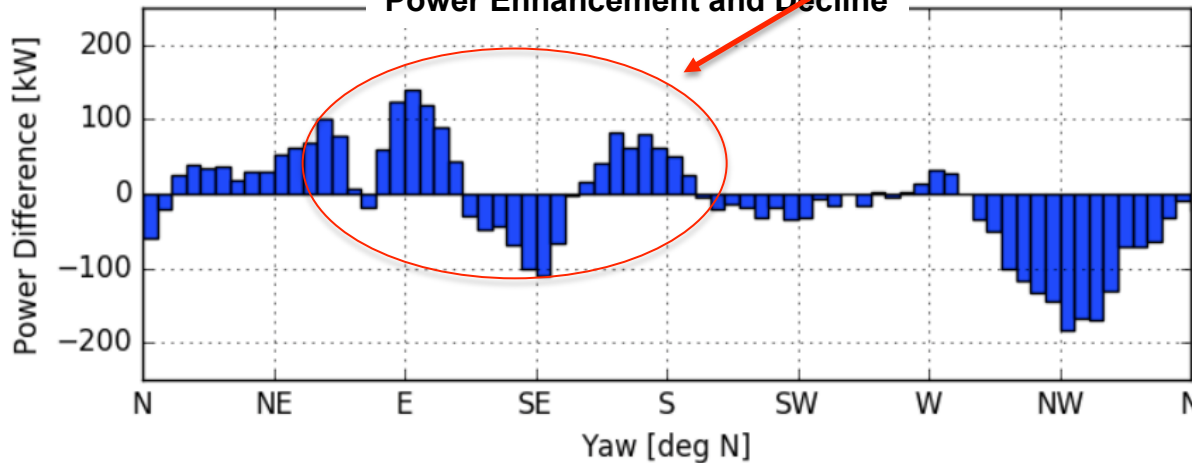
SCADA Diagnostic Tools: Directional power evaluation



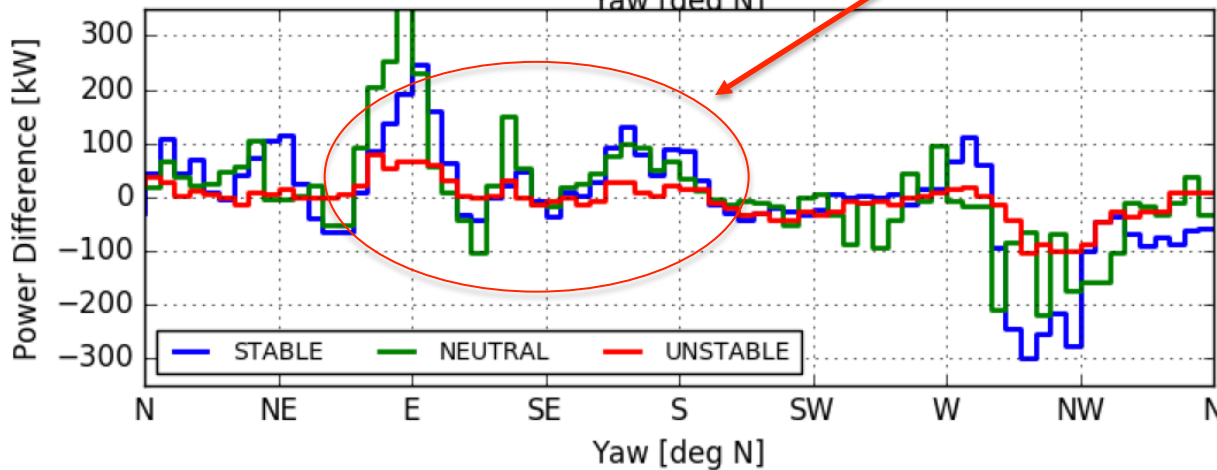
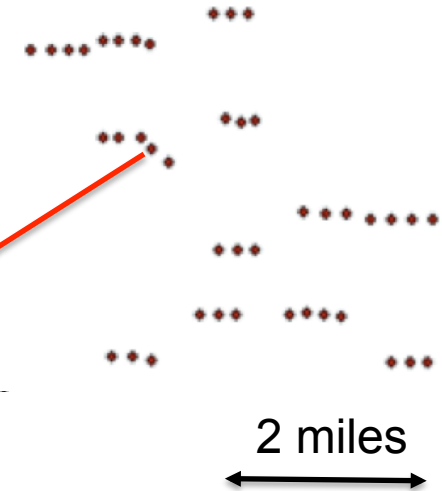
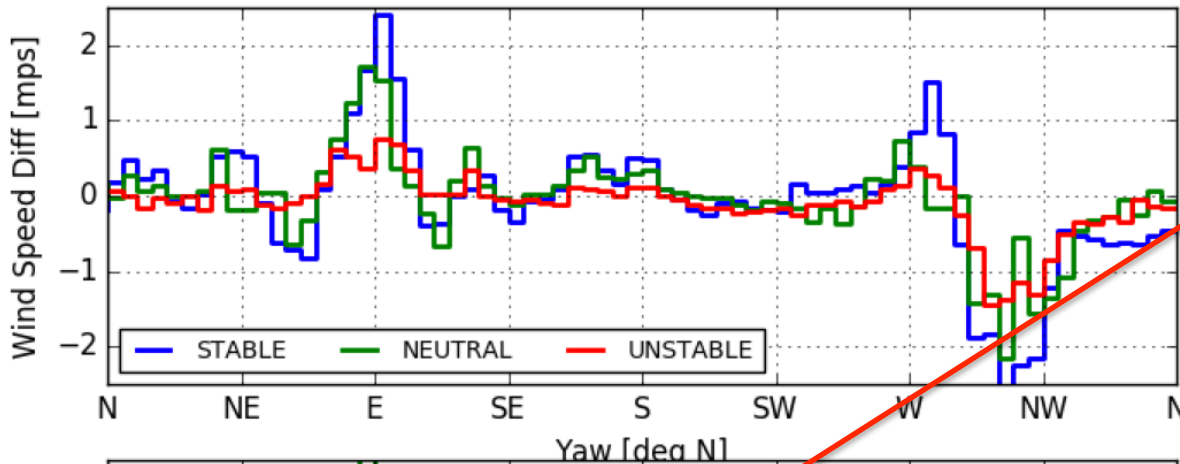
Wind Speed Enhancement and Decline



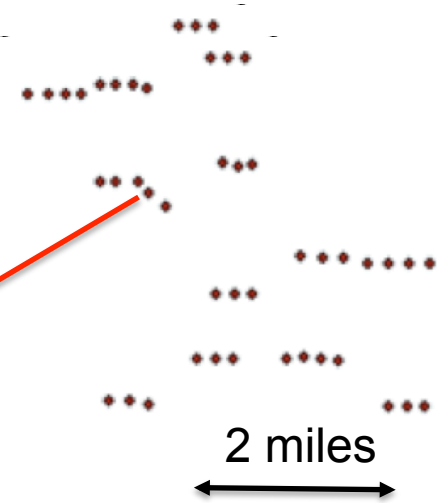
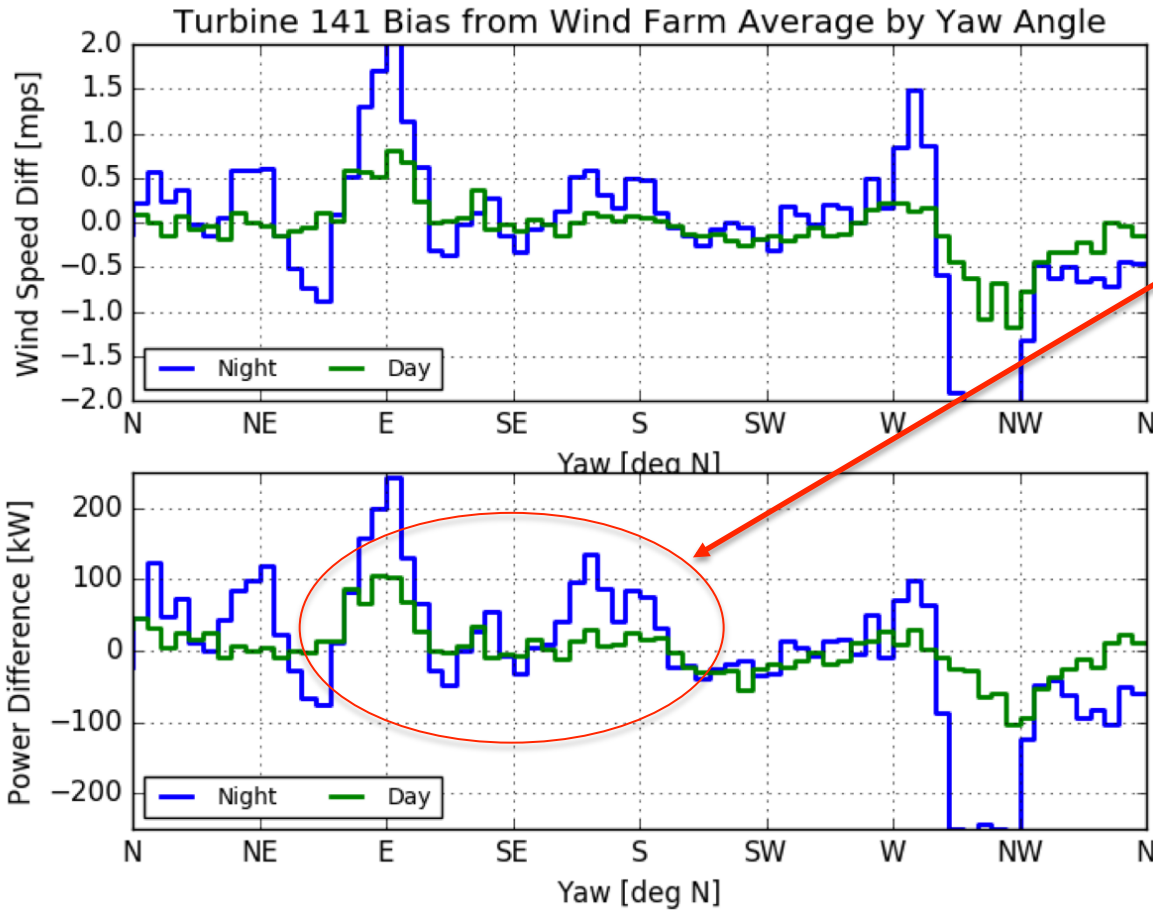
Power Enhancement and Decline



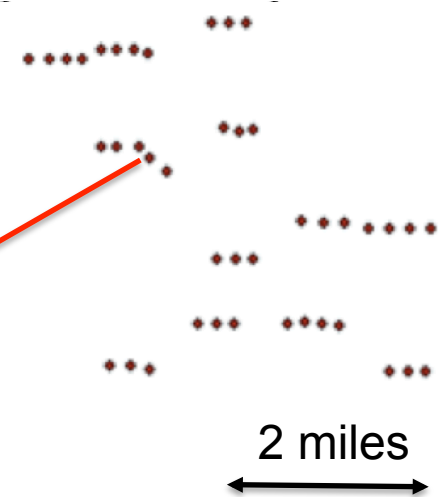
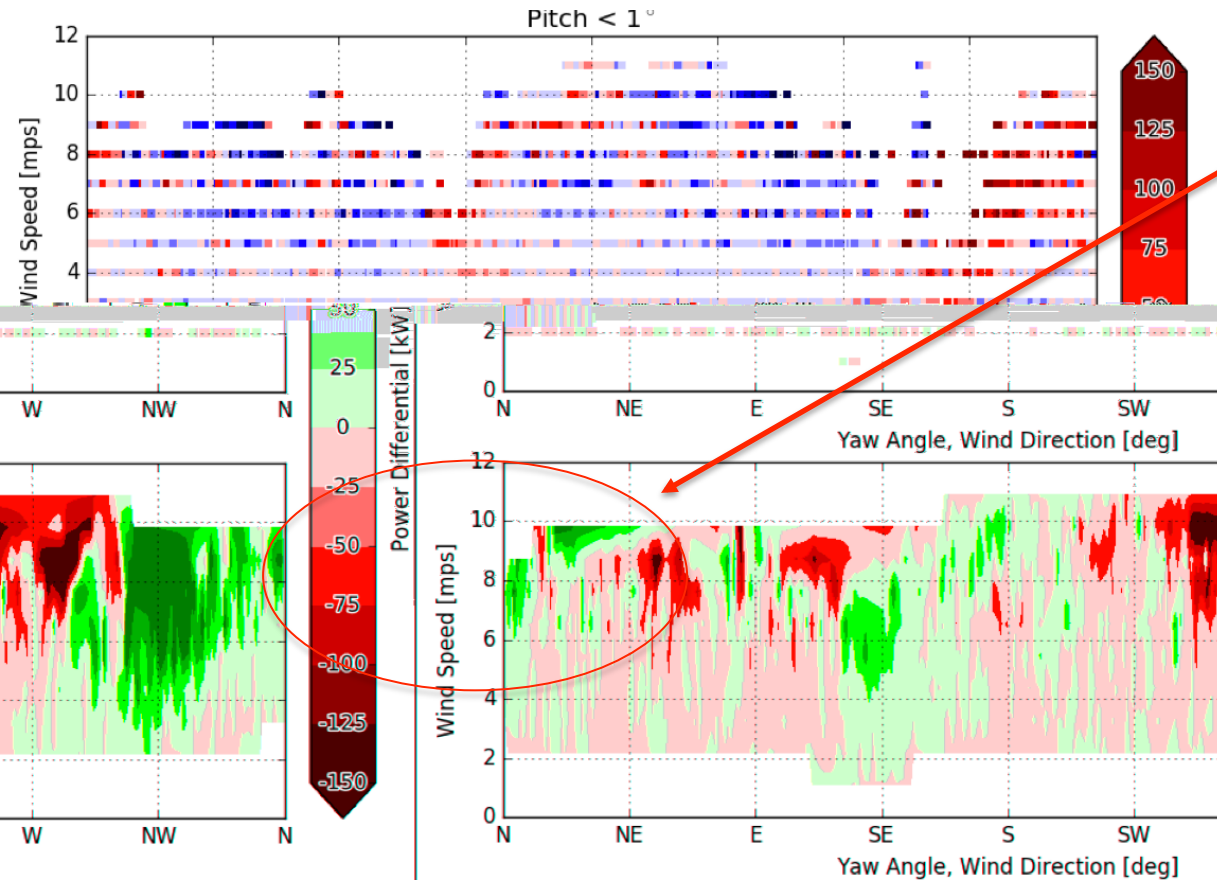
SCADA Diagnostic Tools: Directional power evaluation



SCADA Diagnostic Tools: Directional power evaluation



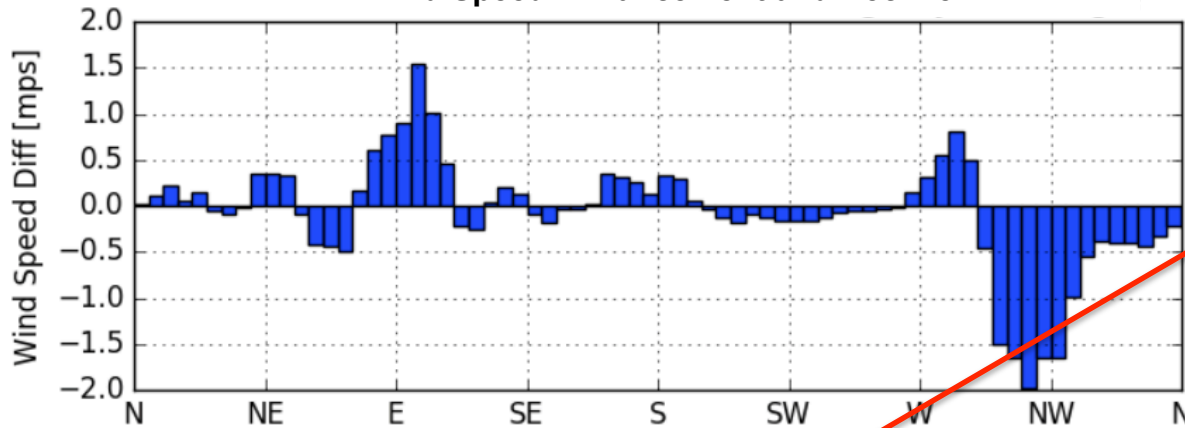
SCADA Diagnostic Tools: Directional power evaluation



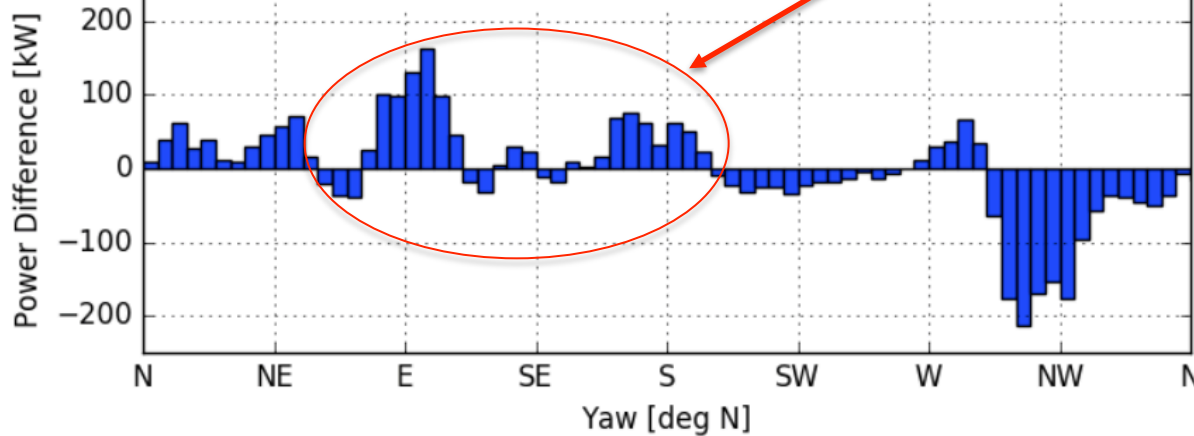
SCADA Diagnostic Tools: Directional power evaluation



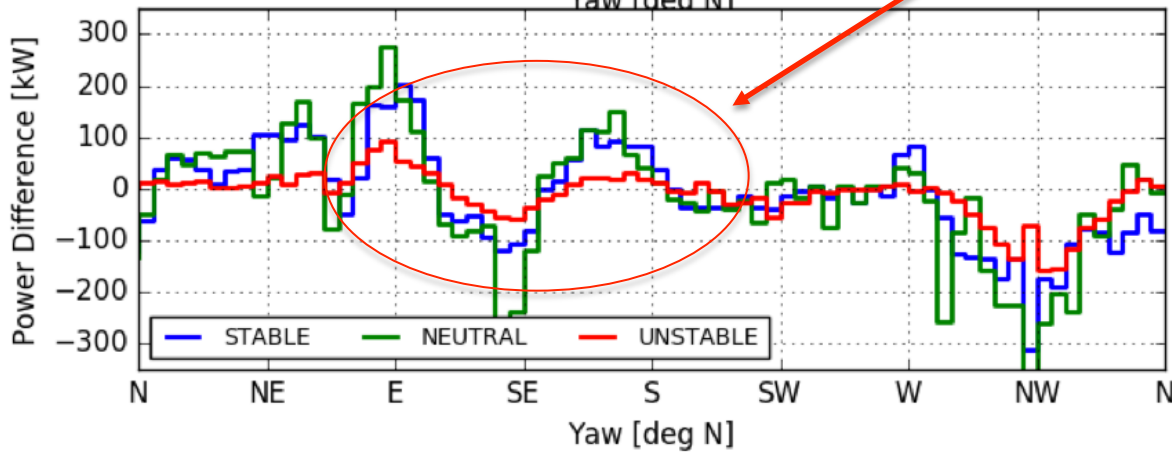
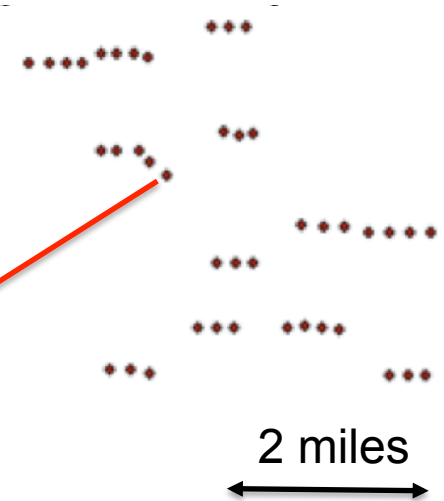
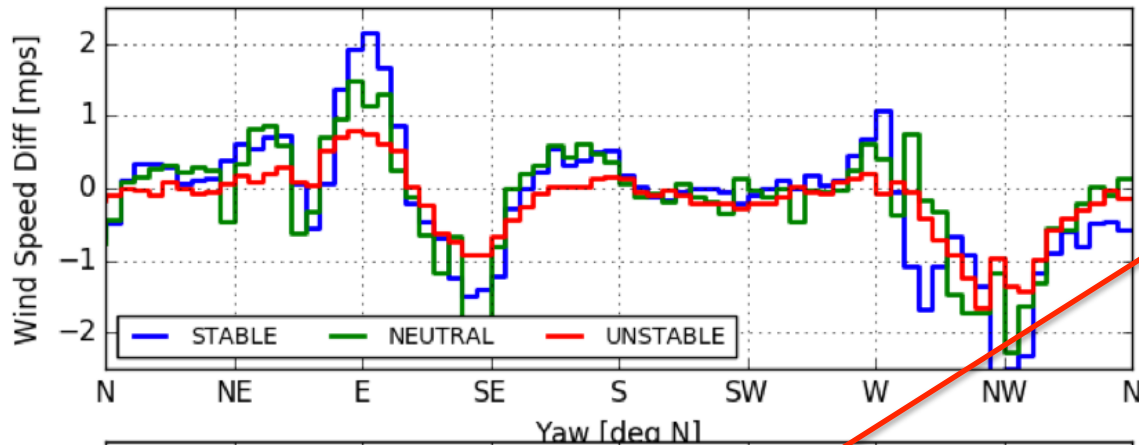
Wind Speed Enhancement and Decline



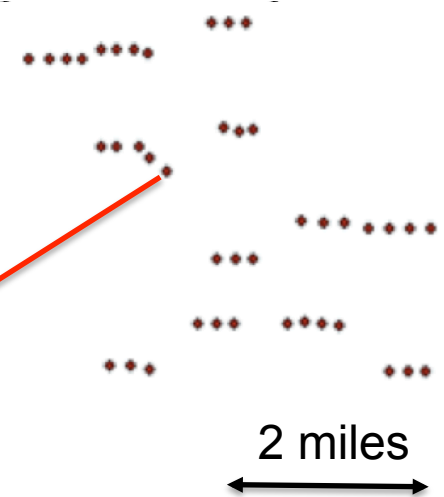
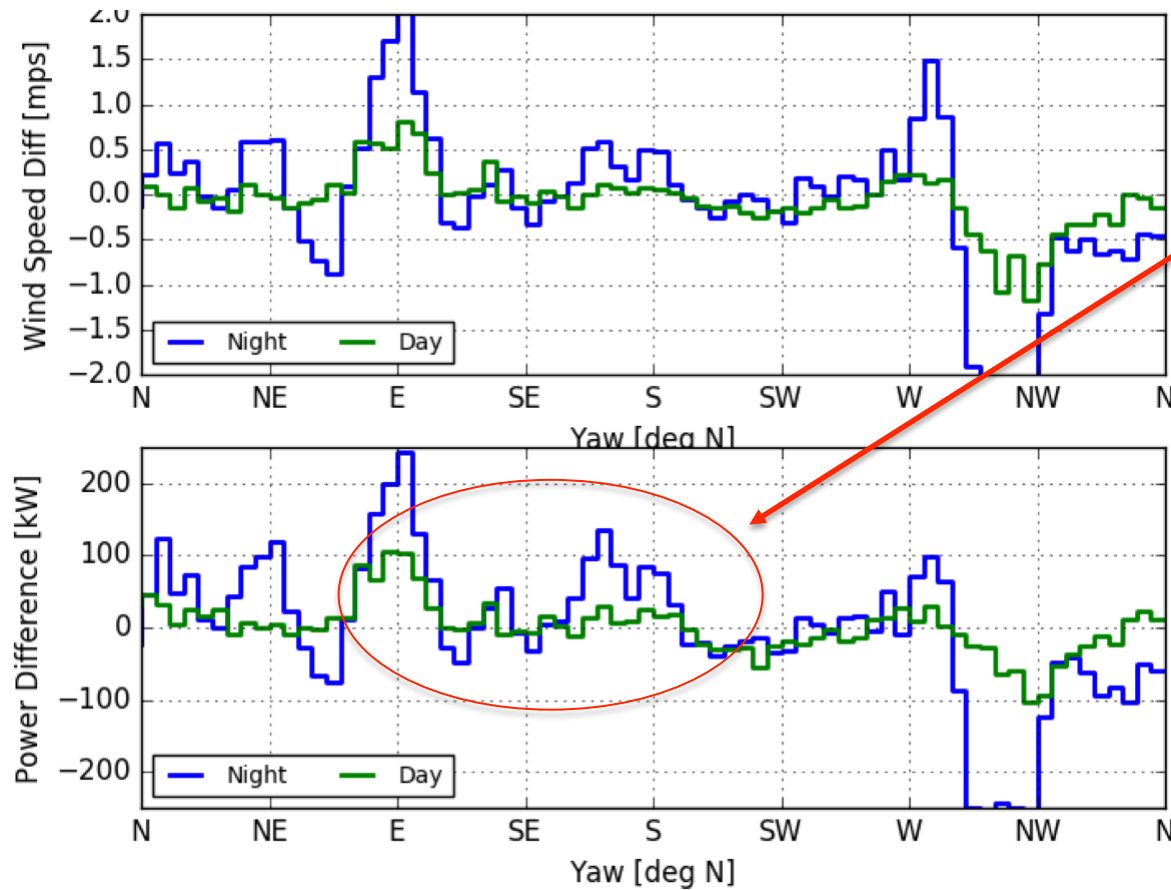
Power Enhancement and Decline



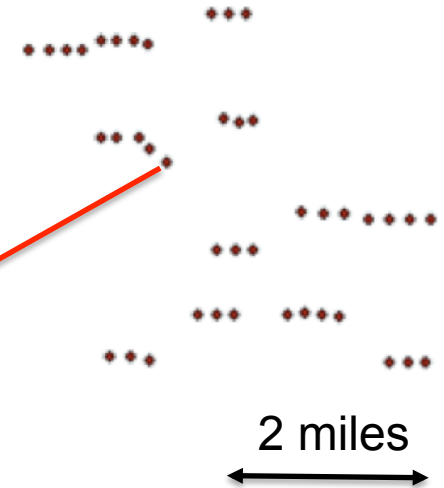
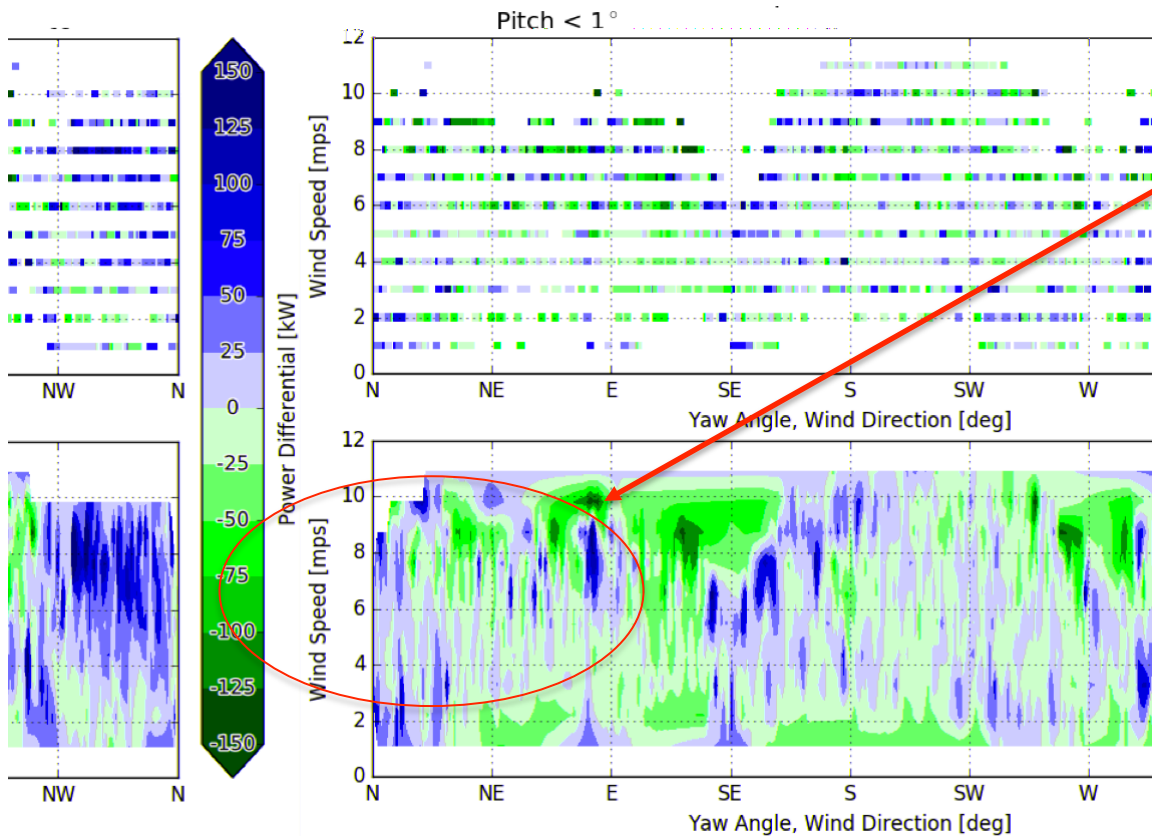
SCADA Diagnostic Tools: Directional power evaluation



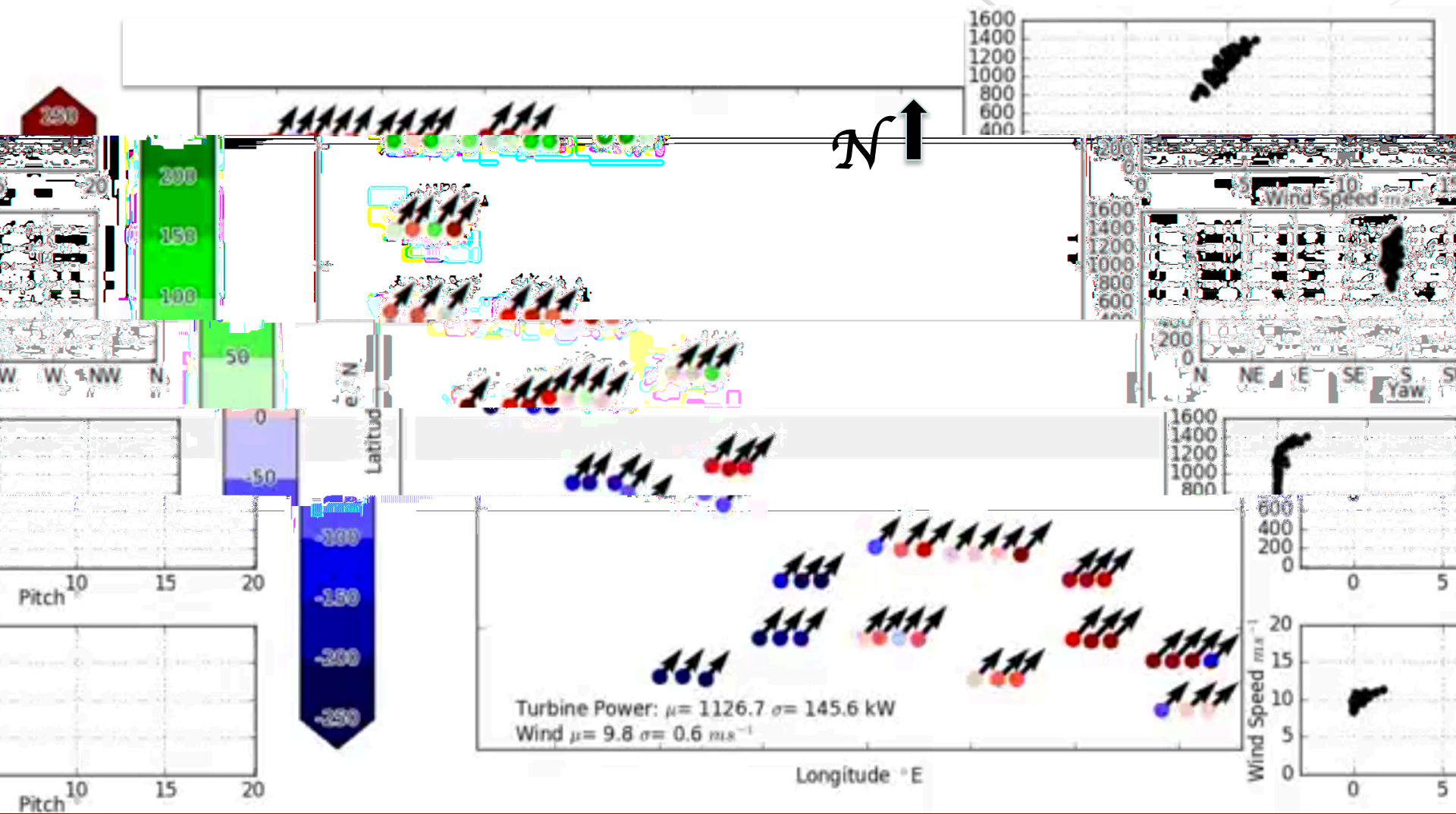
SCADA Diagnostic Tools: Directional power evaluation



Stability and directional variability Wake Concept Tool



SCADA Diagnostic Tools: Wind-plant power-differential animation



Stability and directional variability

Wake Concept Tool

Methodology

- Combine CWEX-13 measurements from multiple platforms to determine wake variability
 - **ISU 2** flux station (ambient stratification)
 - **CU 1** LiDAR (ambient hub-height wind speed and wind direction)
- [Courtesy of Julie Lundquist and Michael Rhodes, CU]
- SCADA power (10-minute resolution) from owner of wind farm

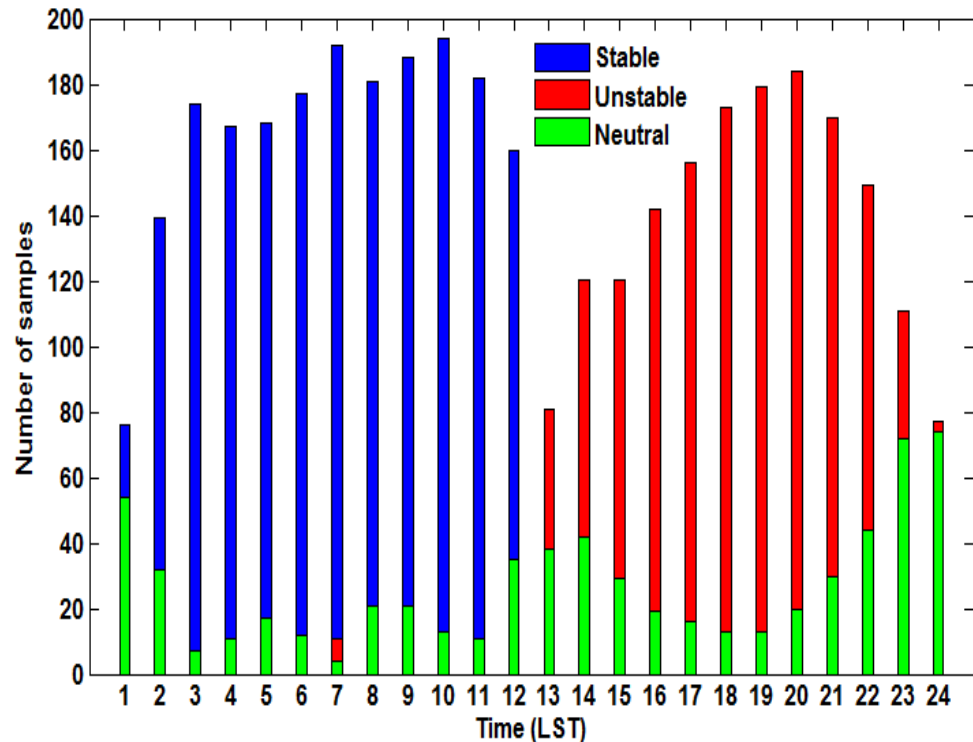
Stability and directional variability

Wake Concept Tool

Stability classification

- Determine Obukhov length (L) from reference surface flux station **ISU 2** (south of P_0)
- Separate stability categories into 3-category system
 - **STABLE** $0 < L < 200$ m
 - **UNSTABLE** $0 > L > -200$ m
 - **NEUTRAL** $|L| \geq 200$ m

Diurnal distribution of stability for non-waked upwind directions

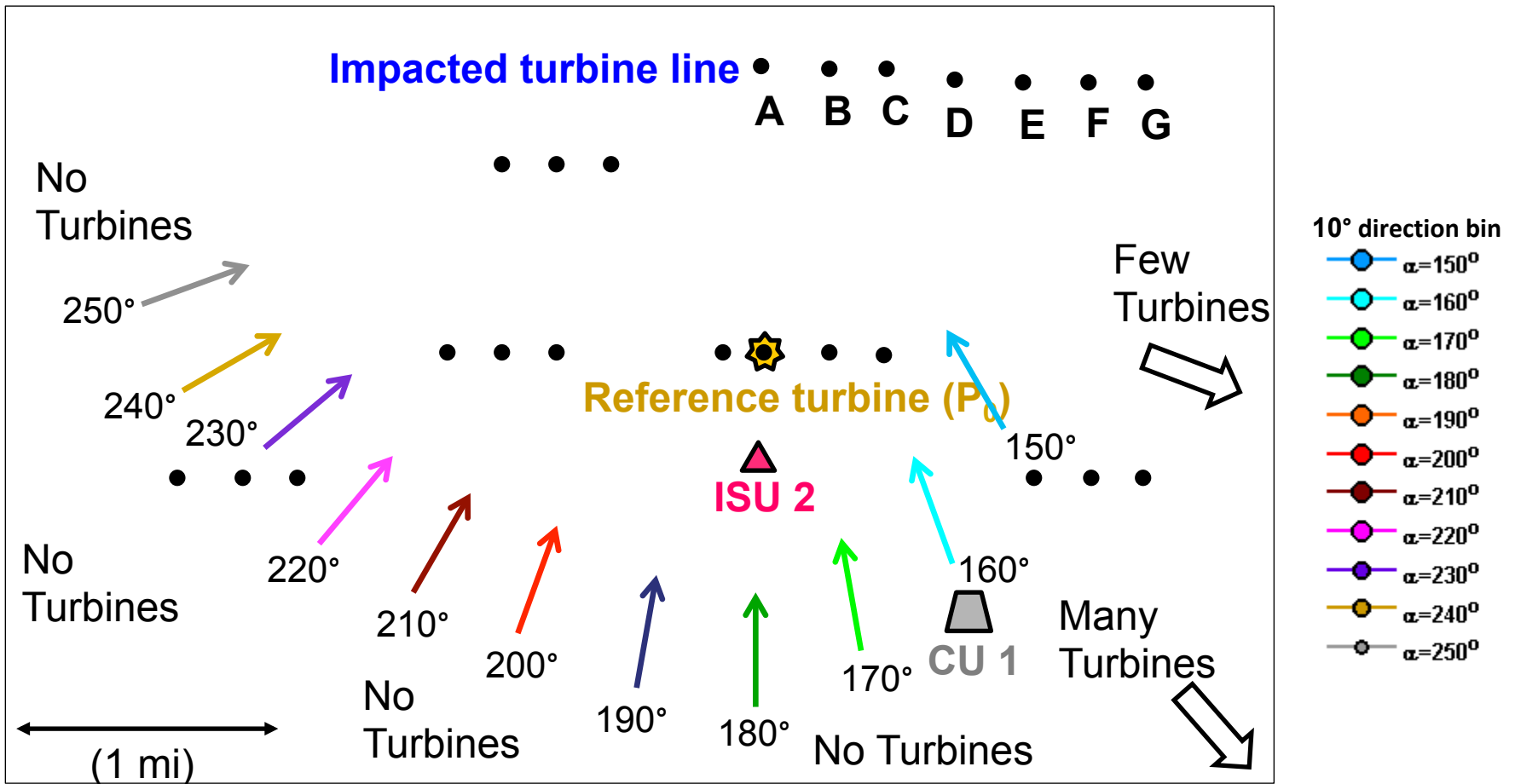


Non-waked wind directions at CU 1 LiDAR from 145° to 255°

Stability and directional variability

Wake Concept Tool

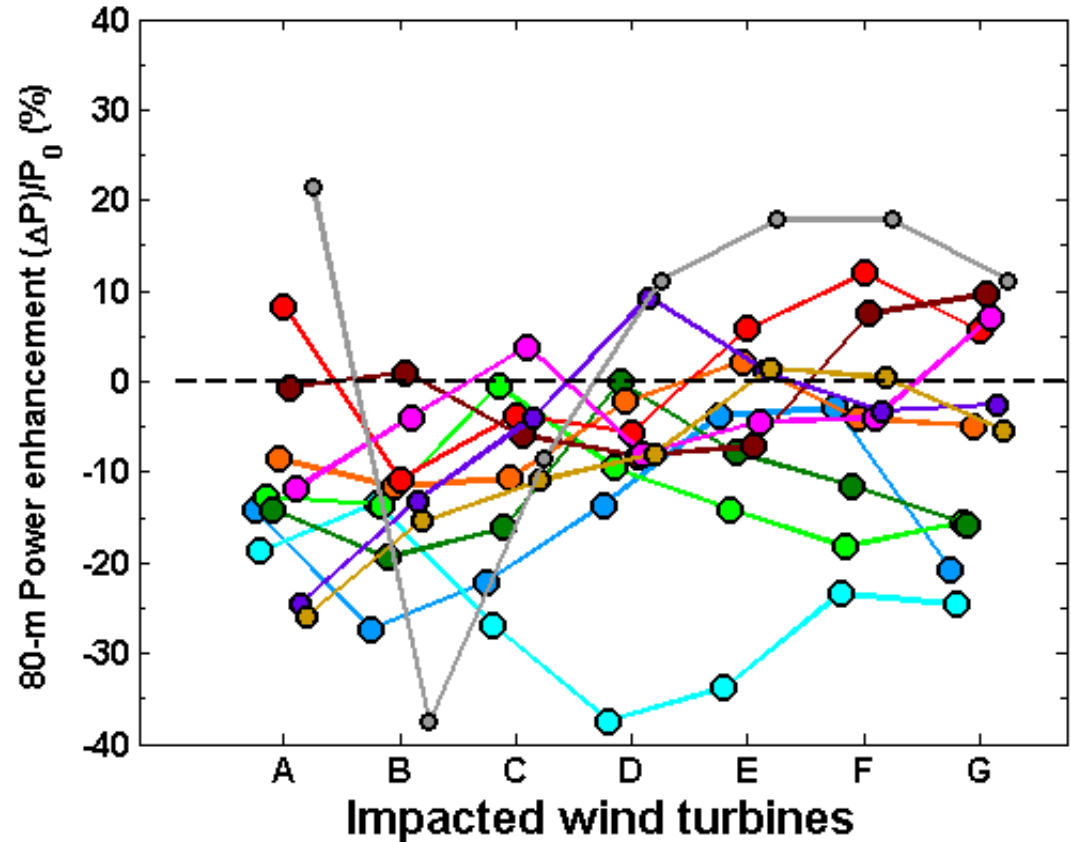
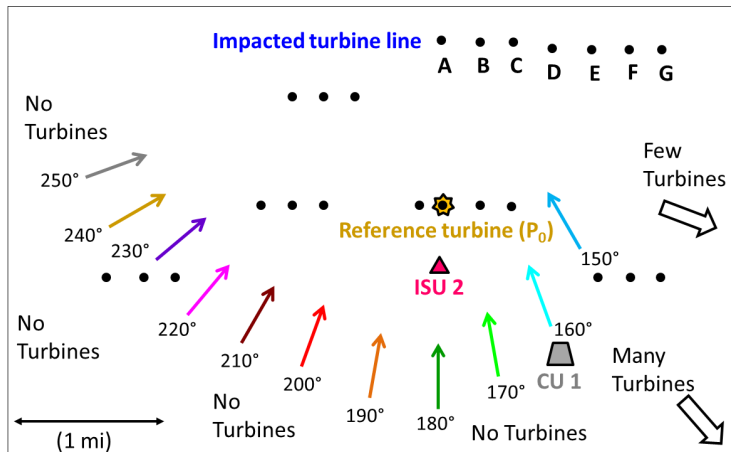
Layout: sorting by wake-distance categories



Stability and directional variability

Wake Concept Tool

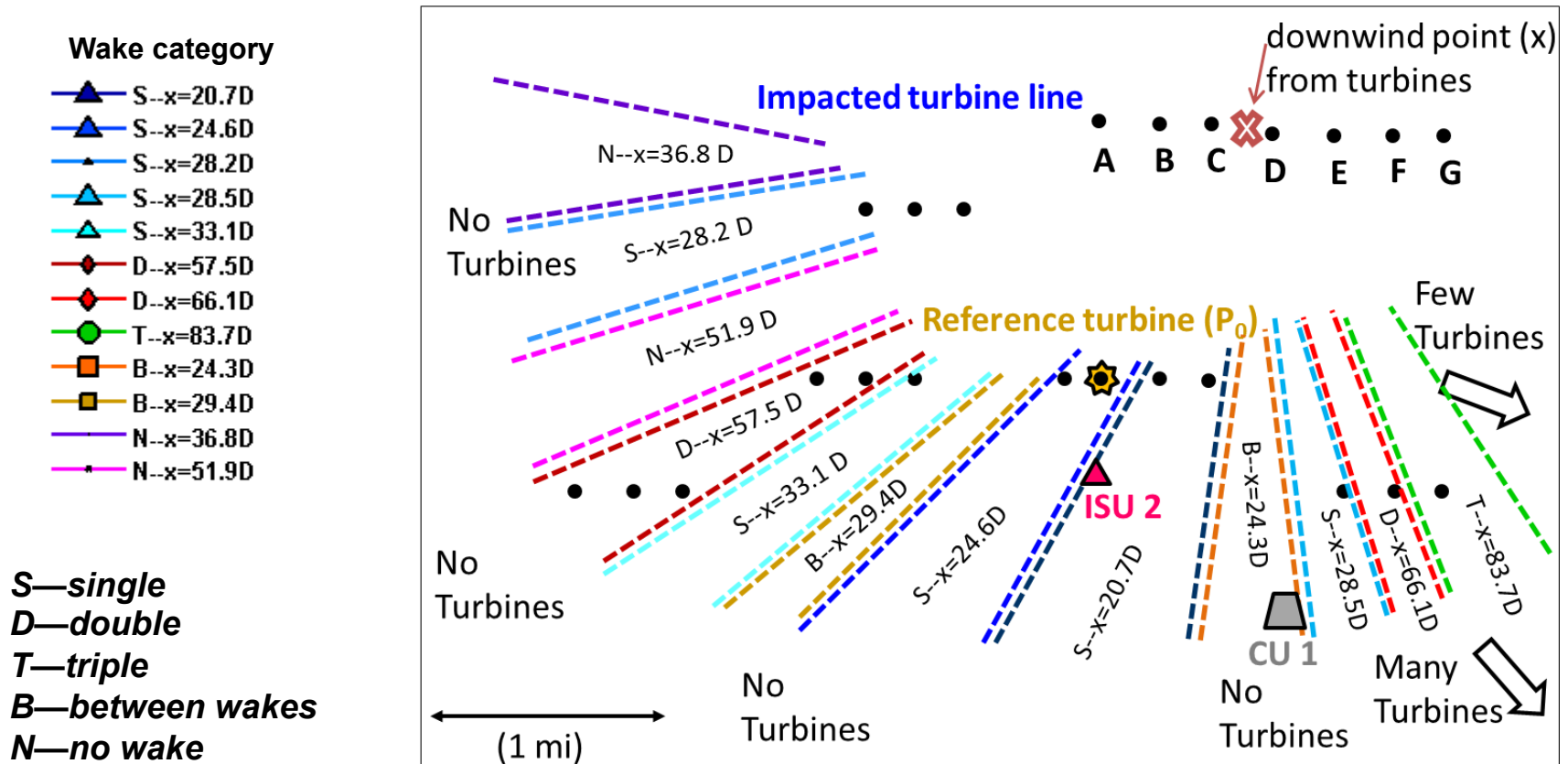
Stable stratification



Stability and directional variability

Wake Concept Tool

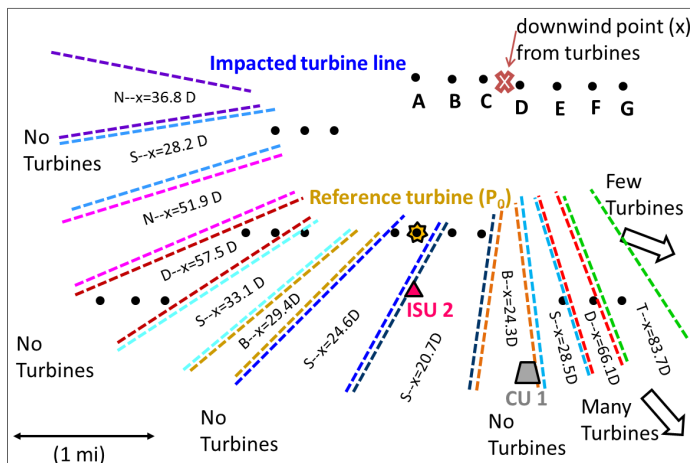
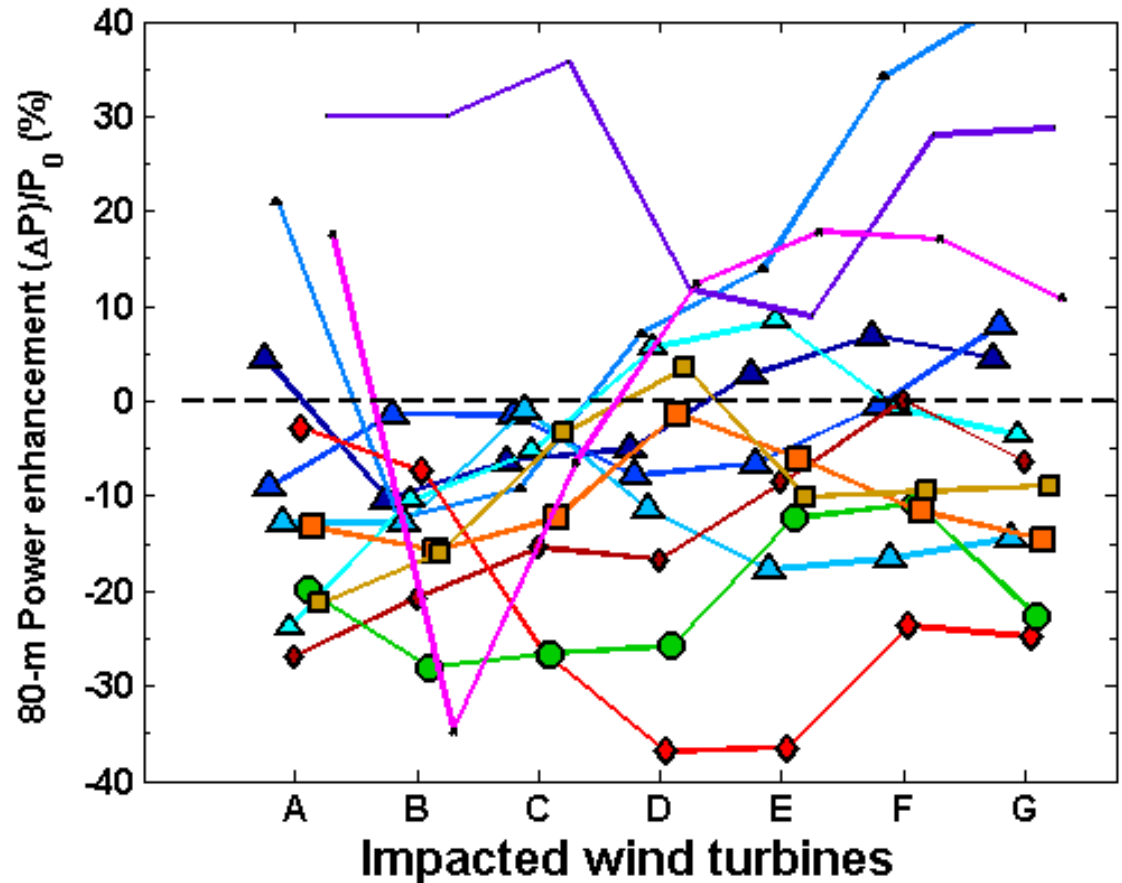
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Stability and directional variability

Wake Concept Tool

Stable stratification



Stability and directional variability

Wake Concept Tool

Preliminary results

- Normalized power differential is smaller when referencing mean wind farm power as compared to referencing power from a single upwind turbine
- Atmospheric stability variations on power differential:
 - between +10-15% for unstable conditions
 - between +5-20% for neutral conditions
 - between +10 to 50% for stable stratification
- Strongest power reduction (30-40%) occurs from influence of two consecutive turbine wakes
- Single wakes reduce power (10-20%)
- Least change in power (0-10%) across a turbine line when flow is between two individual turbine wakes

SCADA Diagnostic Tools:

Power visualization

Animation 2