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
22 June 2016

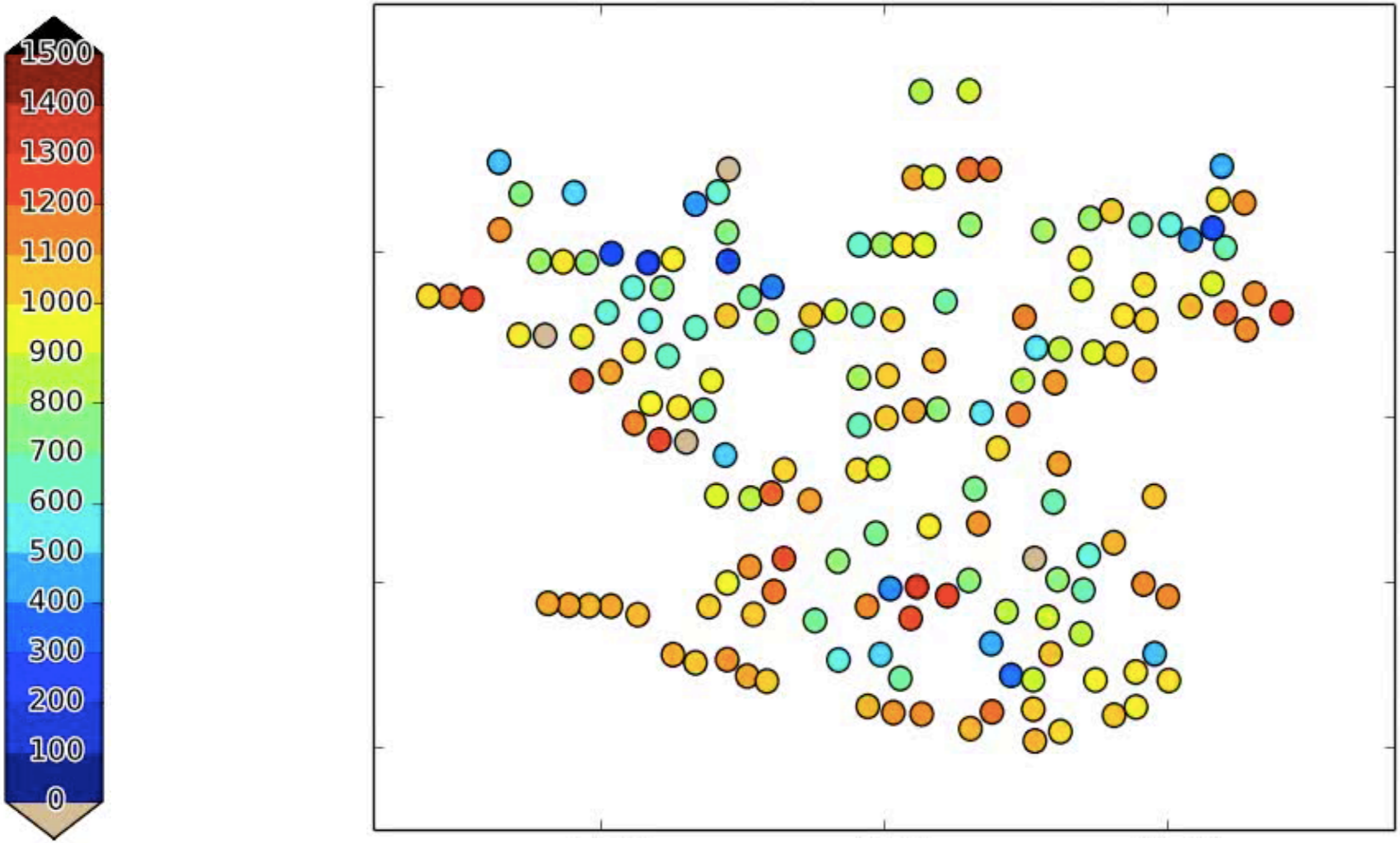
ISU Wind Science Research Facilities

- **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

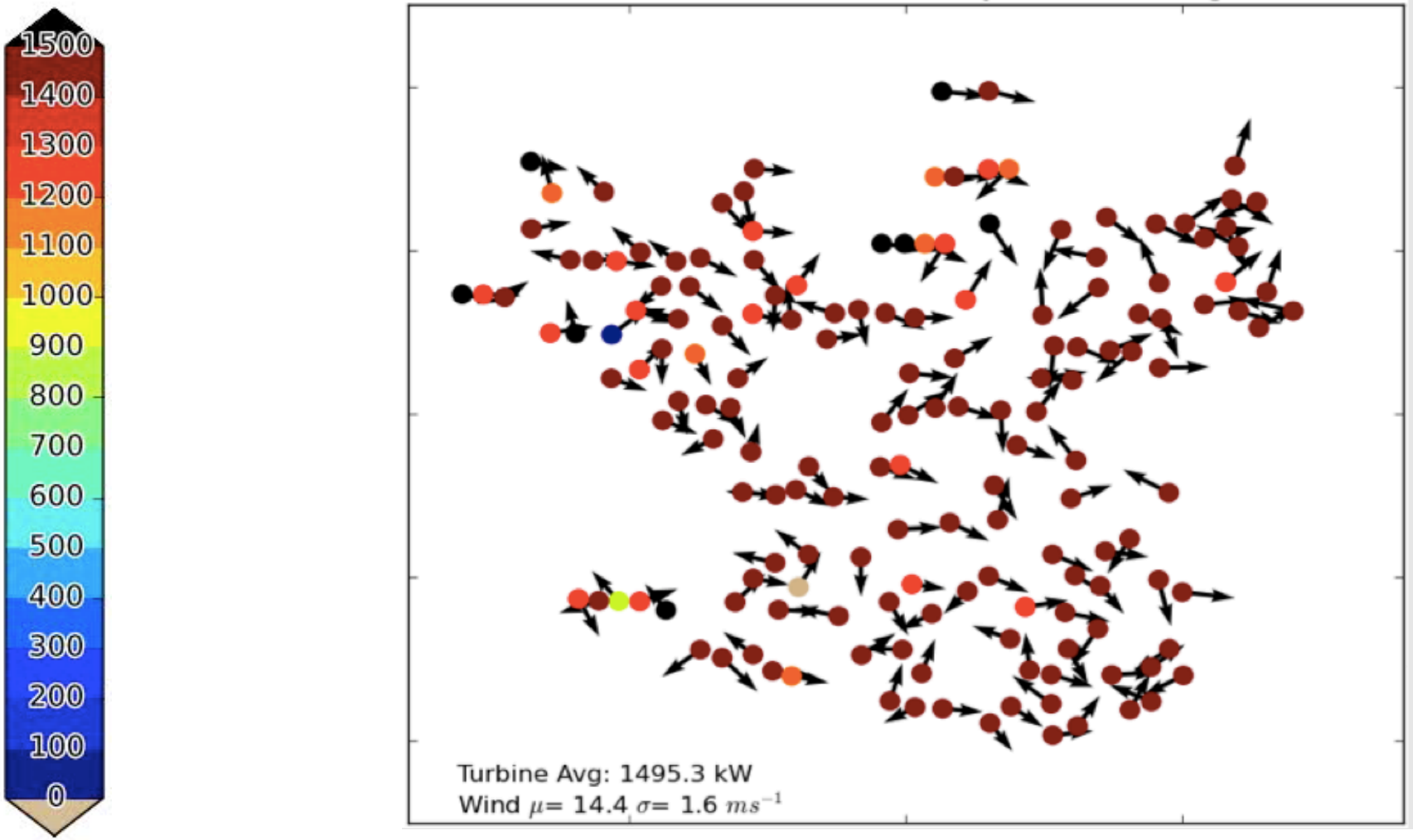
SCADA Diagnostic Tools

- **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



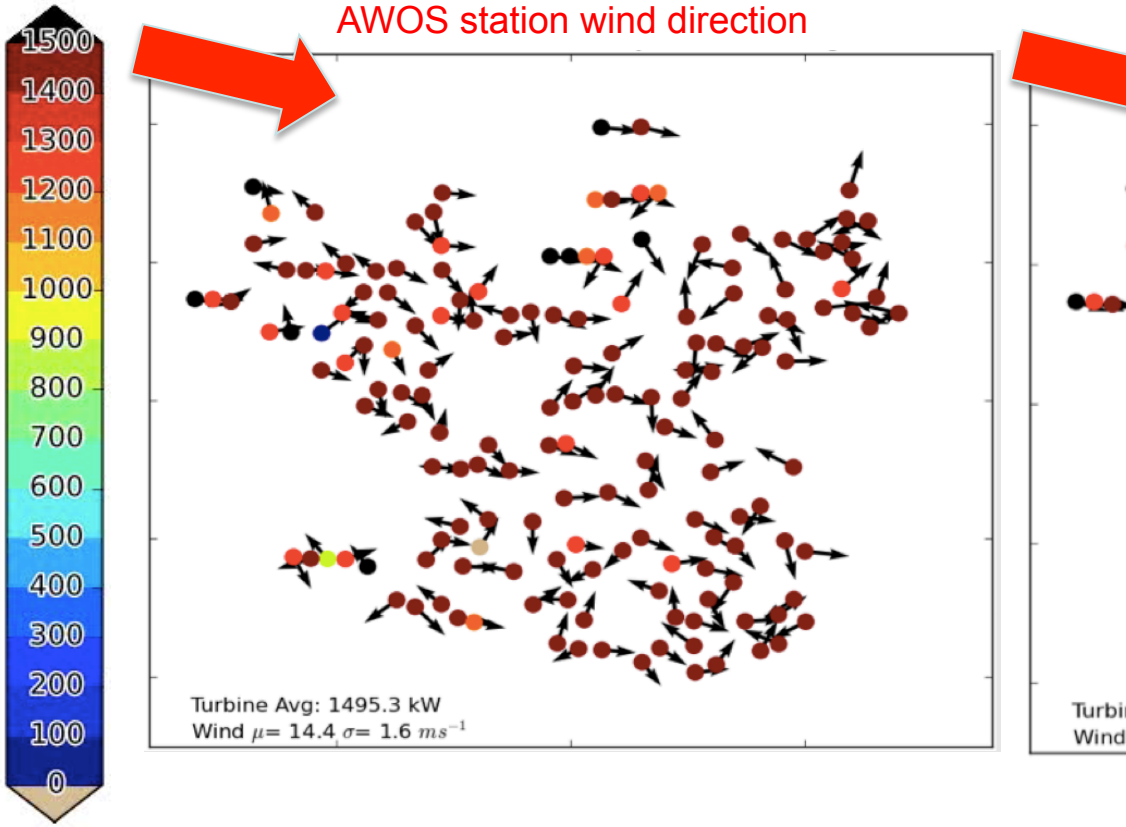
SCADA Diagnostic Tools:
Power visualization



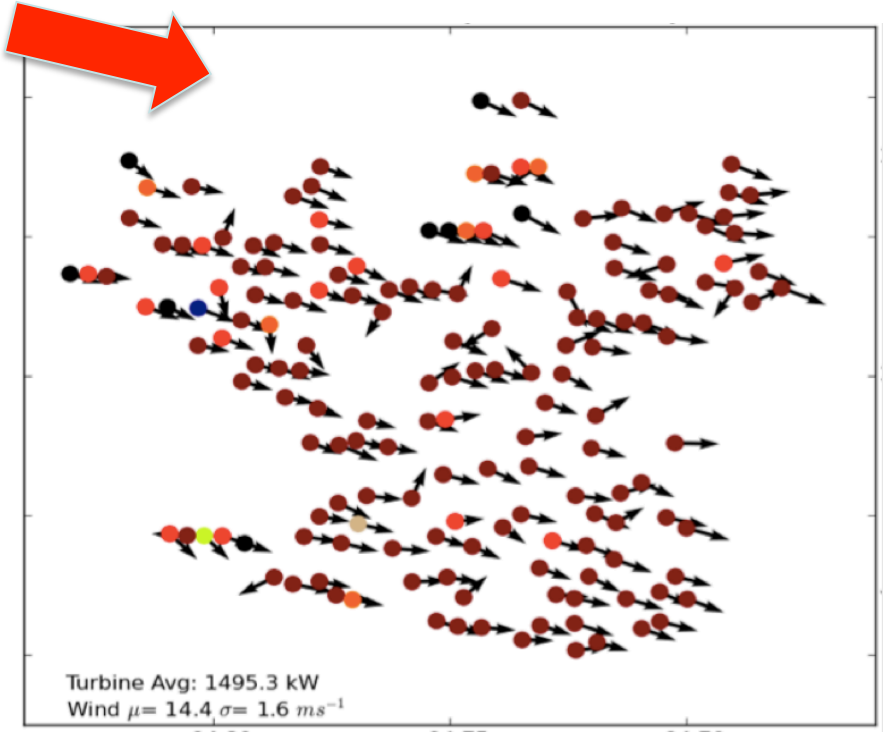
SCADA Diagnostic Tools:
Power visualization

Before

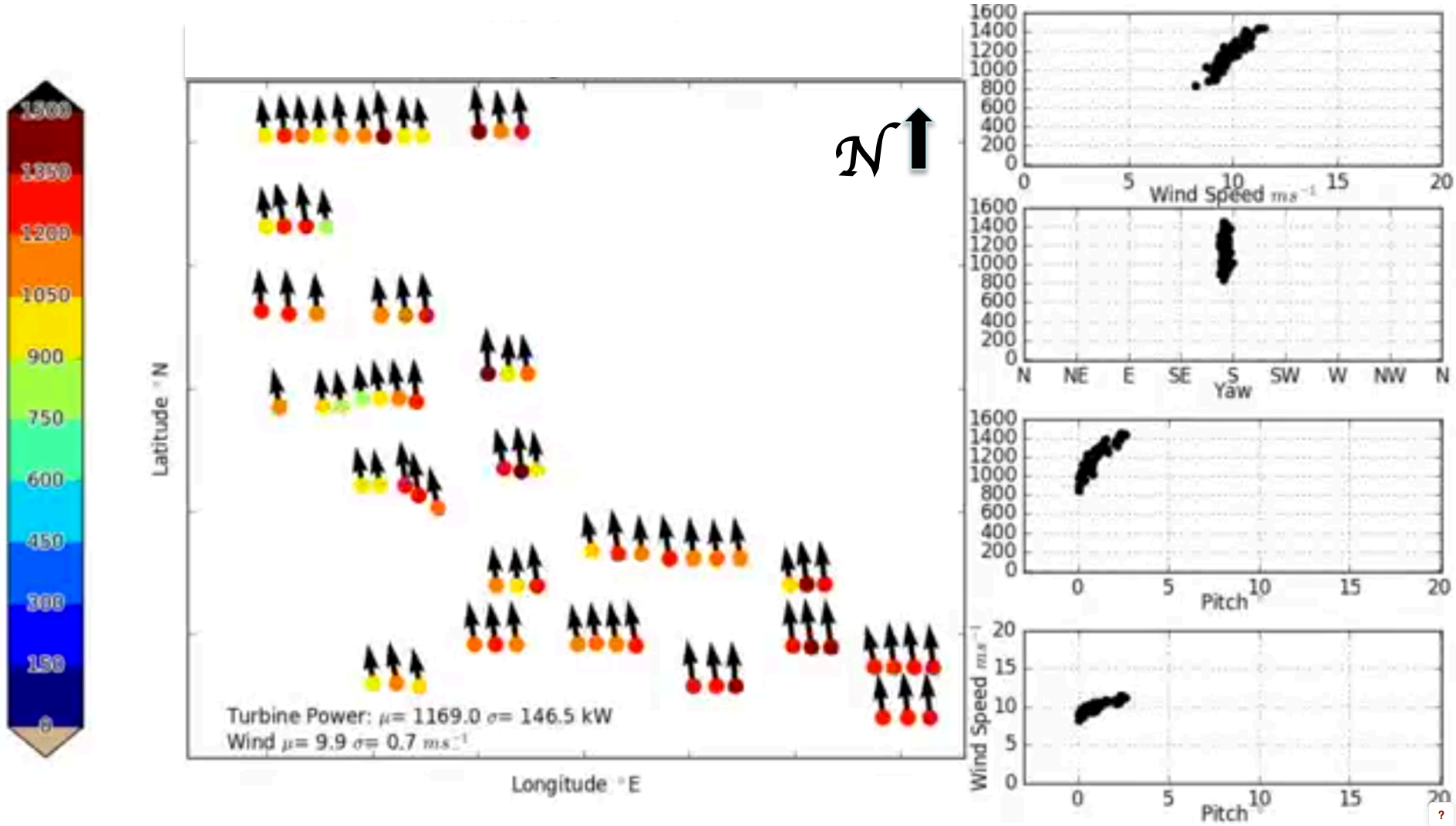
AWOS station wind direction



After

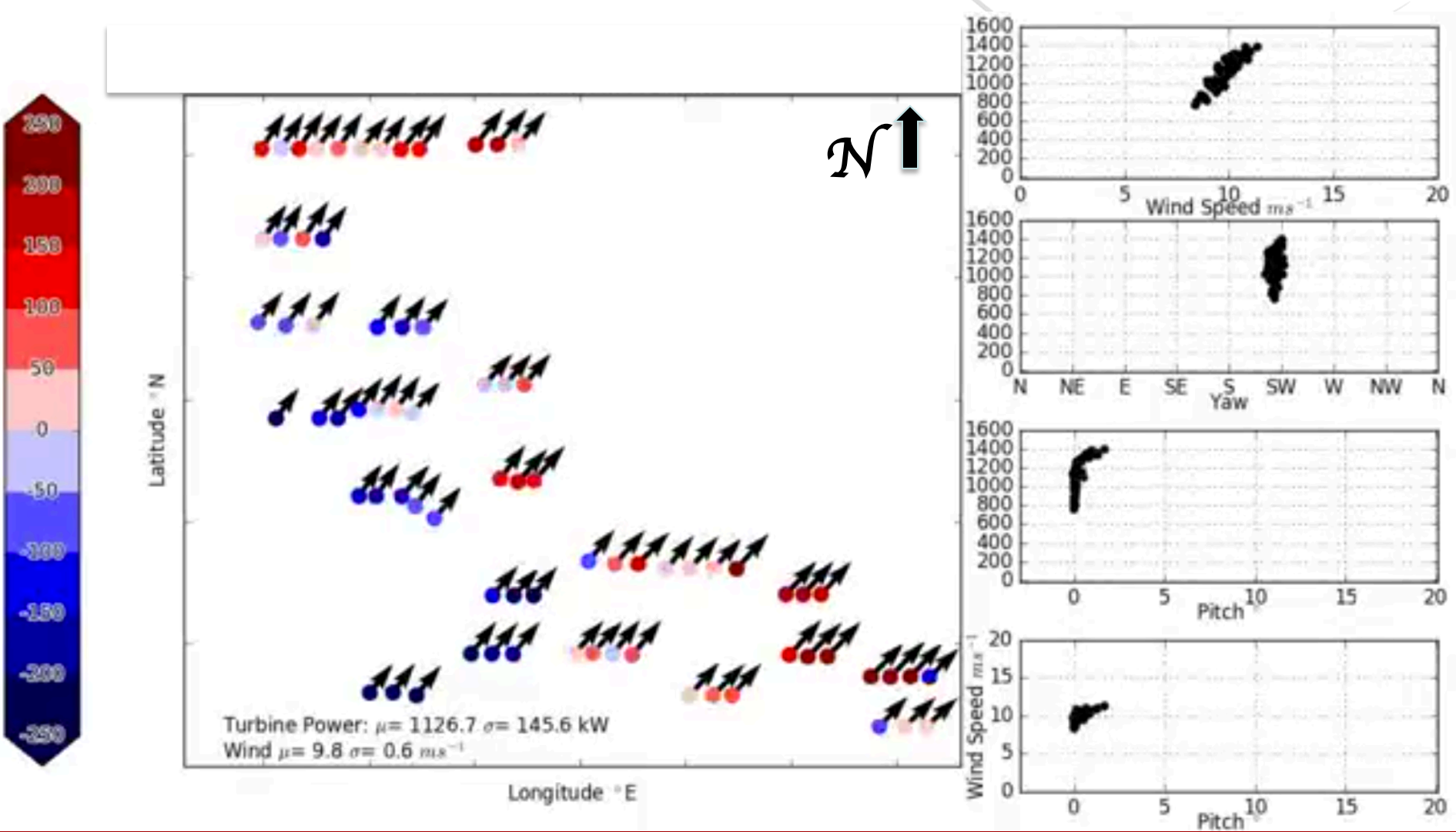


SCADA Diagnostic Tools:
Power visualization



SCADA Diagnostic Tools:

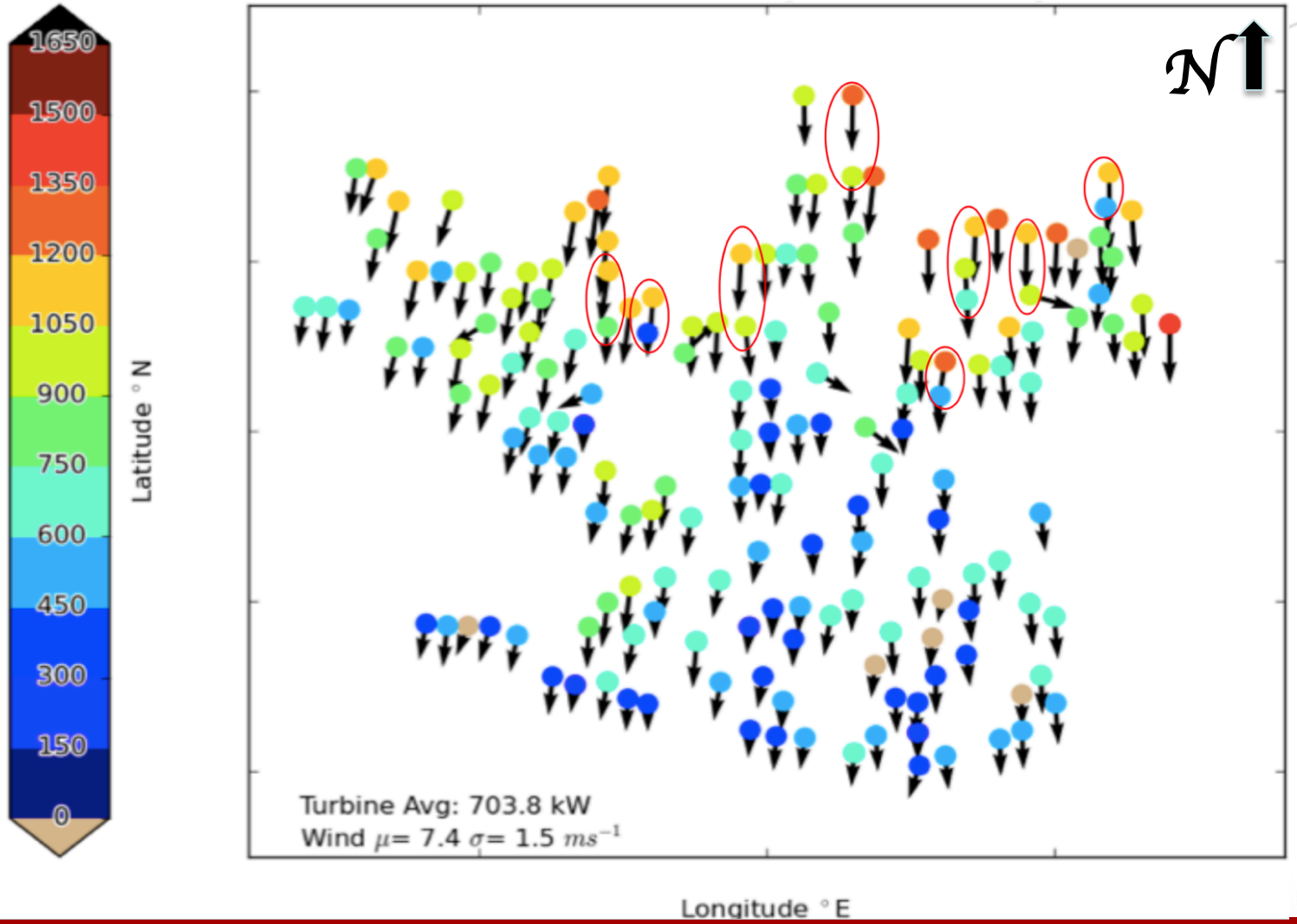
Wind-Plant Turbine Power-Differential Tool



SCADA Diagnostic Tools:
Power visualization

Animation 1

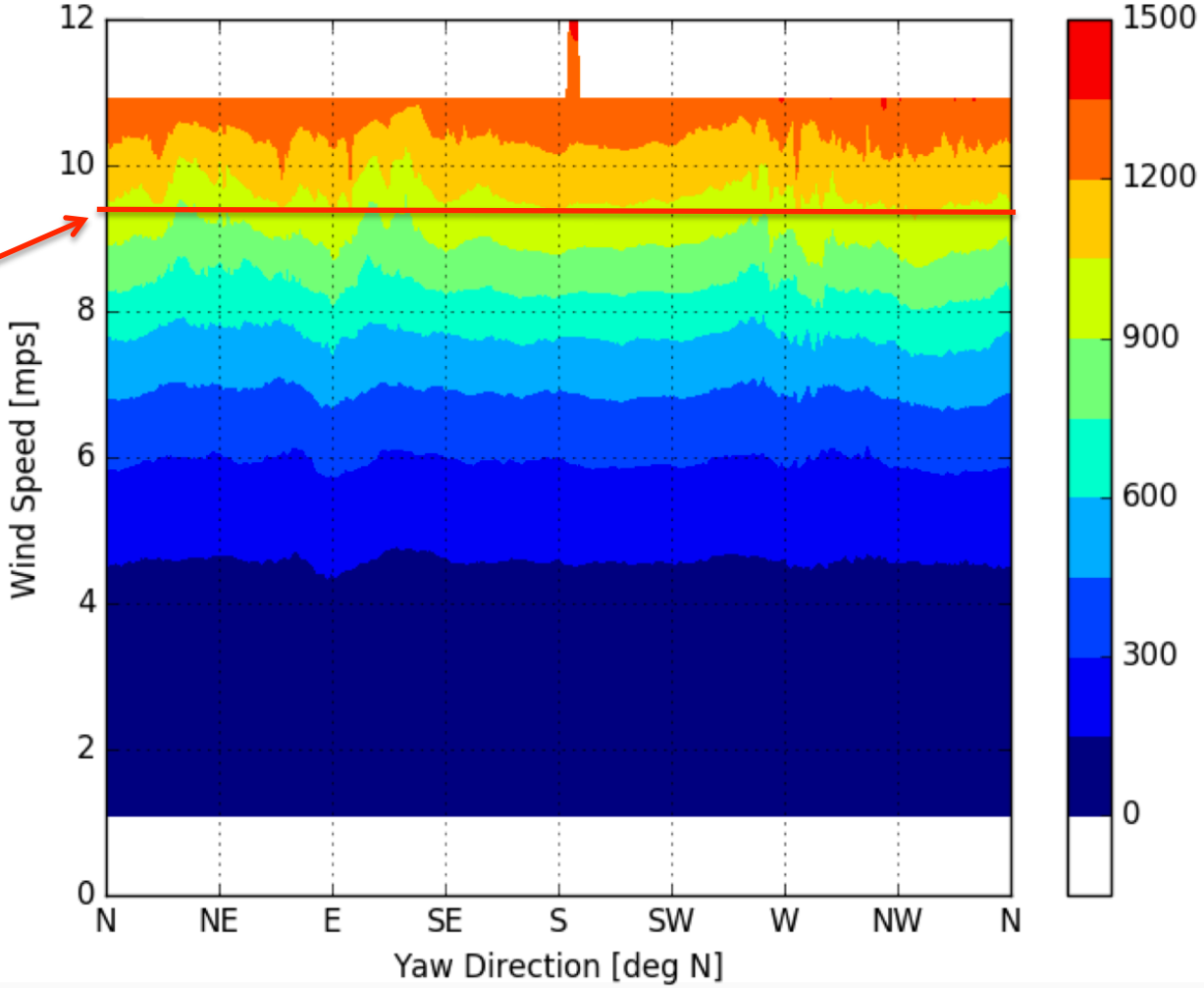
SCADA Diagnostic Tools:
Power visualization



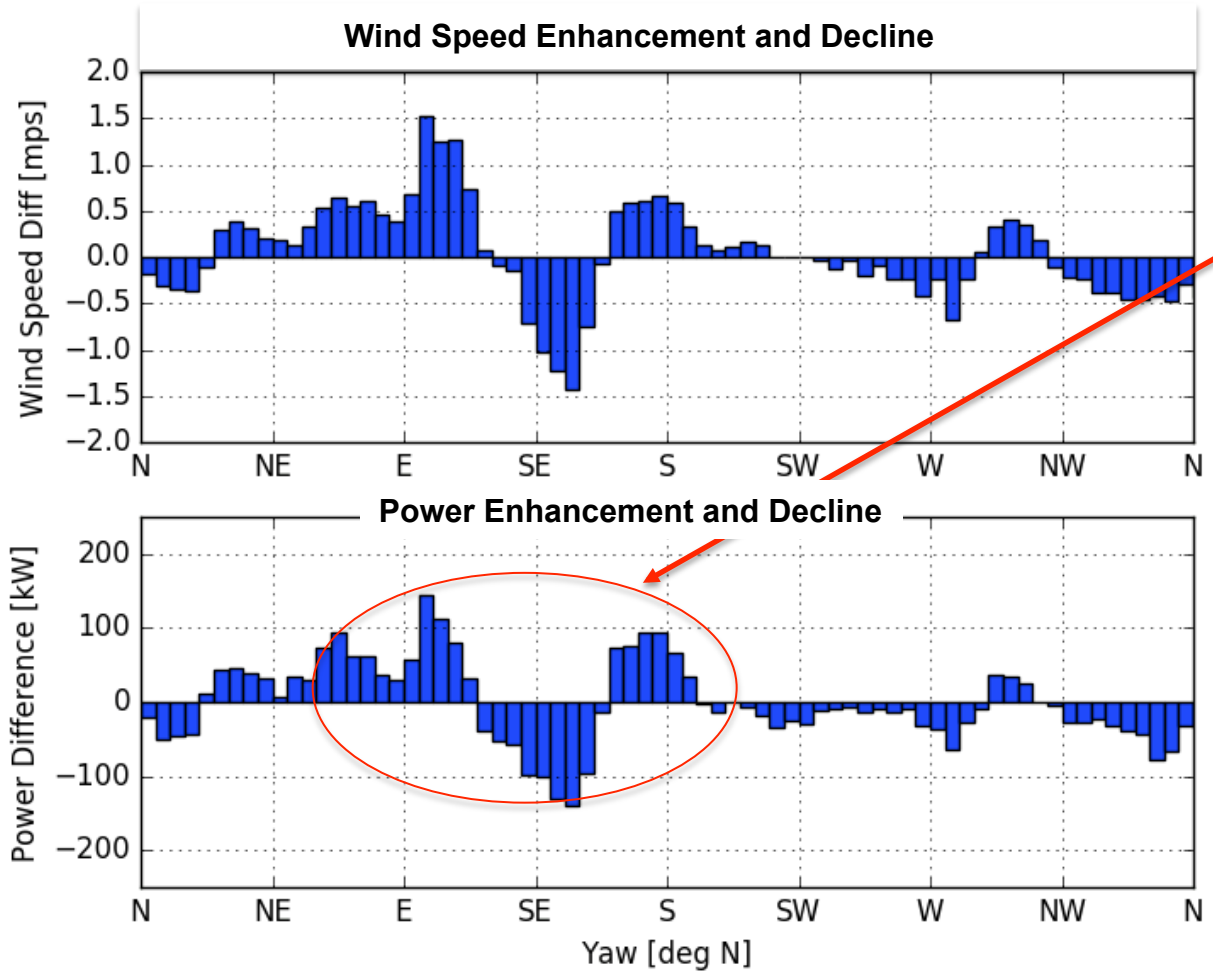
SCADA Diagnostic Tools:

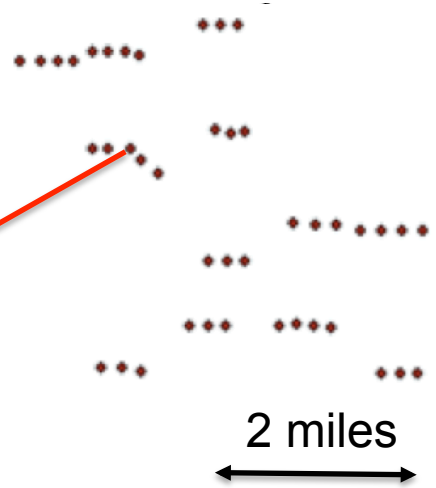
Directional Power visualization

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



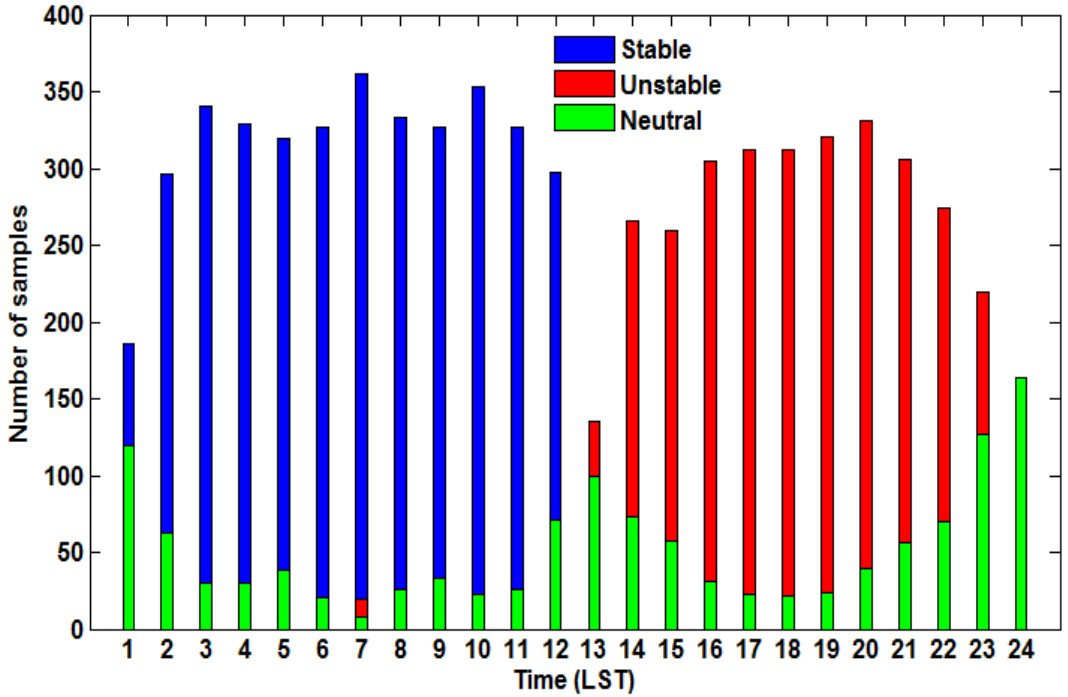


Stability and directional variability

Stability classification

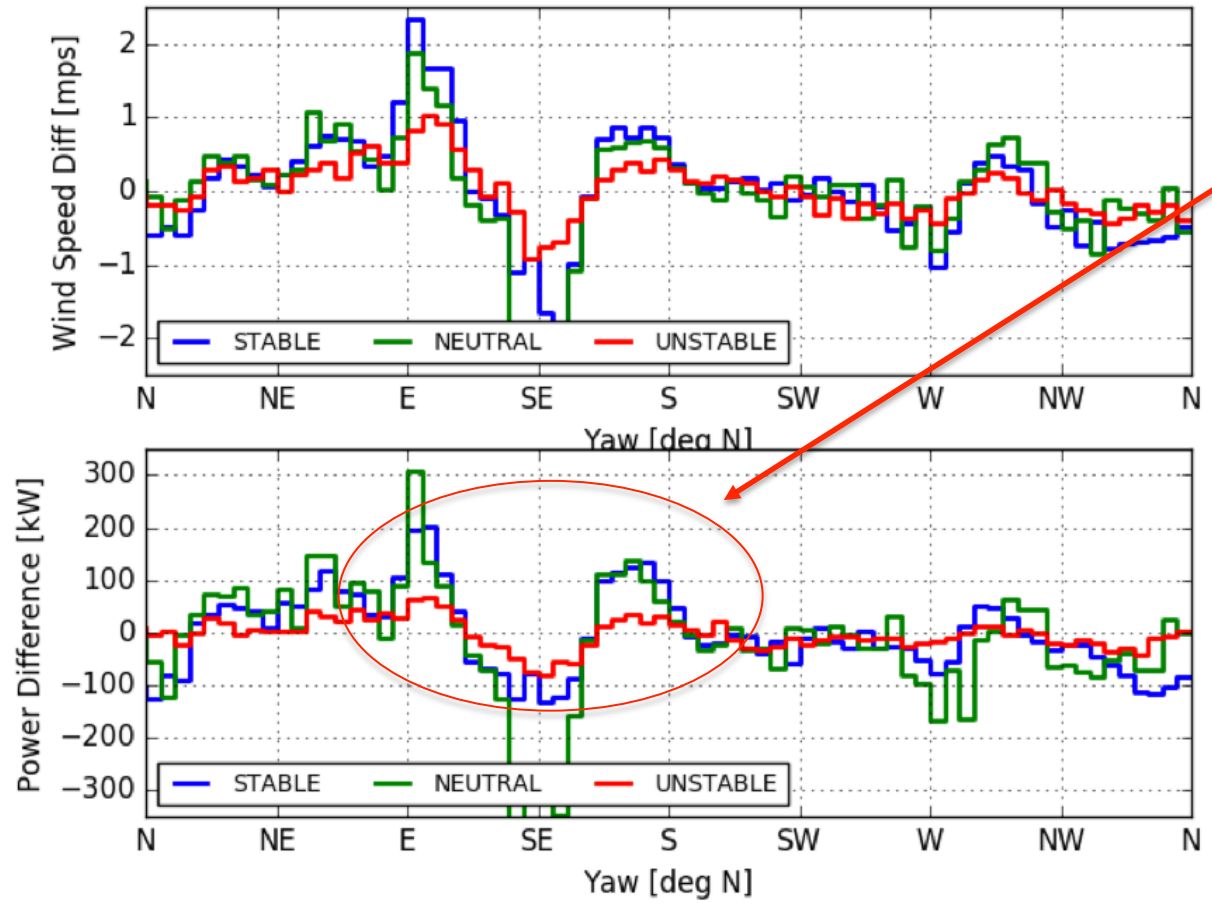
- Determine Obukhov length (L) from reference surface flux station **ISU 2** (south of P_0)
- Stability categories
  - **STABLE** 0 m<L<200m
  - **UNSTABLE** 0 m>L>-200 m
  - **NEUTRAL** |L|≥200 m

Diurnal distribution of stability



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

SCADA Diagnostic Tools:
Directional power evaluation

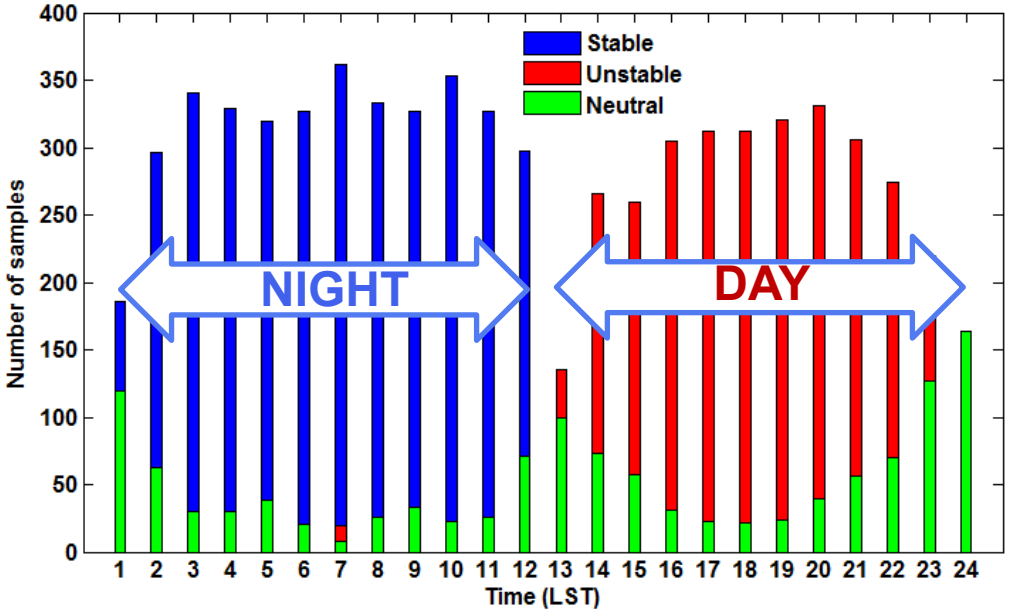


Stability and directional variability Wake Concept Tool

Stability classification

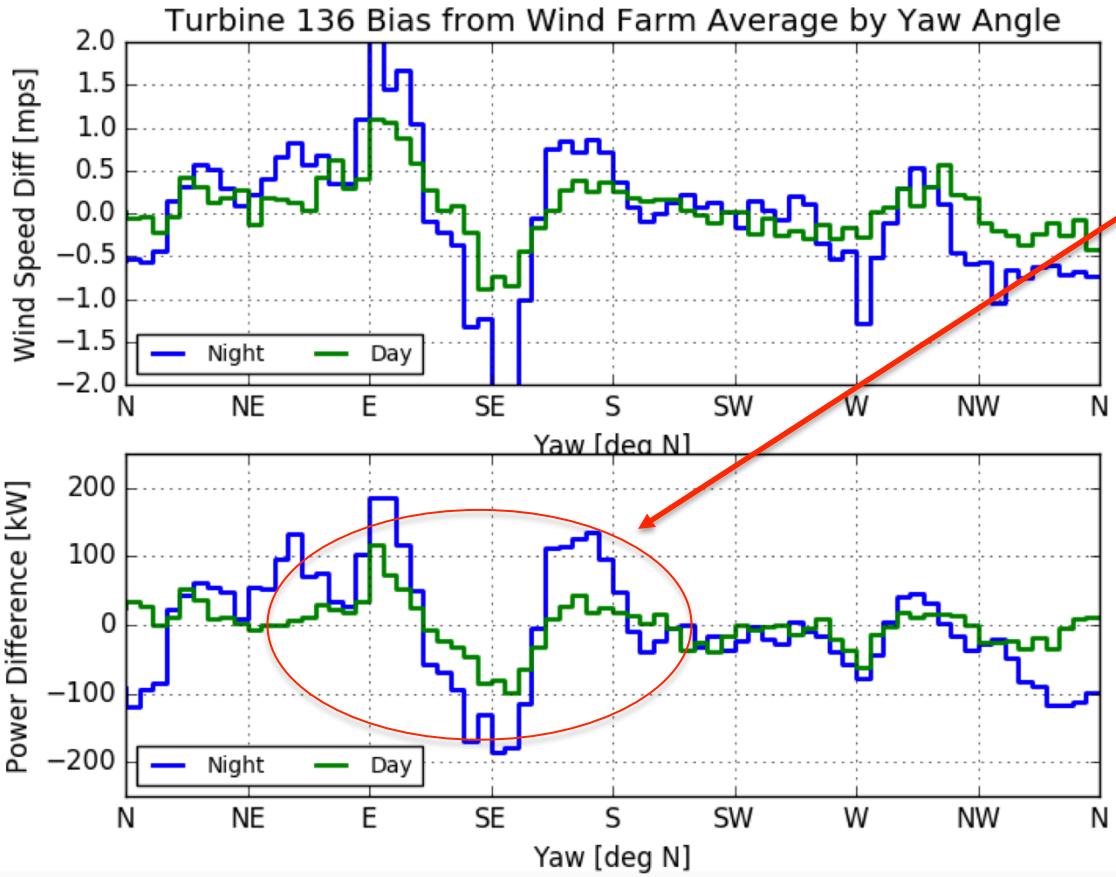
- Determine Obukhov length (L) from reference surface flux station **ISU 2** (south of P_0)
- Stability categories
  - **STABLE** 0 m<L<200m
  - **UNSTABLE** 0 m>L>-200 m
  - **NEUTRAL** |L|≥200 m
- Stability categories
  - **NIGHT**
  - **DAY**

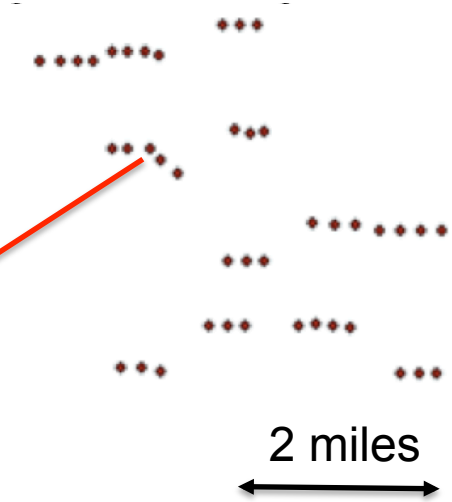
Diurnal distribution of stability (summer case)



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

SCADA Diagnostic Tools:
Directional power evaluation





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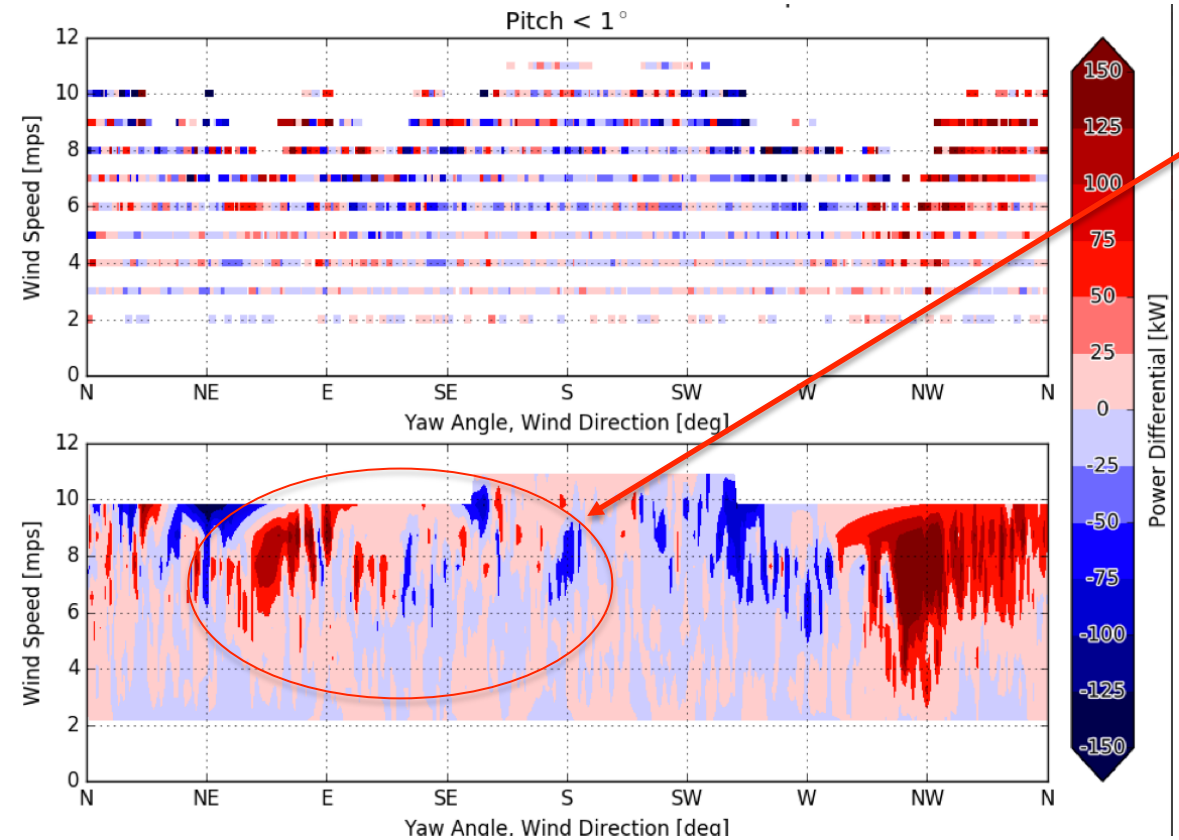

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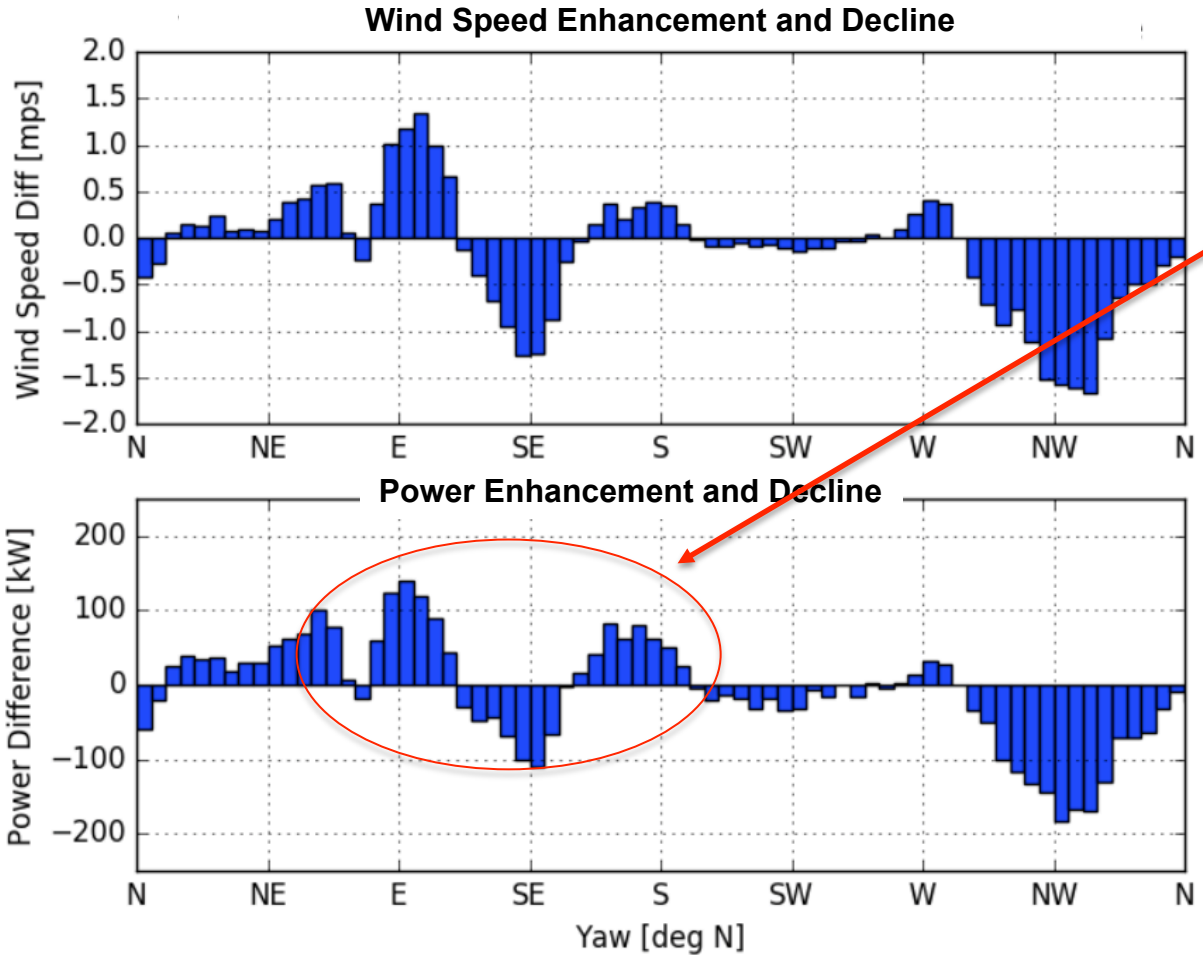

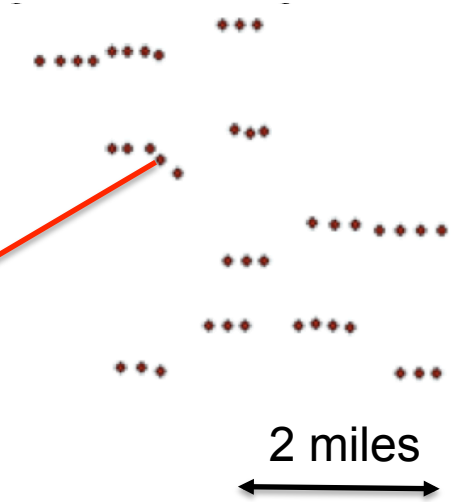

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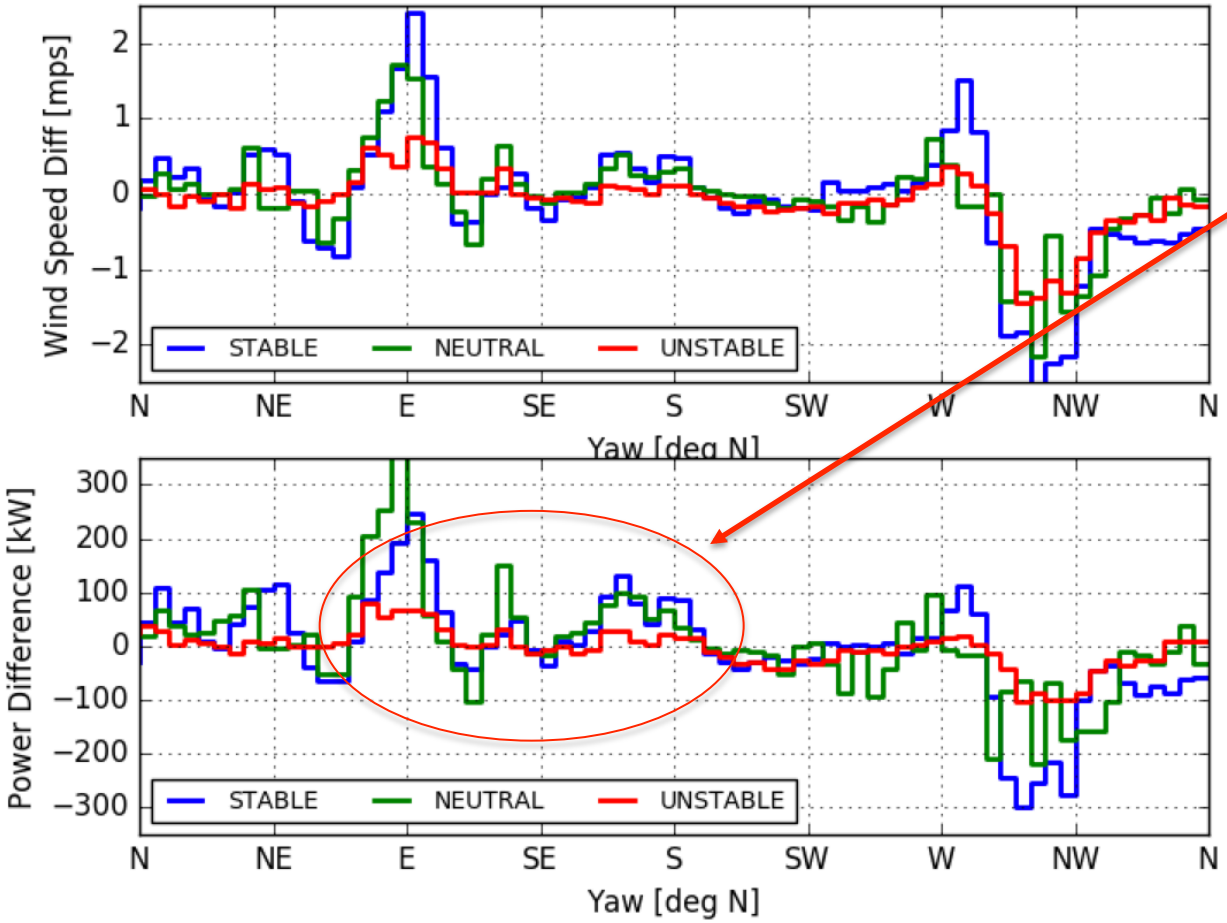

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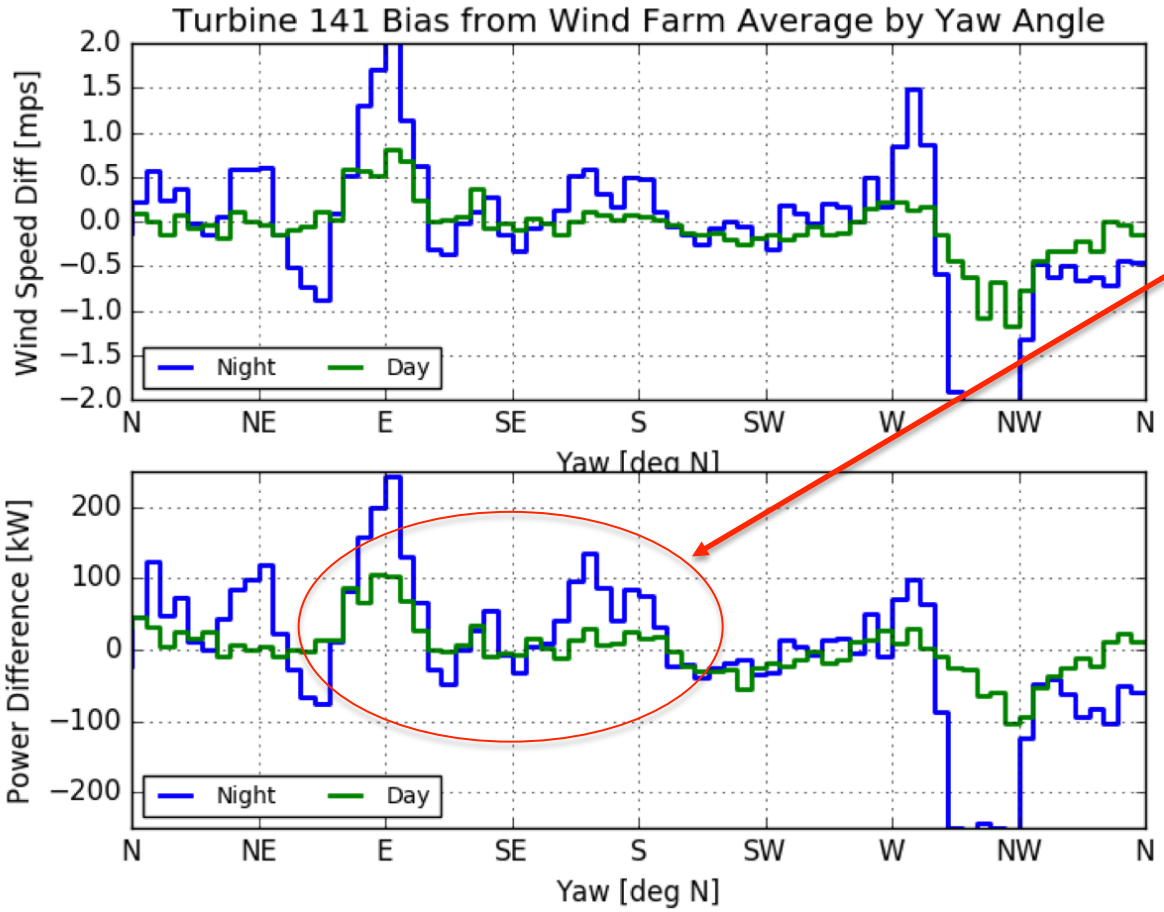

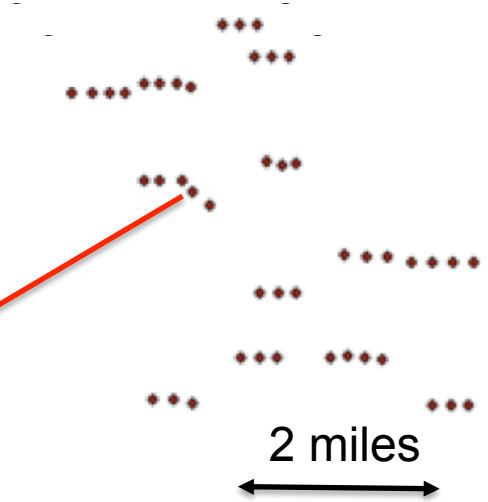

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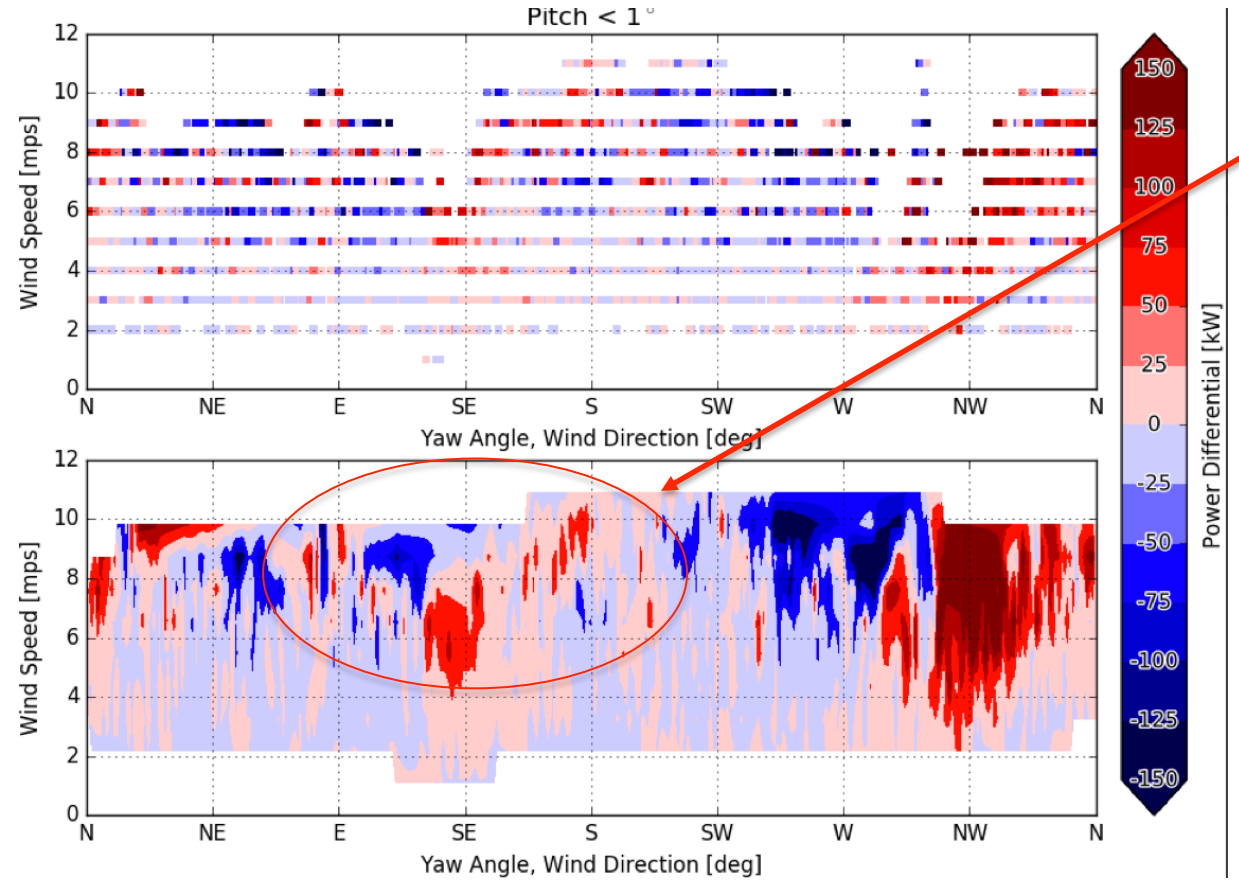

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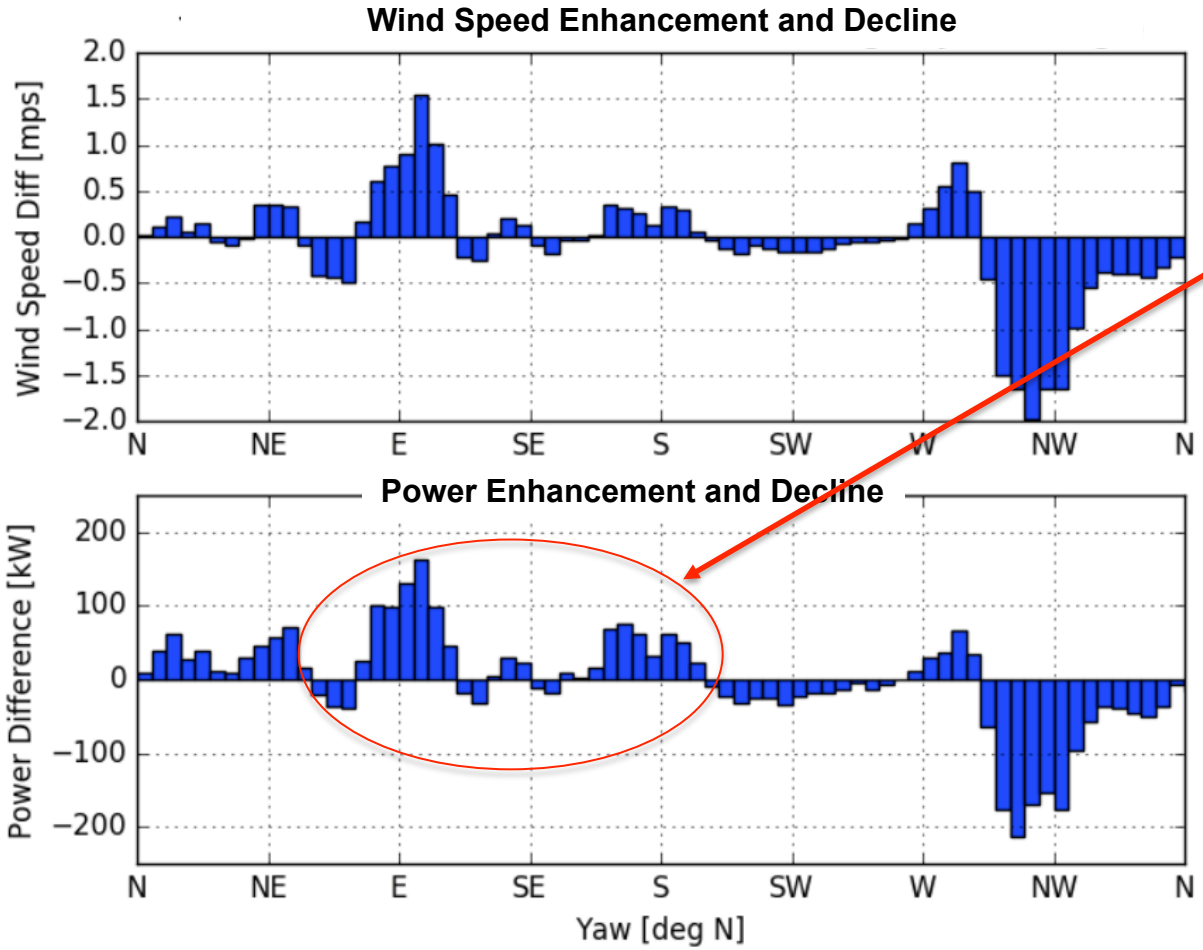

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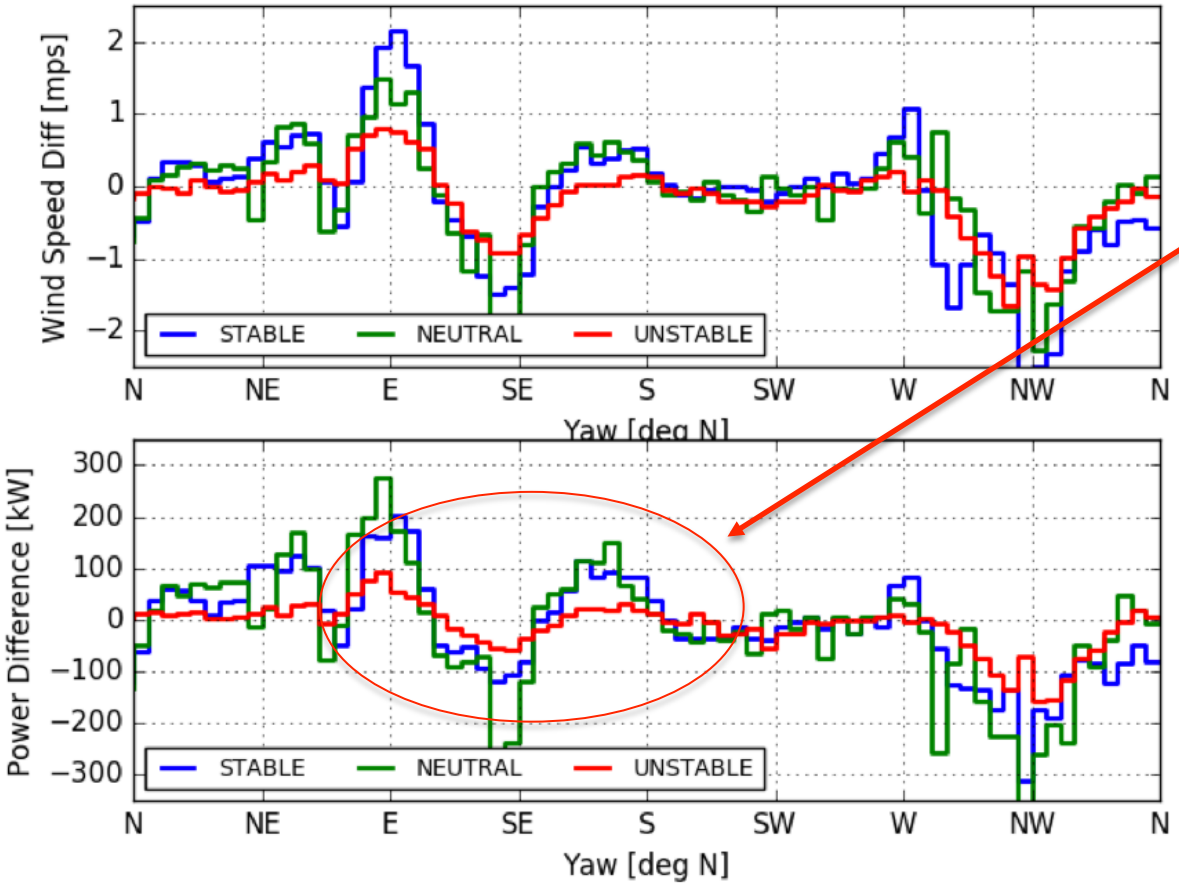

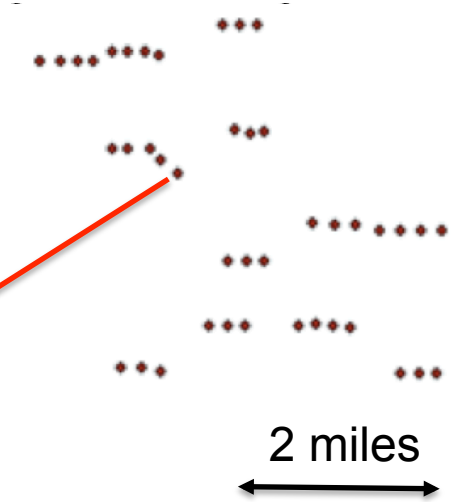

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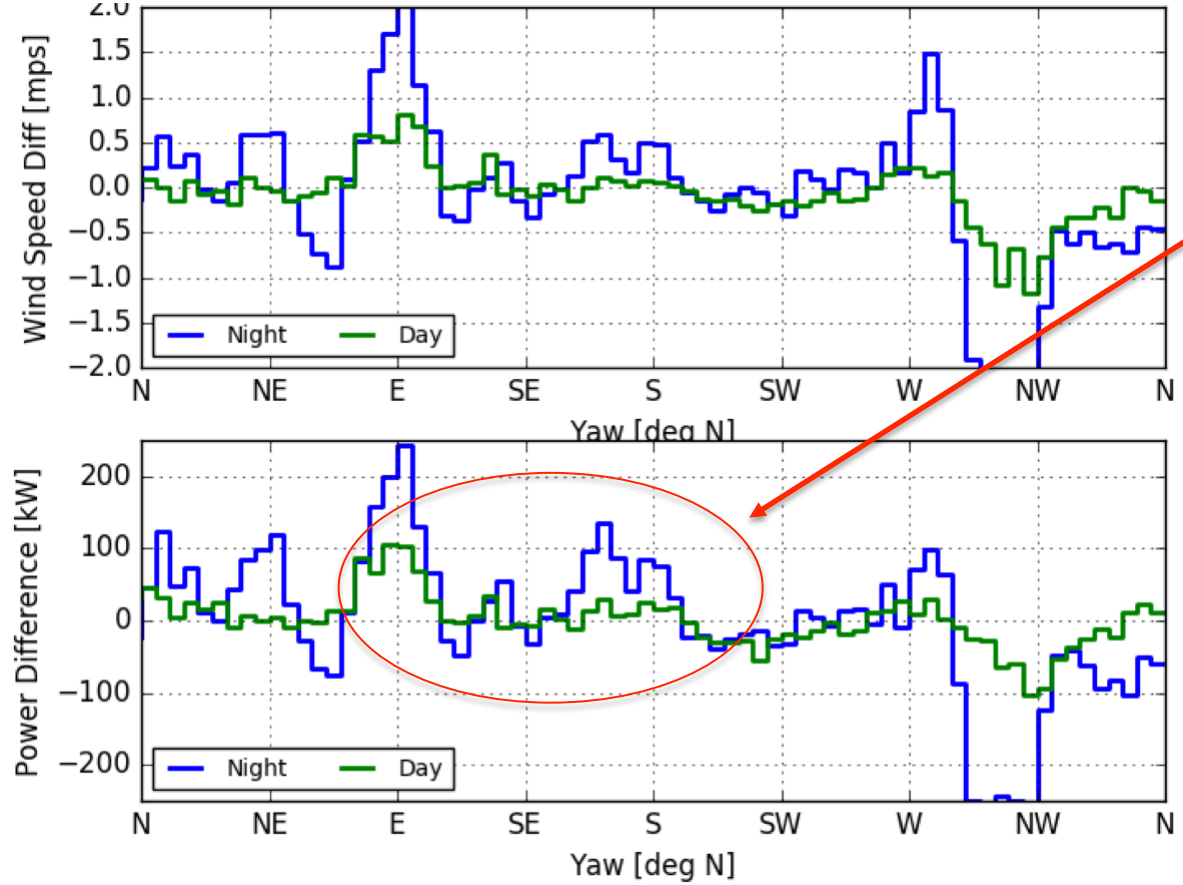
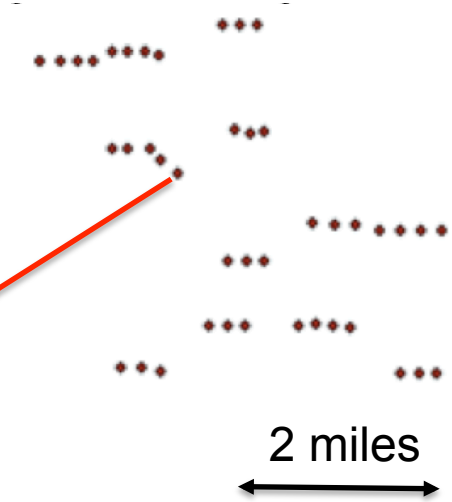
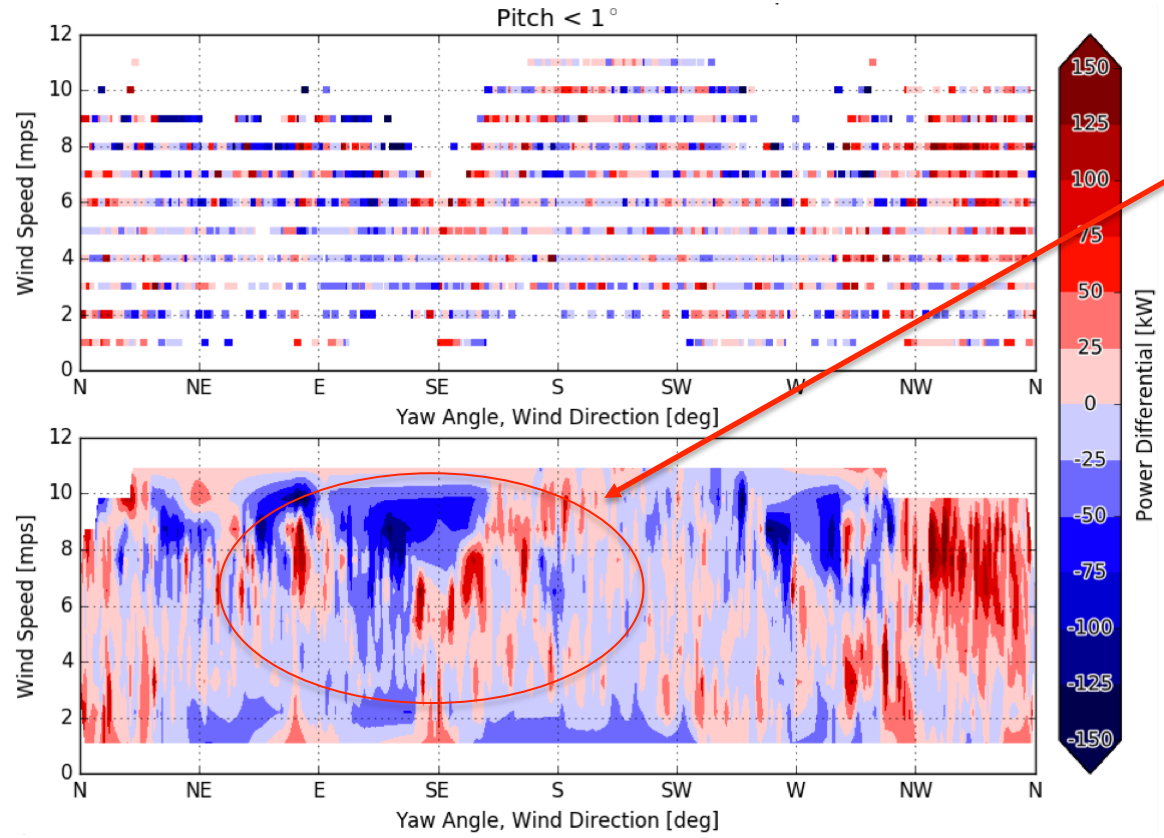
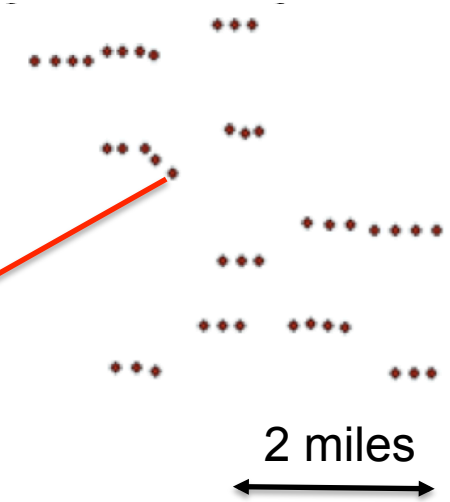




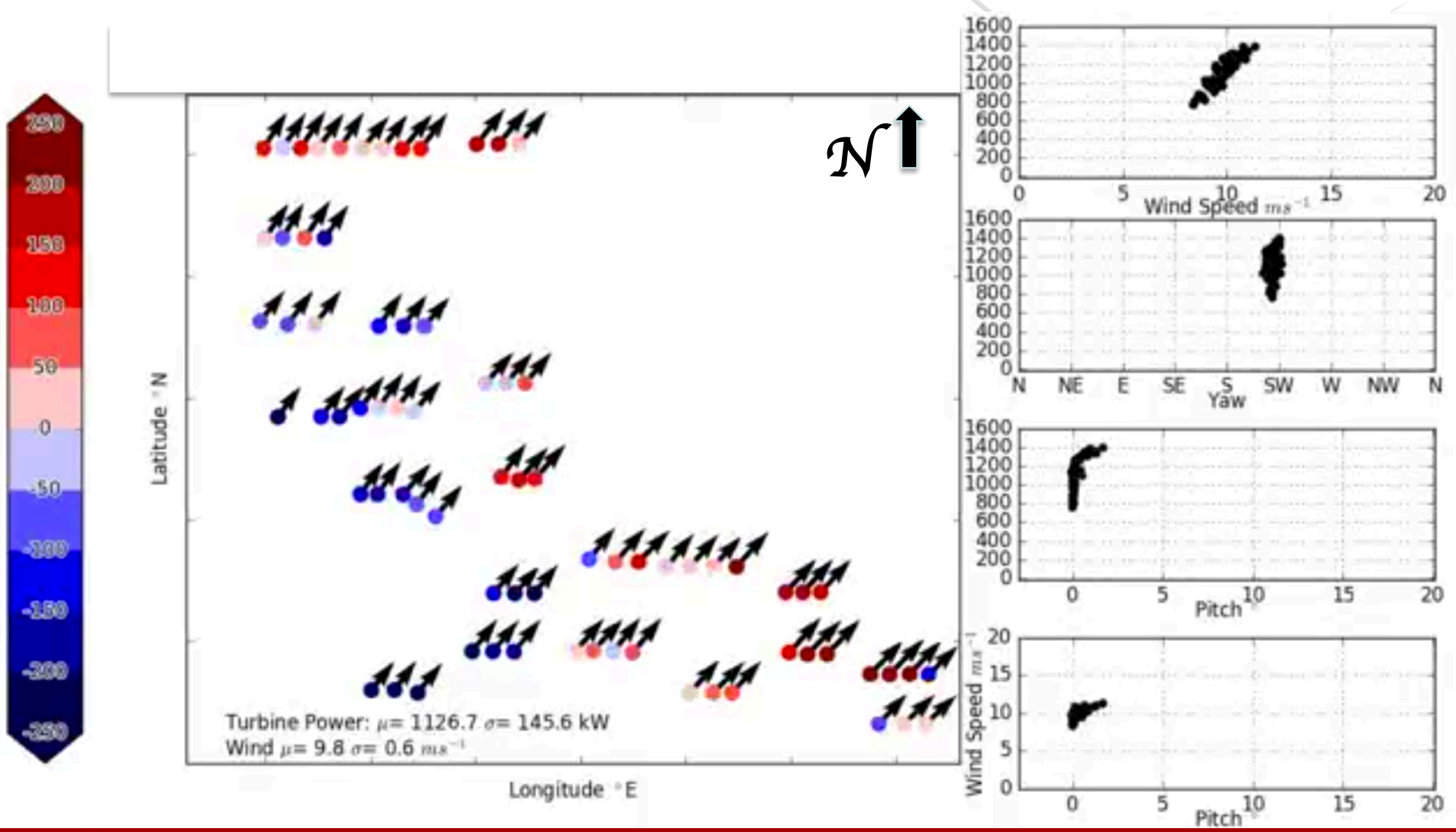
Stability and directional variability
Wake Concept Tool





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 m<L<200m
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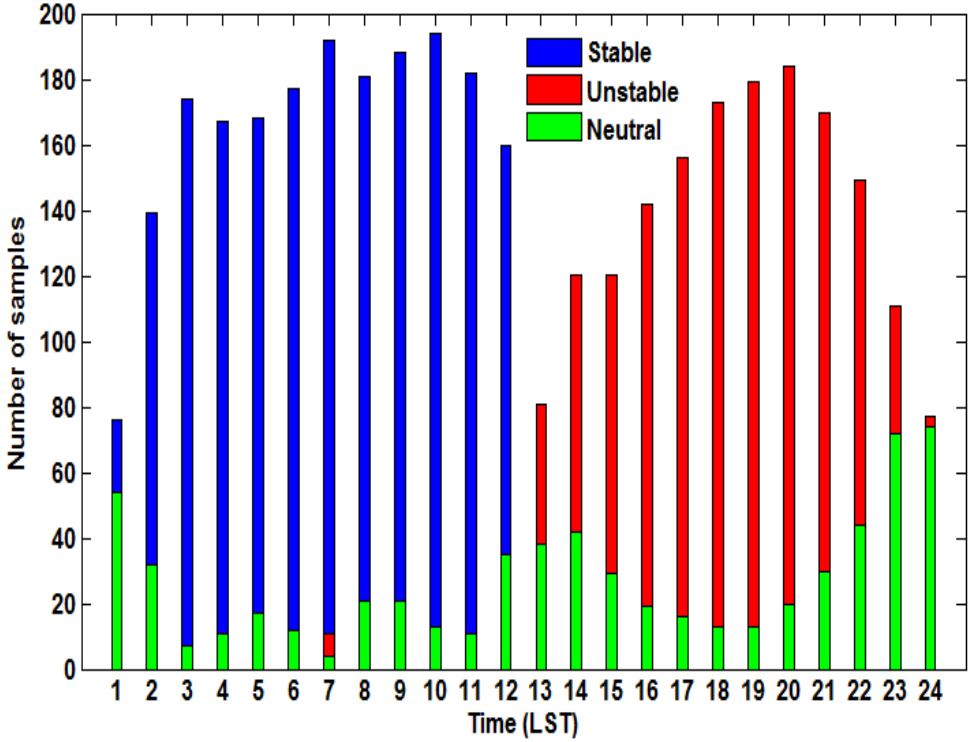
  - **NEUTRAL** |L|≥200 m

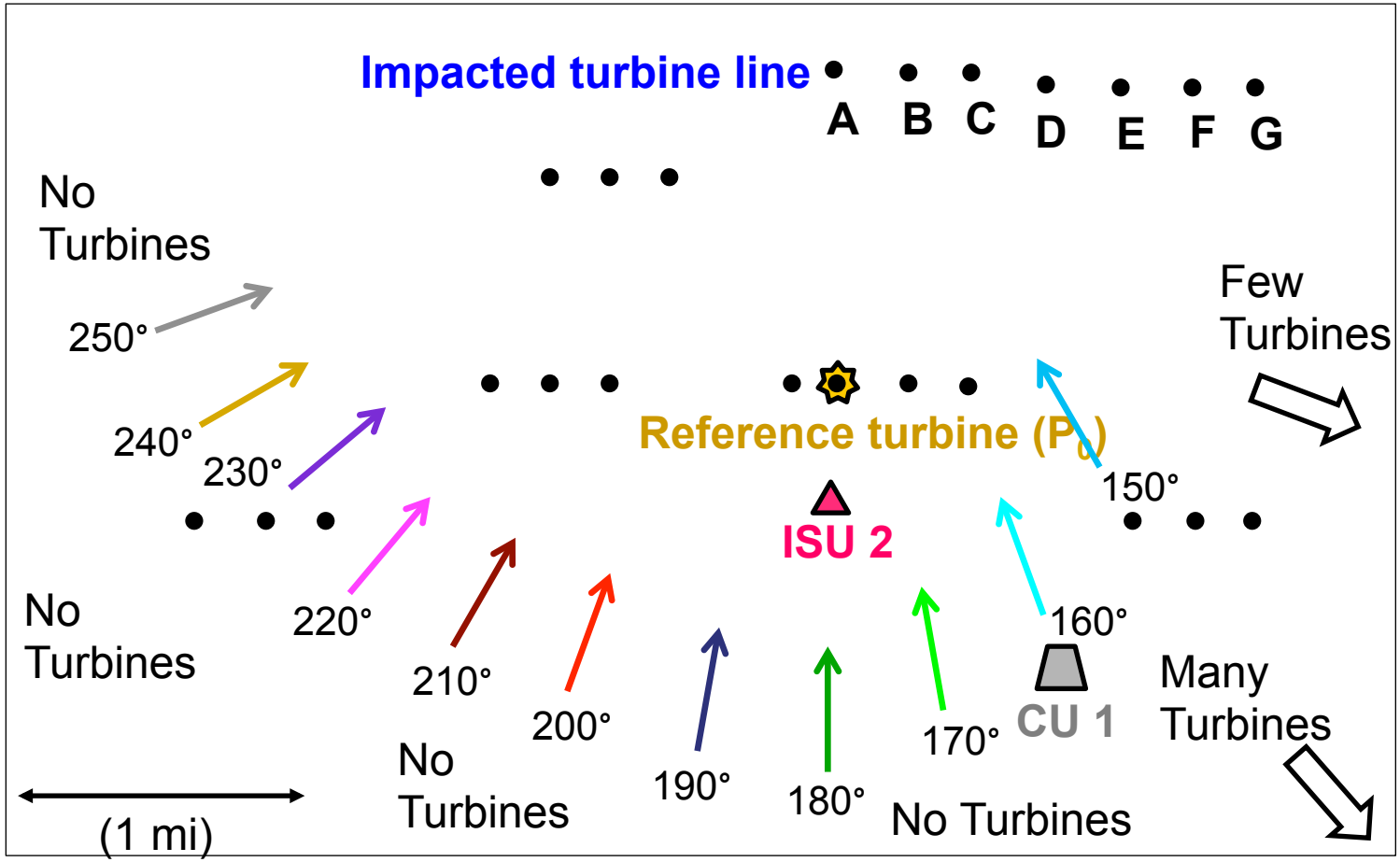
Diurnal distribution of stability for non-waked upwind directions



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

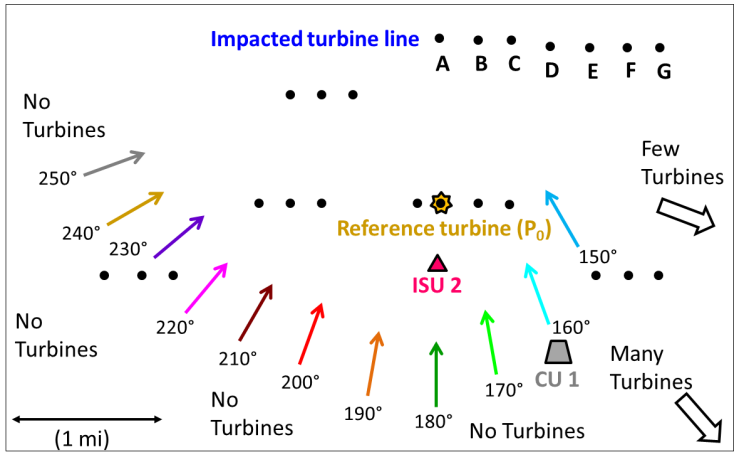
Stability and directional variability Wake Concept Tool

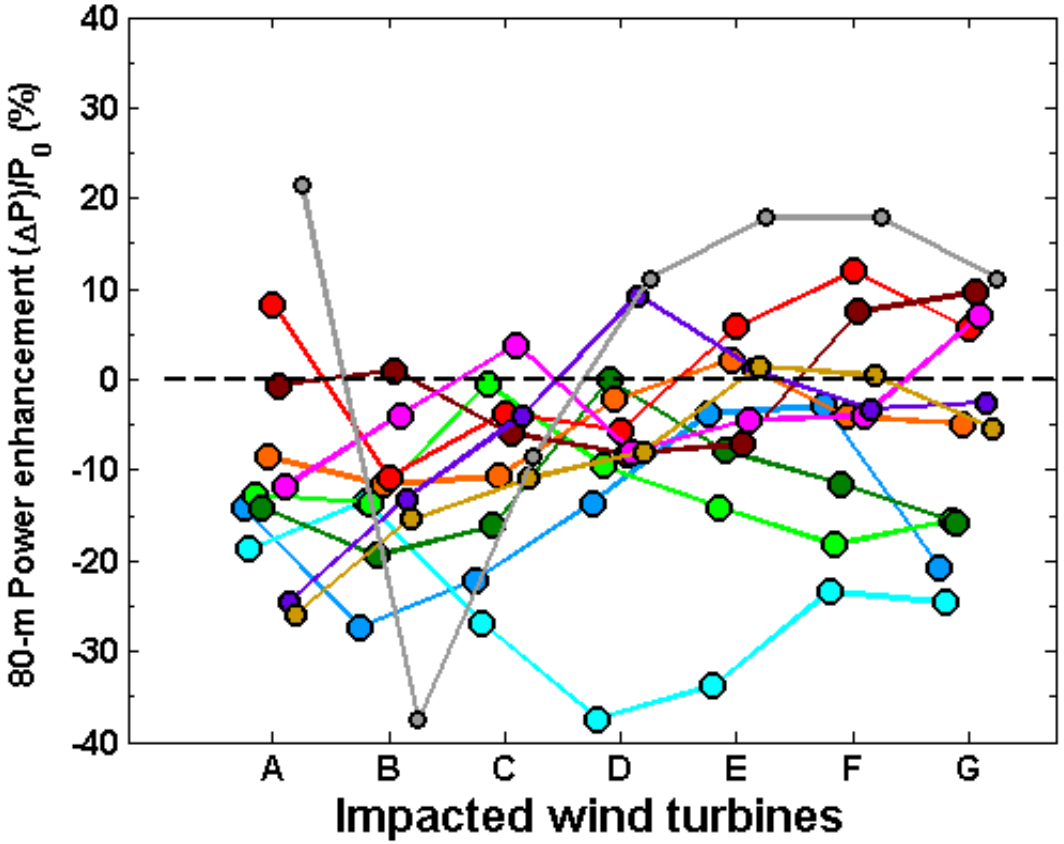
Layout: sorting by wake-distance categories



Stability and directional variability Wake Concept Tool

Stable stratification





Stability and directional variability Wake Concept Tool

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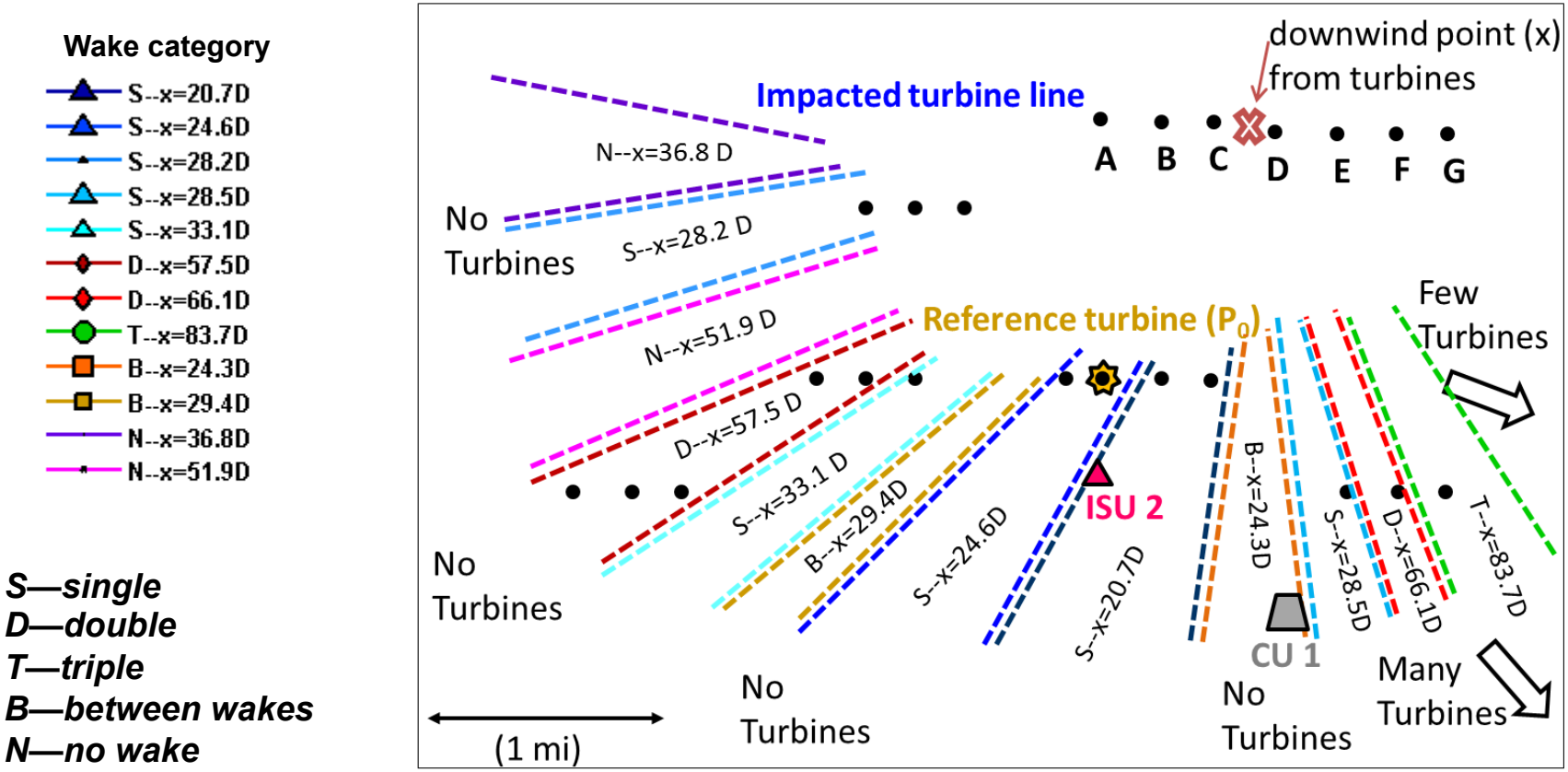
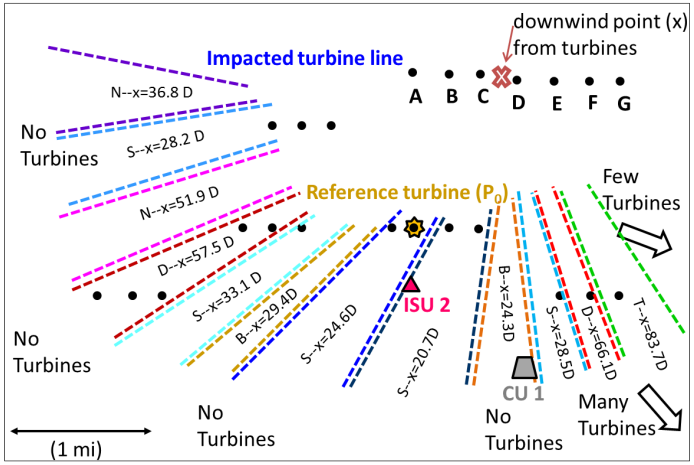
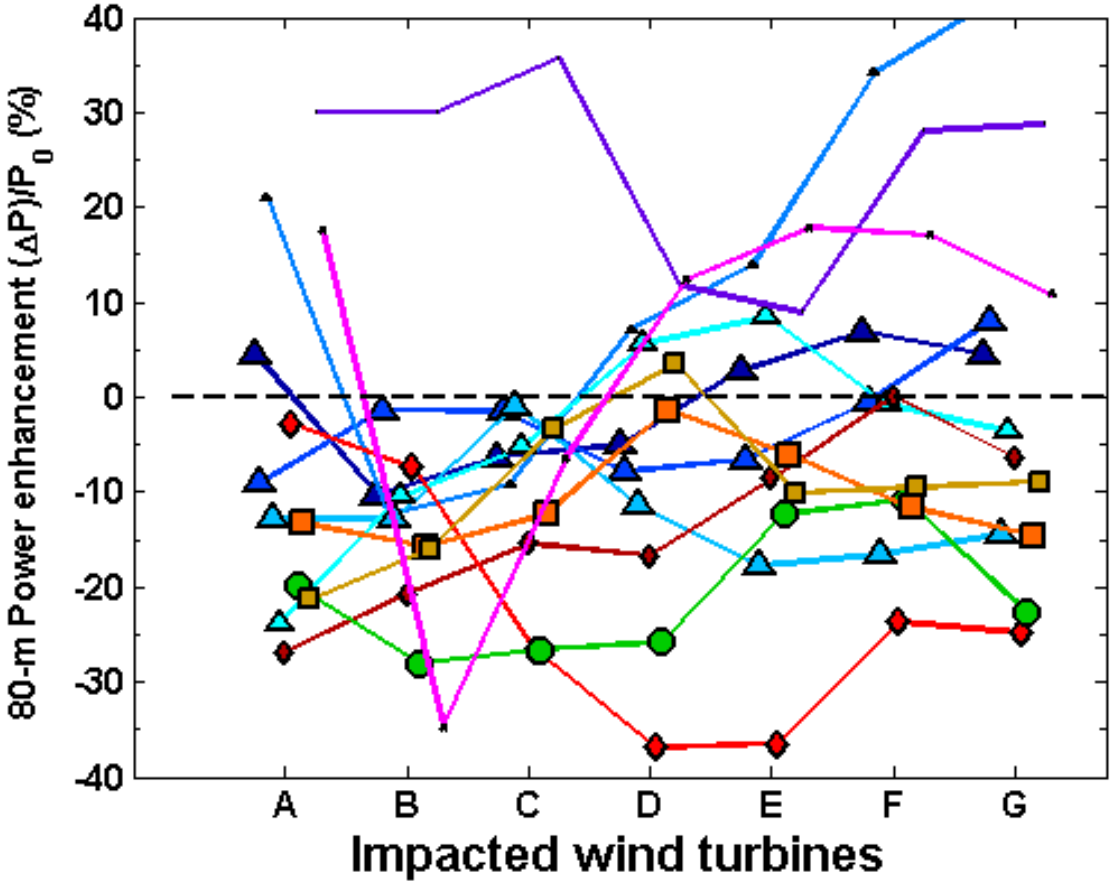


Stability and directional variability Wake Concept Tool

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