Iowa State University

College of Engineering

Variations in Turbine-Specific Power-Production in a Low-Density Wind Farm with Applications to Wake Steering

Eugene S. Takle

Daryl Herzmann, and Dan Rajewski

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

Iowa State University

Ames, IA

Wind Energy Science, Engineering and Policy 594

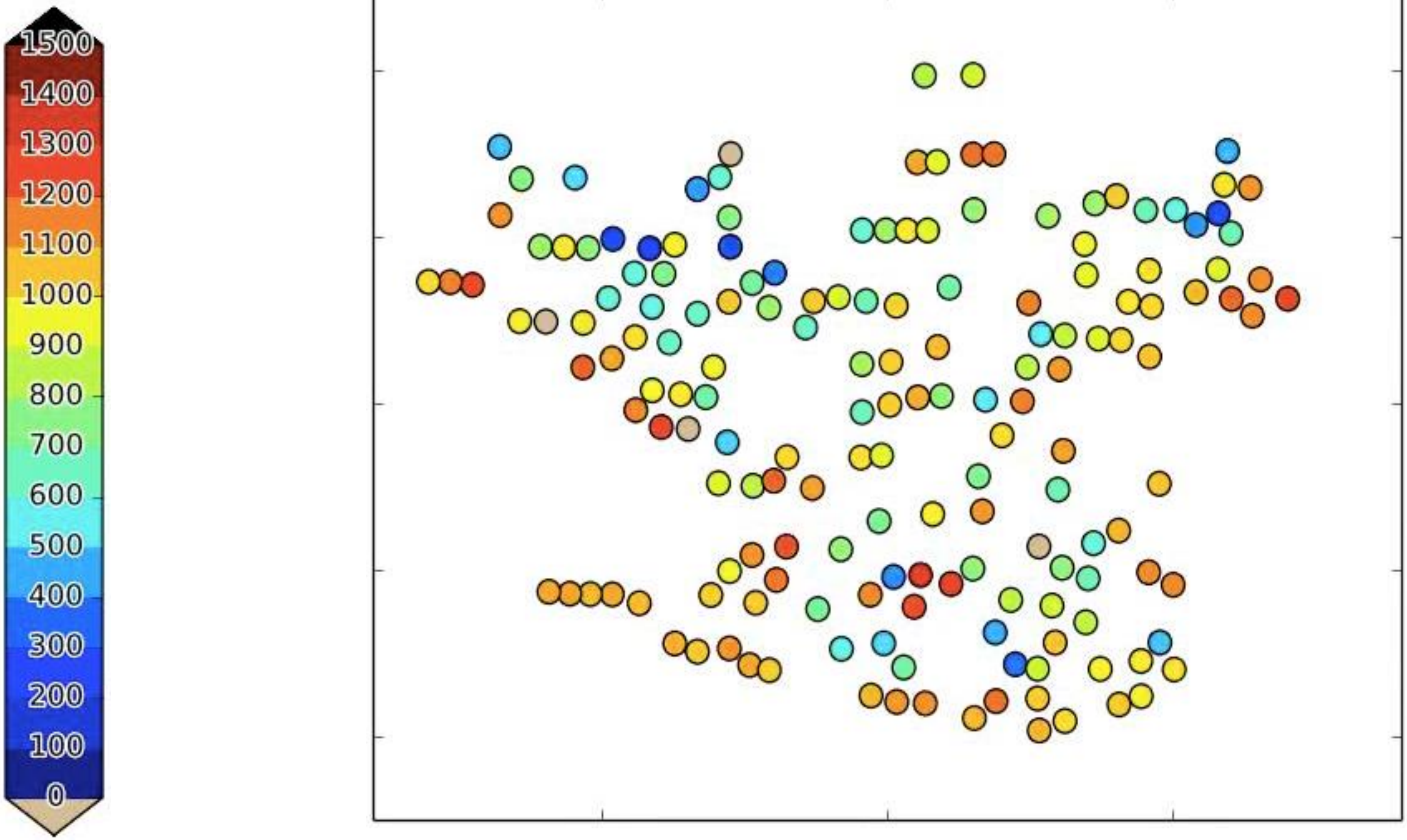
4 October 2016

Overview

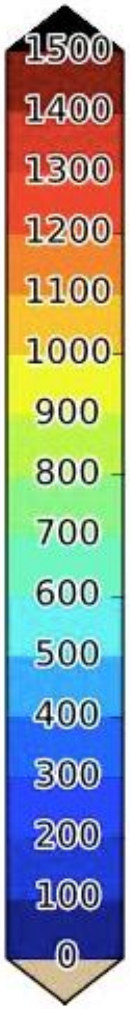
- Hansen (2011)* provided guidelines for wind farm wake analysis with applications to high density (distance between turbines < 10 rotor diameters; i.e., x < 10D).
- For low-density (e.g., x > 15 D) wind farms, or sections of wind farms we demonstrate simpler sorting and visualization tools that reveal wake interactions and opportunities for wind farm power prediction and wake steering.
- SCADA data from a segment of a large mid-continent wind farm, together with surface flux measurements and lidar data are subjected to analysis and visualization of wake interactions.

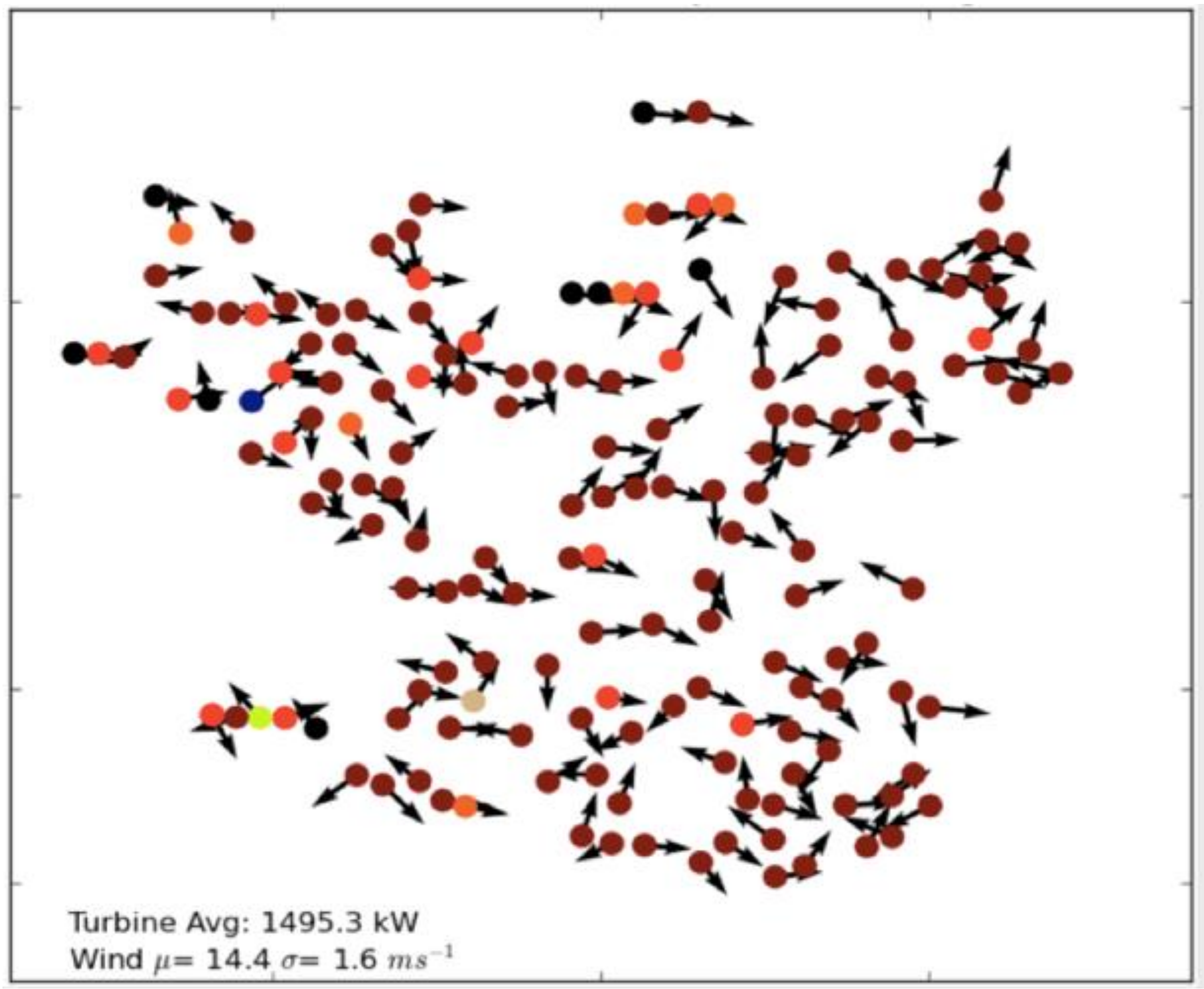
* Hansen, Kurt S., 2011: Guideline to wind farm wake analysis. *In* P.J. Eecen, J. W. Wagenaar, N. Stefanatos, T.F. Peterson, R. Wagner, and K. S. Hansen: Final Report, UPWIND 1A2 Metrology. ECN-E--11-013. [Available online at ftp://ftp.ecn.nl/pub/www/library/report/2011/e11013.pdf]

SCADA Diagnostic Tools:
Power visualization

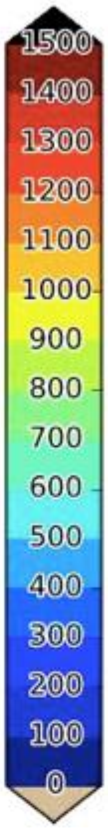


SCADA Diagnostic Tools:
Power visualization



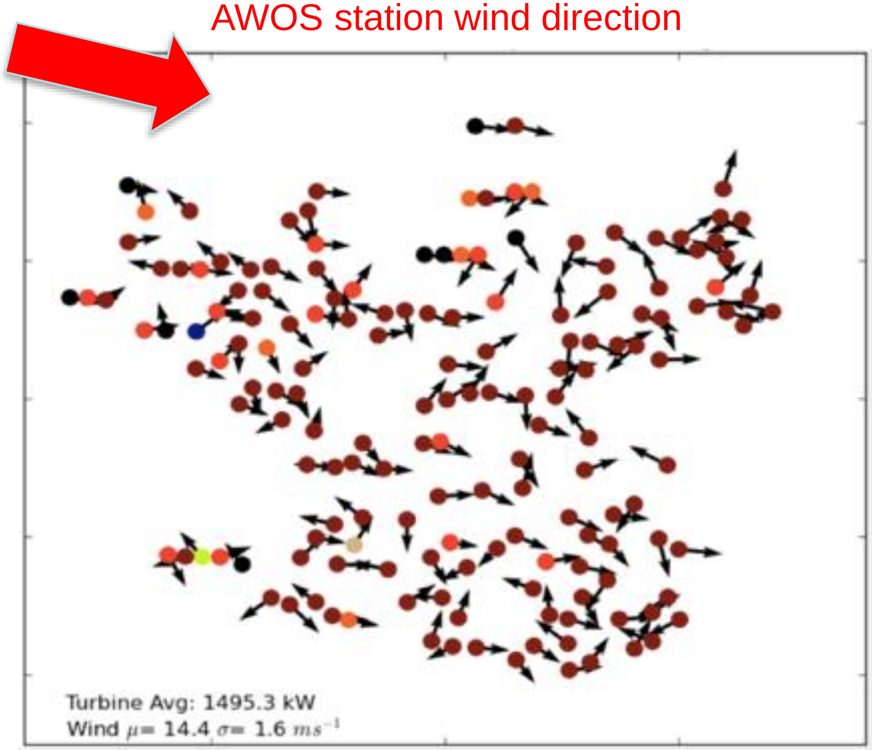


SCADA Diagnostic Tools:
Power visualization

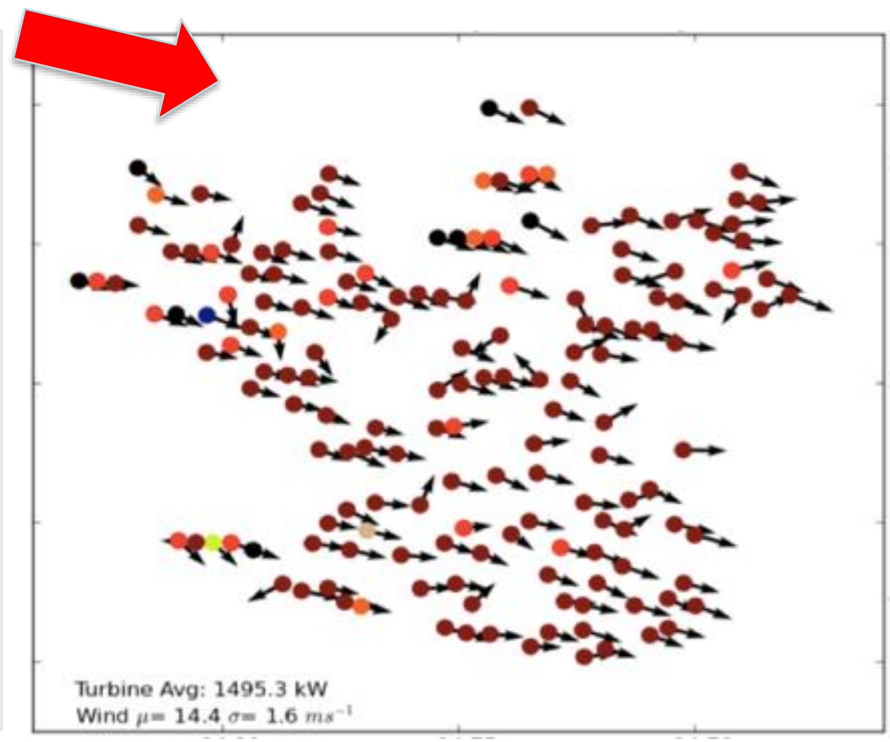


Before

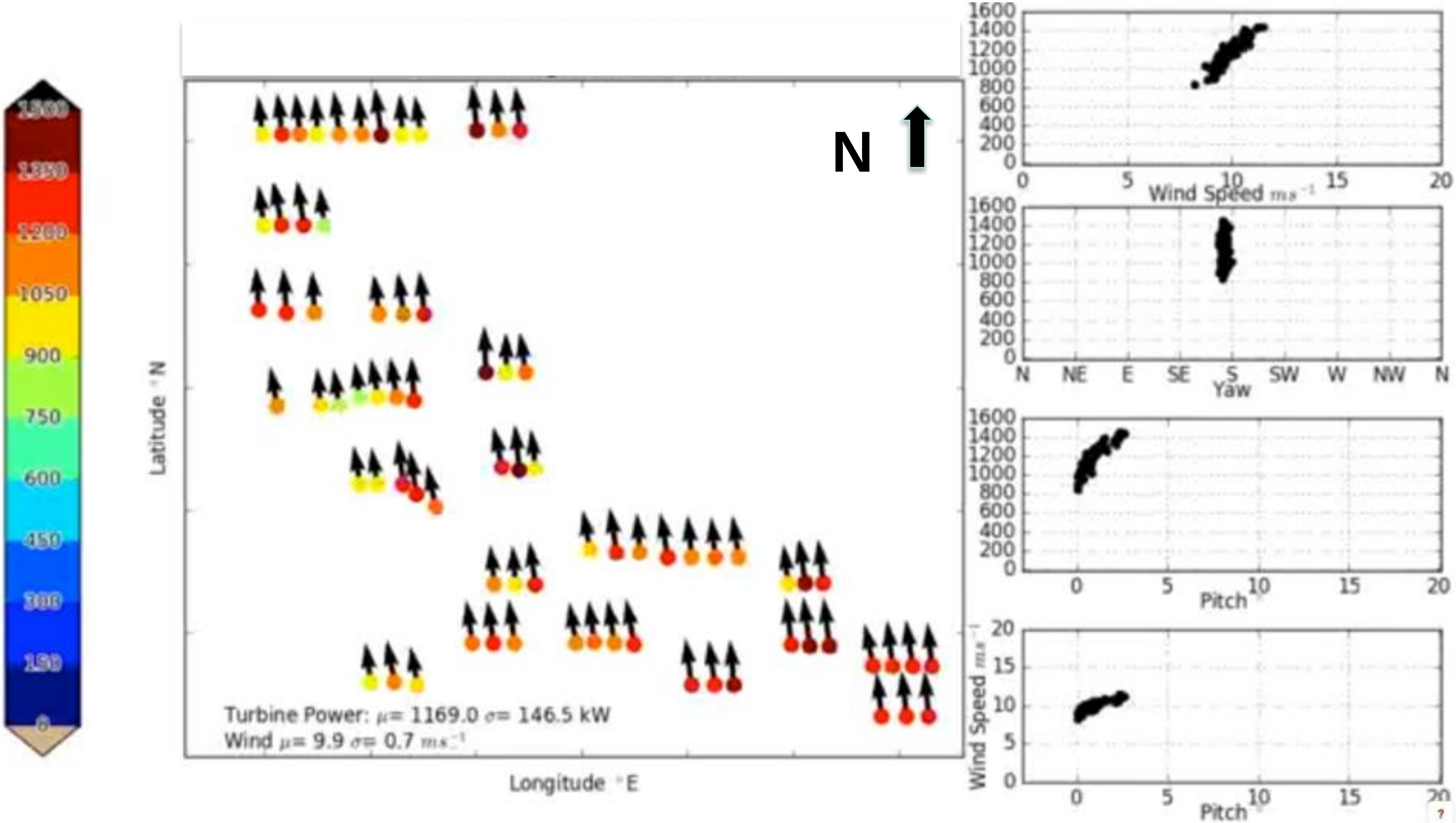
AWOS station wind direction



After

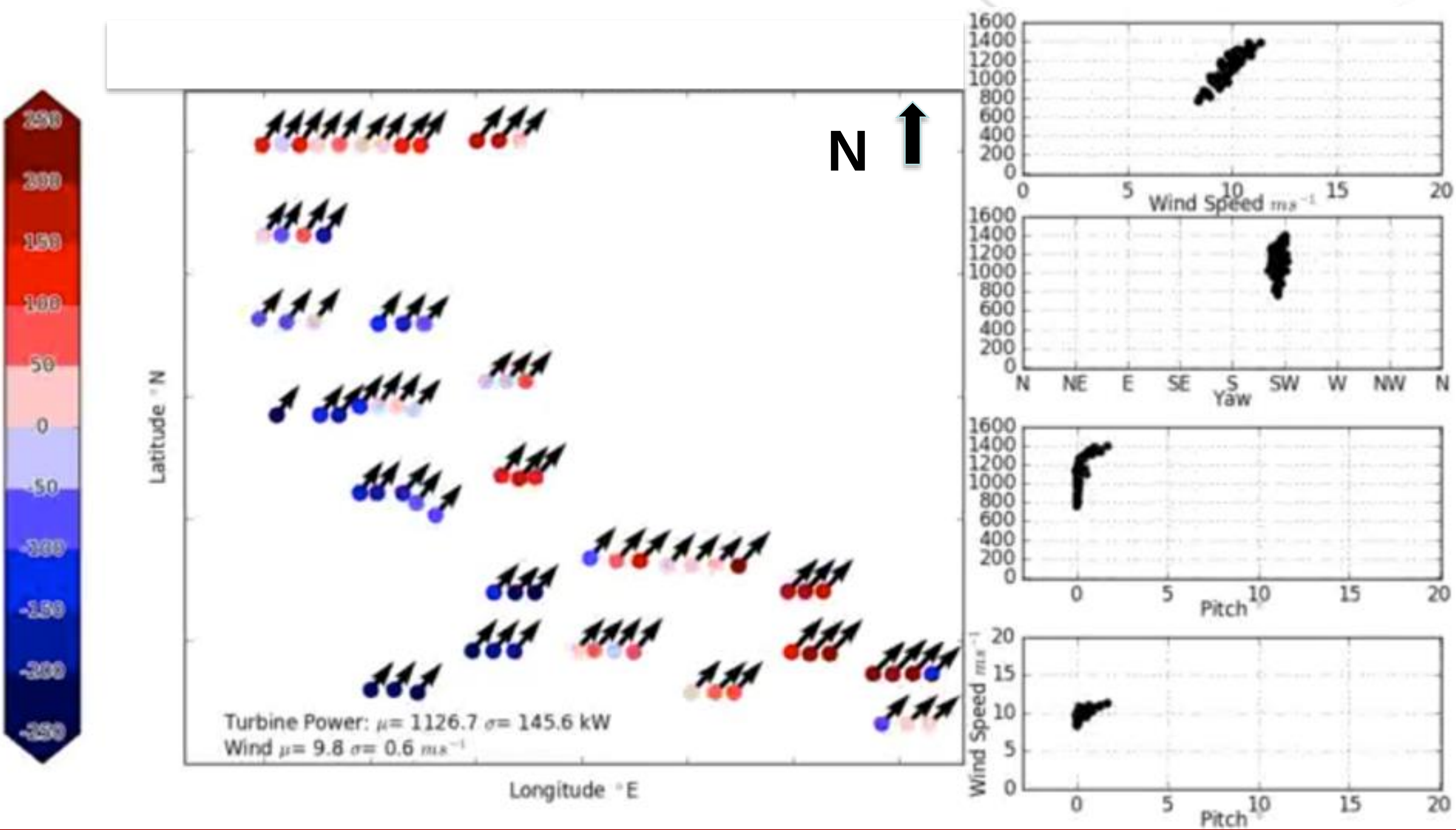


SCADA Diagnostic Tools:
Power visualization

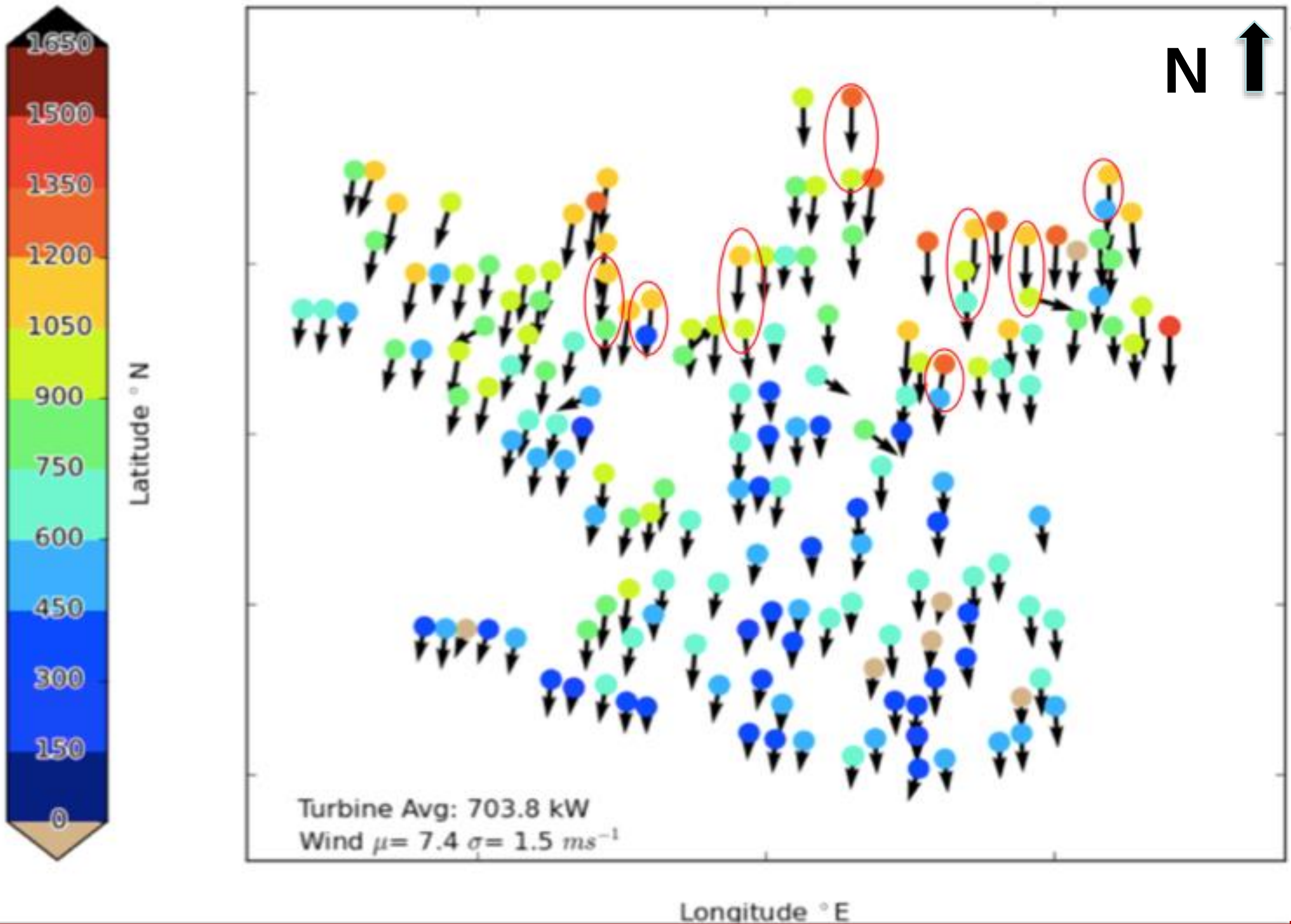


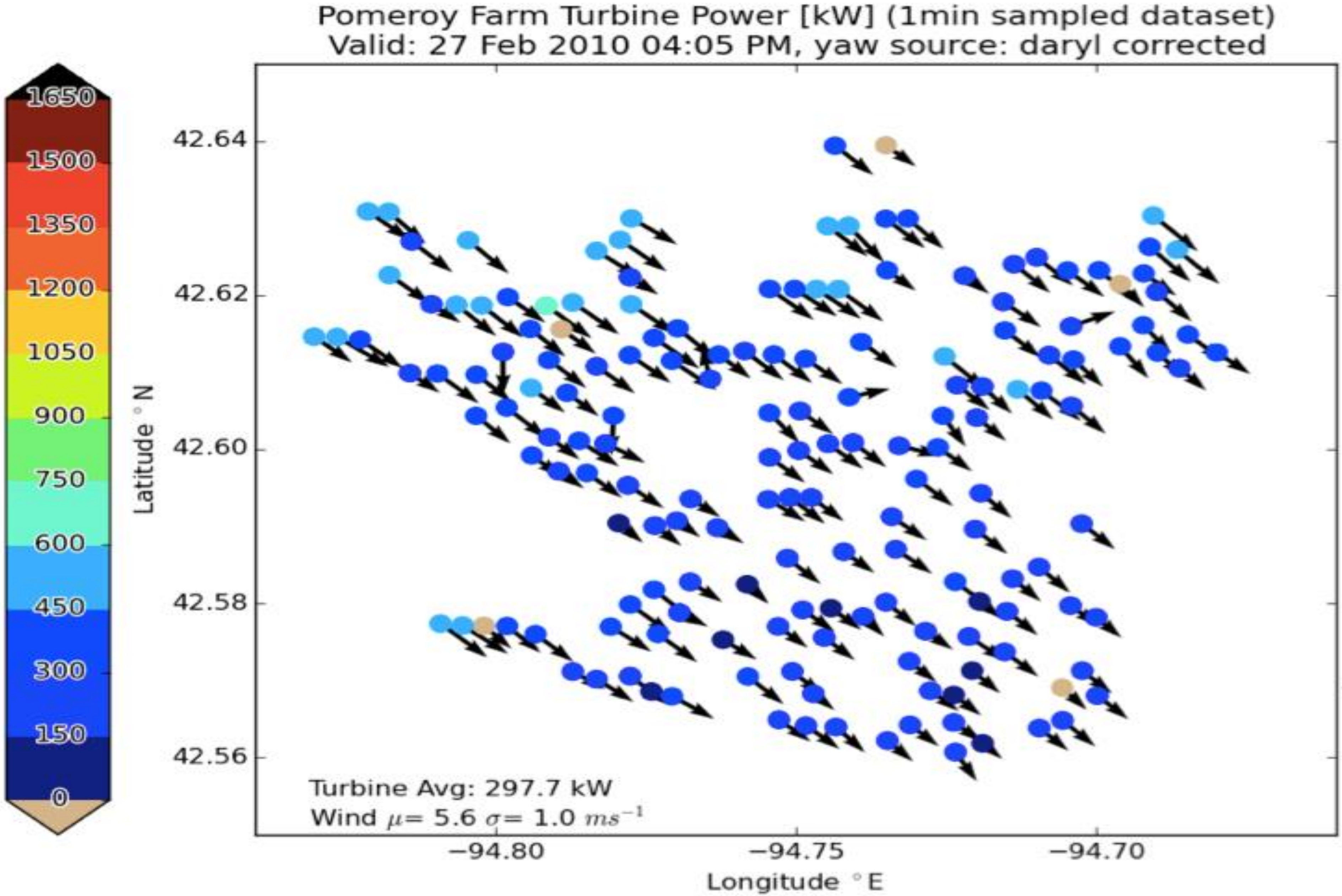
SCADA Diagnostic Tools:

Wind-Plant Turbine Power-Differential Tool



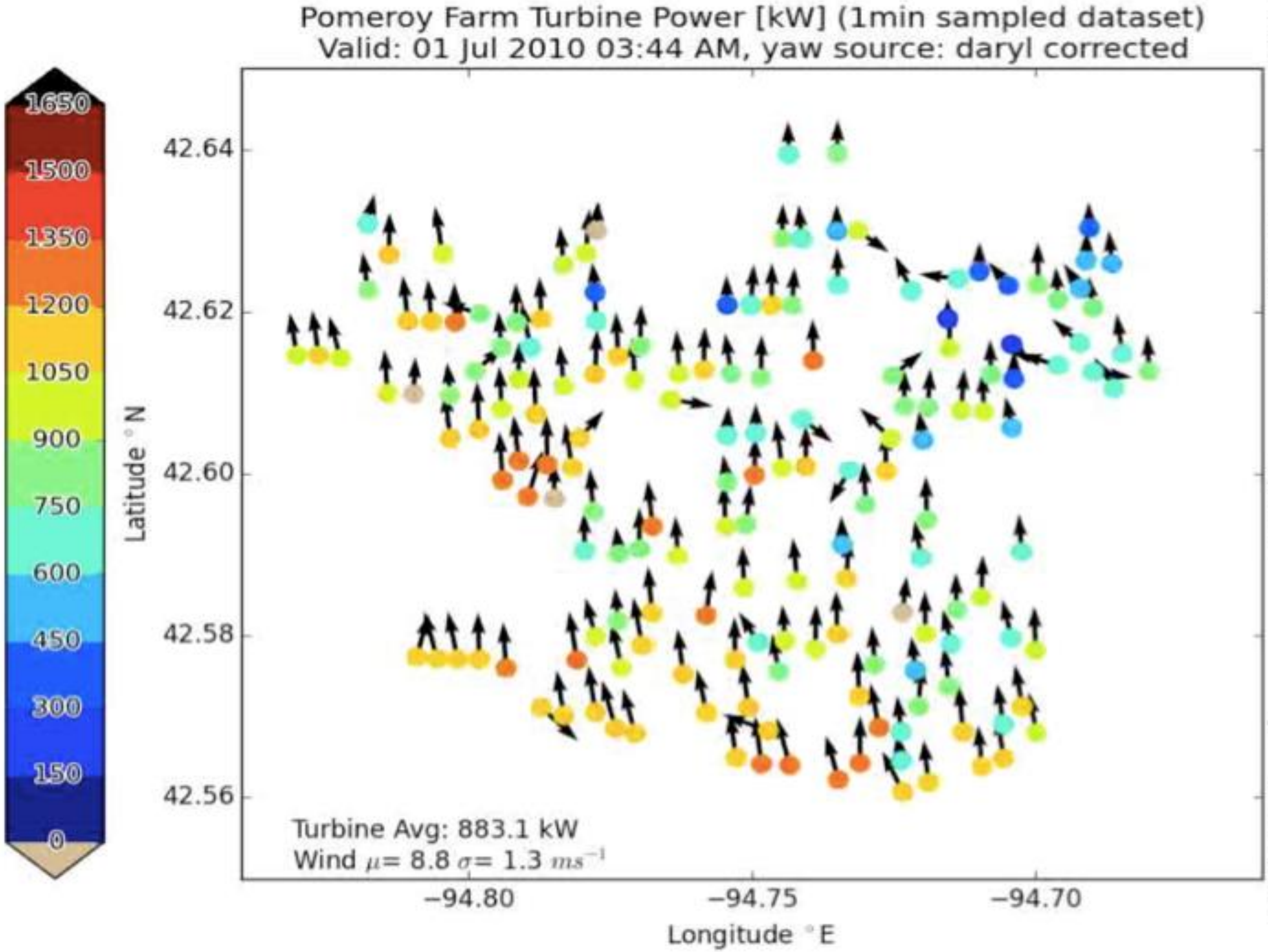
SCADA Diagnostic Tools:
Power visualization





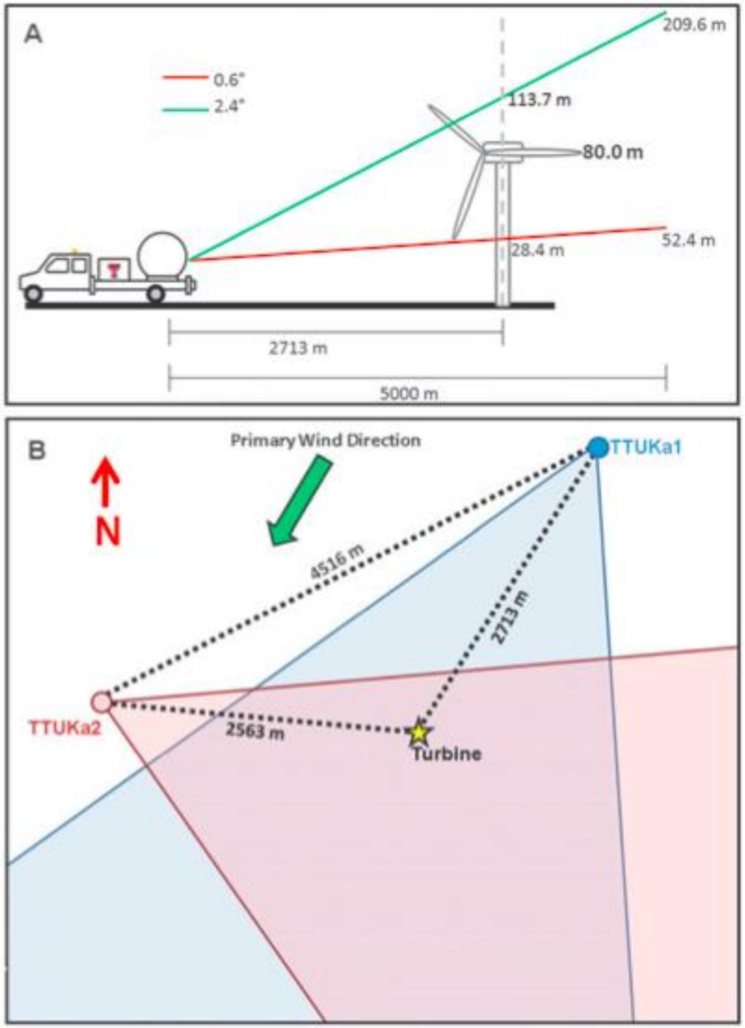
Pomeroy Farm Turbine Power [kW] (1min sampled dataset)
Valid: 27 Feb 2010 04:05 PM, yaw source: daryl corrected
1650
1500
1350
1200
1050
900
750
600
450
300
150
0
42.64
42.62
42.60
42.58
42.56
Latitude ° N
Turbine Avg: 297.7 kW
Wind $\mu = 5.6$ $\sigma = 1.0$ ms^{-1}
−94.80
−94.75
−94.70
Longitude ° E

a


Pomeroy Farm Turbine Power [kW] (1min sampled dataset)
Valid: 01 Jul 2010 03:44 AM, yaw source: daryl corrected
1650
1500
1350
1200
1050
900
750
600
450
300
150
0
Latitude °N
42.64
42.62
42.60
42.58
42.56
Turbine Avg: 883.1 kW
Wind μ= 8.8 σ= 1.3 ms⁻¹
−94.80
−94.75
−94.70
Longitude °E

SCADA Diagnostic Tools:
Power visualization

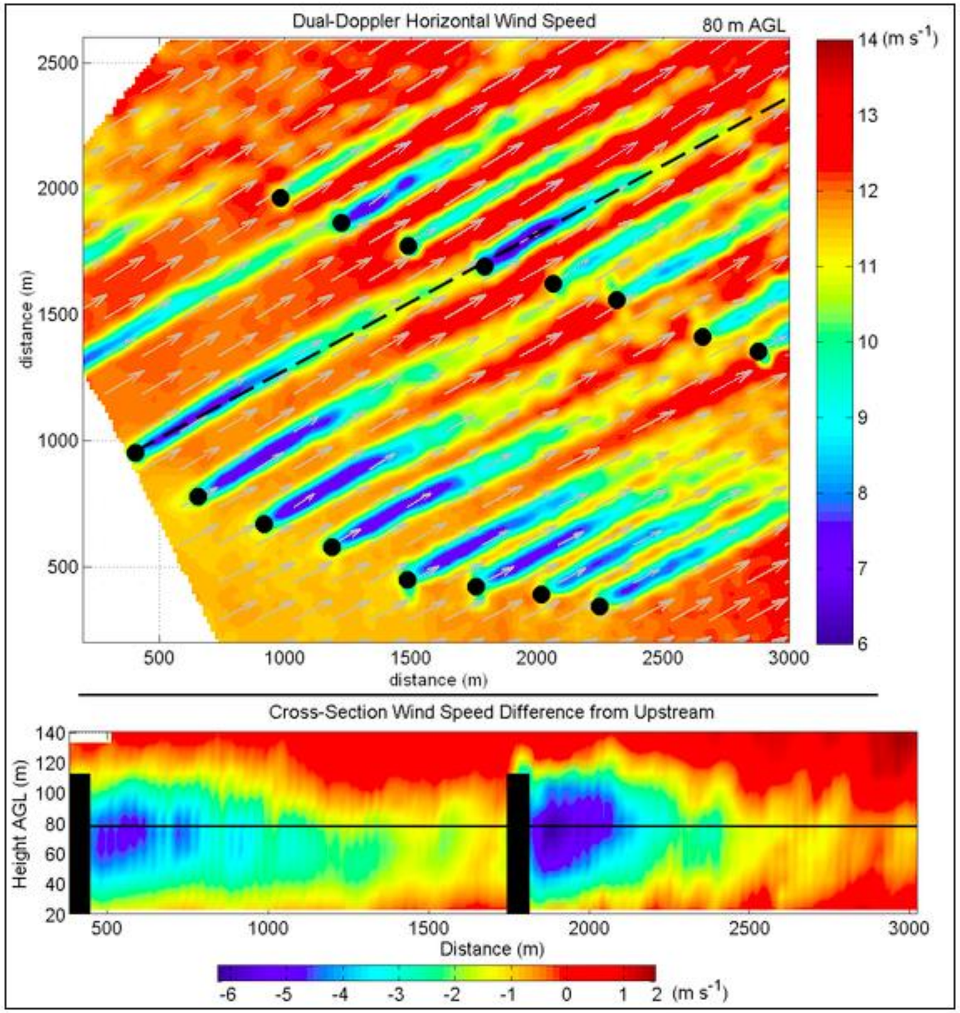
Texas Tech University
Ka Band Radar



Hirth and Schroeder, 2013: *J Appl. Meteorol. Clim*, **52**, 39-46.

Hirth et al., 2014: *Wind Energy* **18**, 529-540.

Plan View of Multiple Wakes



Dual Doppler synthesized horizontal wind speeds near hub height, and a verticle cross section through two turbines.

Hirth et al., 2014: *Wind Energy* **18**, 529-540.

Wake Vertical and Horizontal Structure

40 m agl

60 m agl

80 m agl

100 m agl

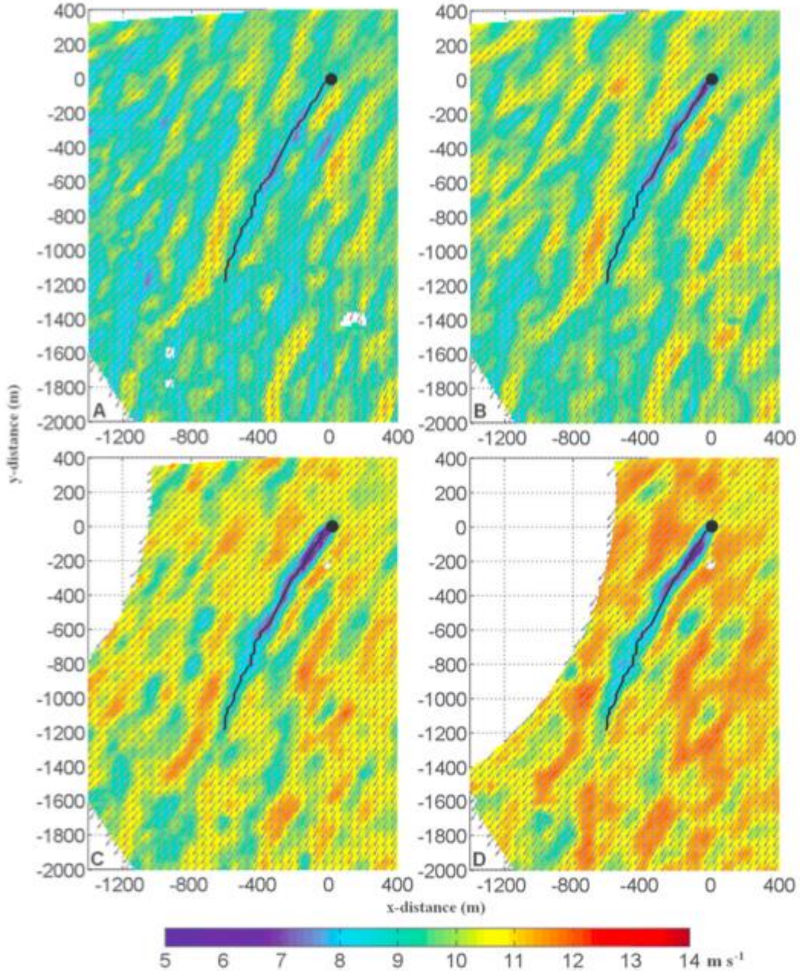


FIG. 2. An example of TTUKa DD-synthesized horizontal wind speed (m s^{-1}) at (a) 40, (b) 60, (c) 80, and (d) 100 m AGL. Horizontal wind vectors are shown. The black dot represents the location of the turbine. The solid black line represents an algorithm-defined wake center to a distance of 15*D*.

Hirth and Schroeder, 2013: J Appl. Meteorol. Clim, **52**, 39-46.

Wake Horizontal Structure

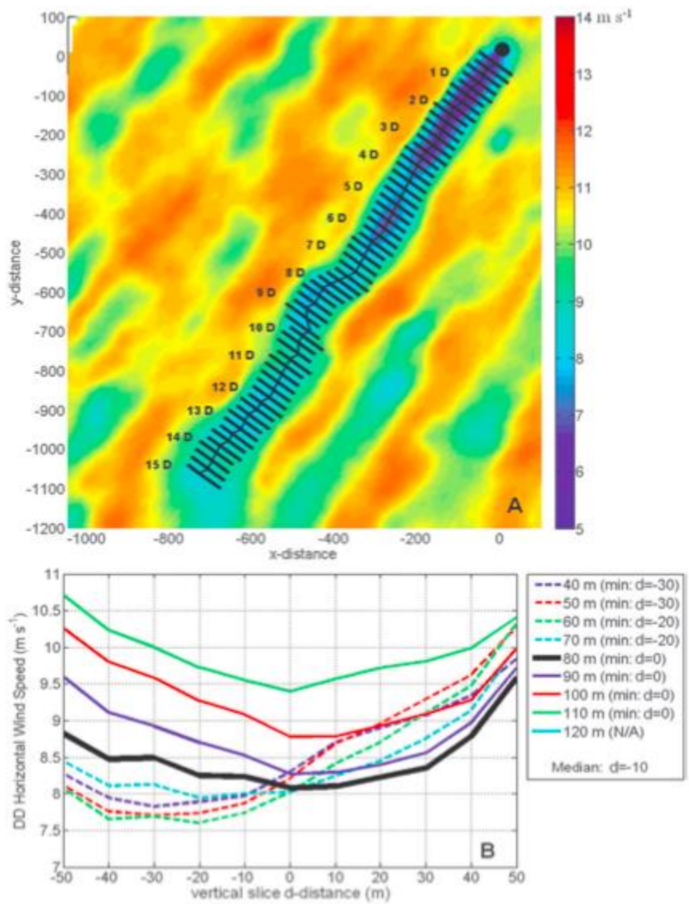


FIG. 3. (a) An example constant horizontal plane of DD horizontal wind speed (m s^{-1}) at 80 m with the wake-algorithm-derived wake centerline and vertical cross-section slices. (b) The DD horizontal wind speed cross-section slices at a downwind distance of 5*D* for the vertical levels between 40 and 110 m. The median location of the minimum horizontal wind speed for all contributing heights in this cross section was $x = -10$ m.

Hirth and Schroeder, 2013: J Appl. Meteorol. Clim, **52**, 39-46.

Wake Changes through Time for a Single Turbine

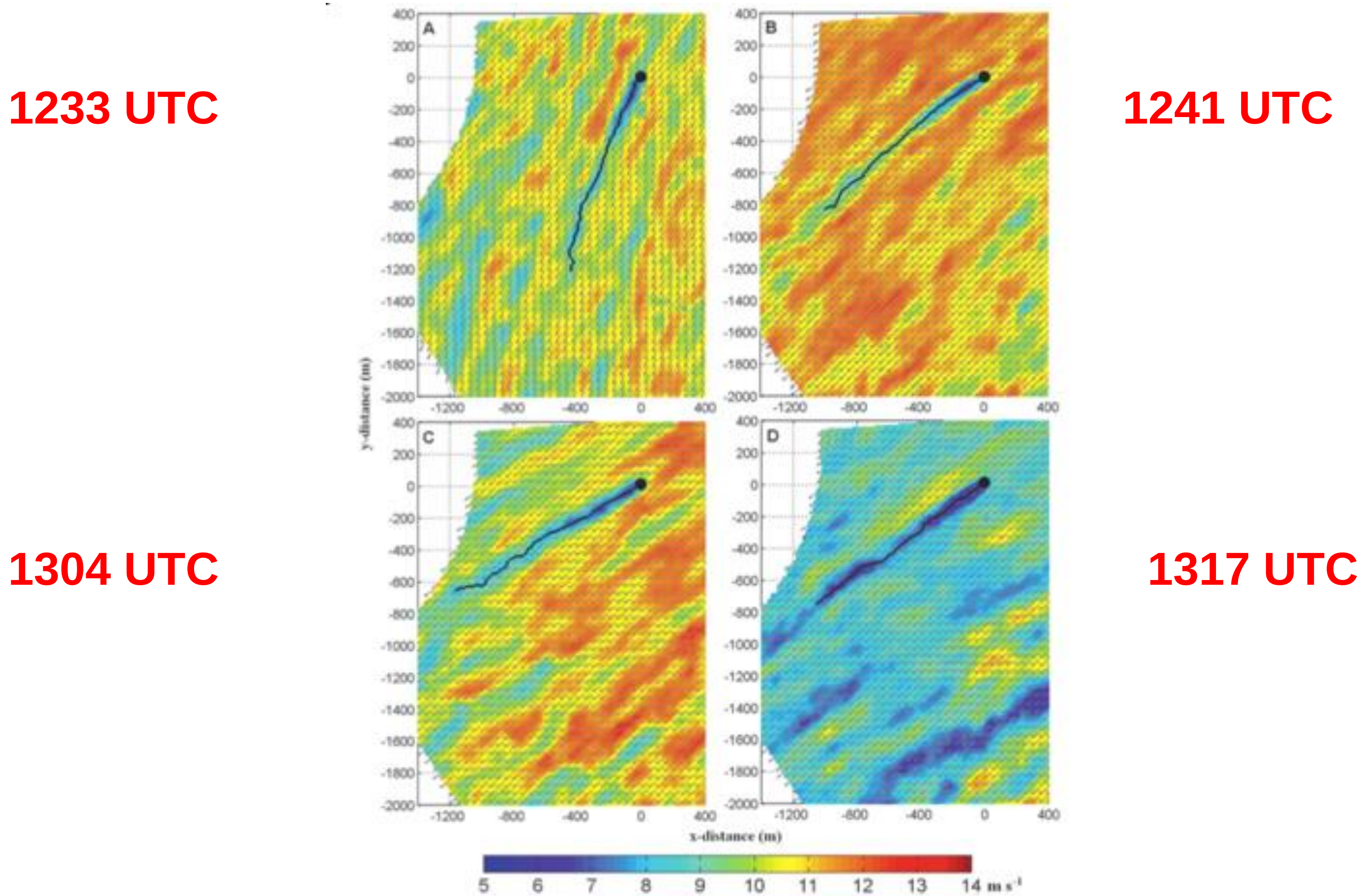


FIG. 4. TTUKa DD-synthesized horizontal wind speed (m s^{-1}) on 27 Oct 2011 at 80 m AGL at (a) 1233, (b) 1241, (c) 1304, and (d) 1317 UTC. Horizontal wind vectors are shown. The black dot represents the location of the turbine. The algorithm-defined wake center to a distance of 15D is denoted by the solid black line.

Hirth and Schroeder, 2013: J Appl. Meteorol. Clim, **52**, 39-46.

Wake Cross Section at Successive Distances Downwind

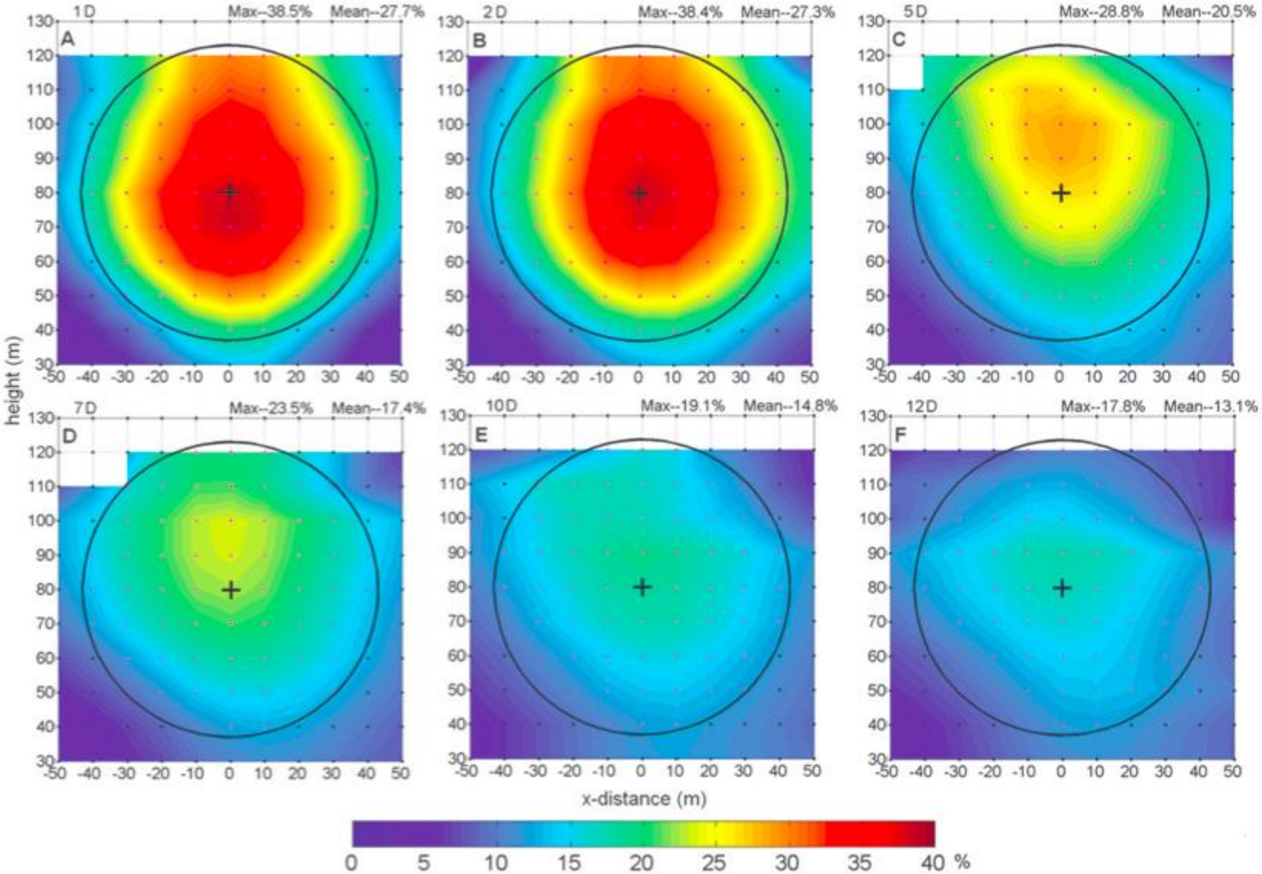
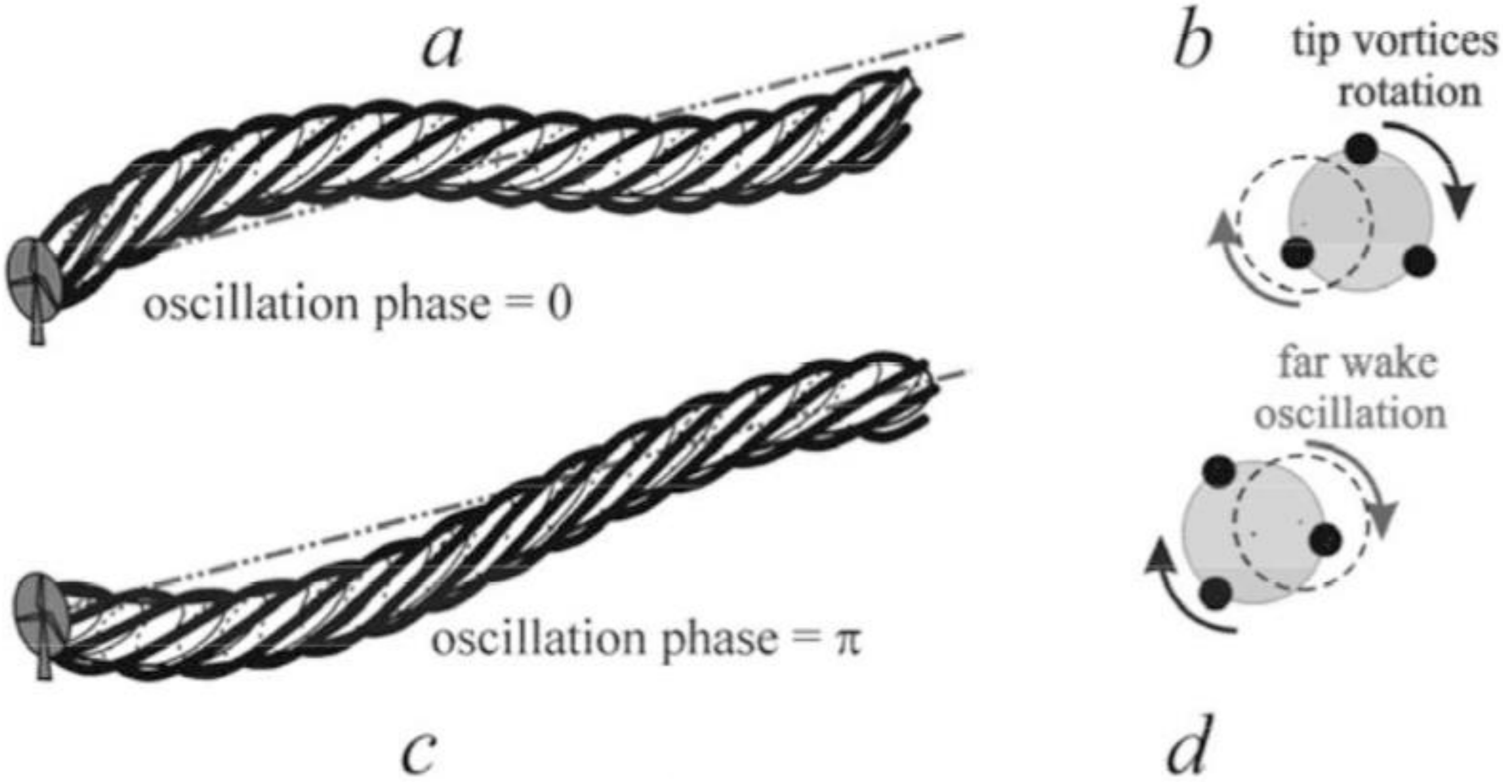


FIG. 5. Vertical slices of the reduction (%) in horizontal wind speed within the wake composited from 72 DD volumes at (a) D, (b) $2D$, (c) $5D$, (d) $7D$, (e) $10D$, and (f) $12D$ downwind. Domain grid points are shown, and magenta grid points represent those contained by the rotor sweep (solid black circle). The black plus sign represents the center of the turbine hub. The maximum and mean reduction values from the contributing rotor-sweep grid points are annotated.

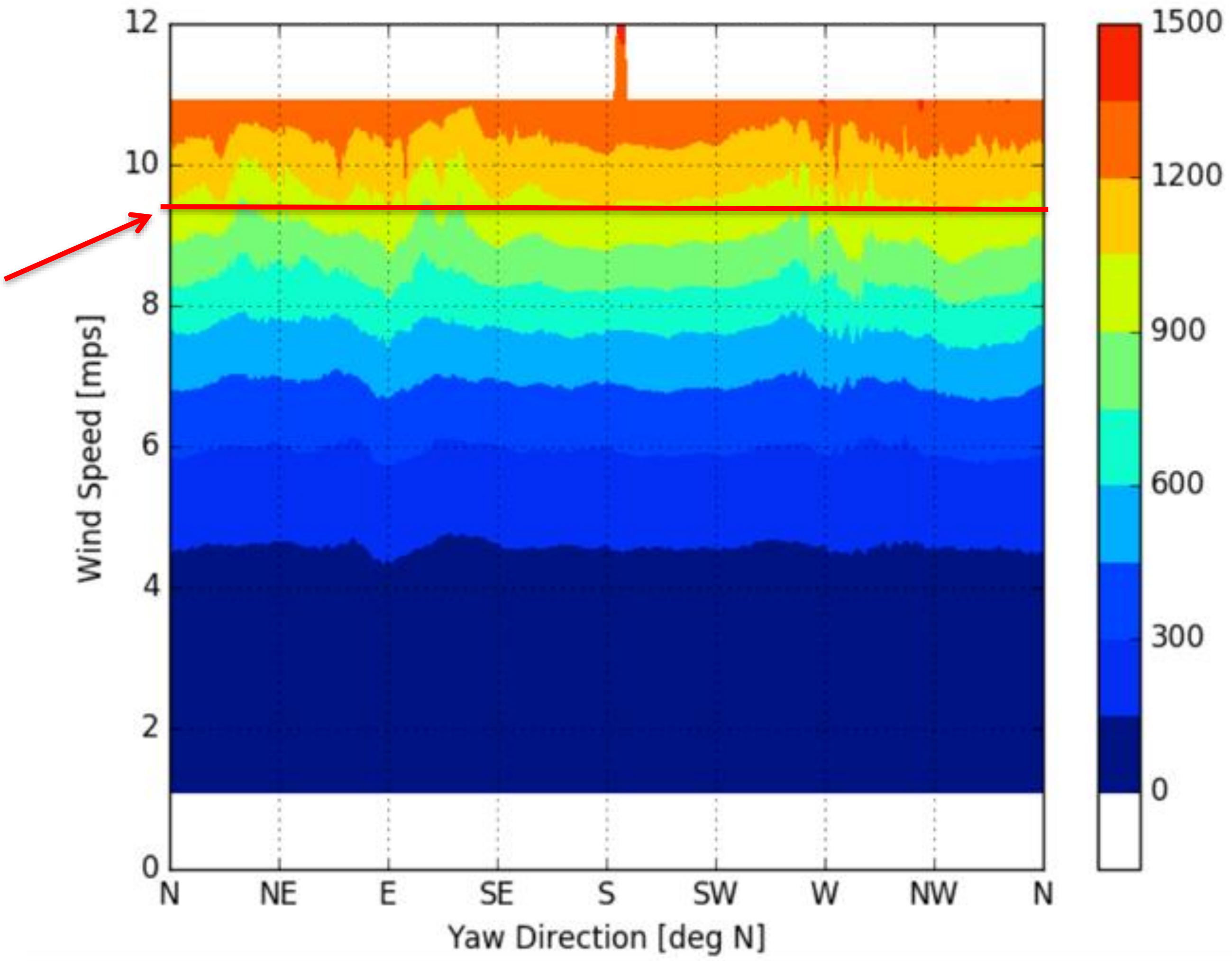
Hirth and Schroeder, 2013: J Appl. Meteorol. Clim, **52**, 39-46.


a
b
tip vortices rotation
oscillation phase = 0
far wake oscillation
oscillation phase = π
c
d

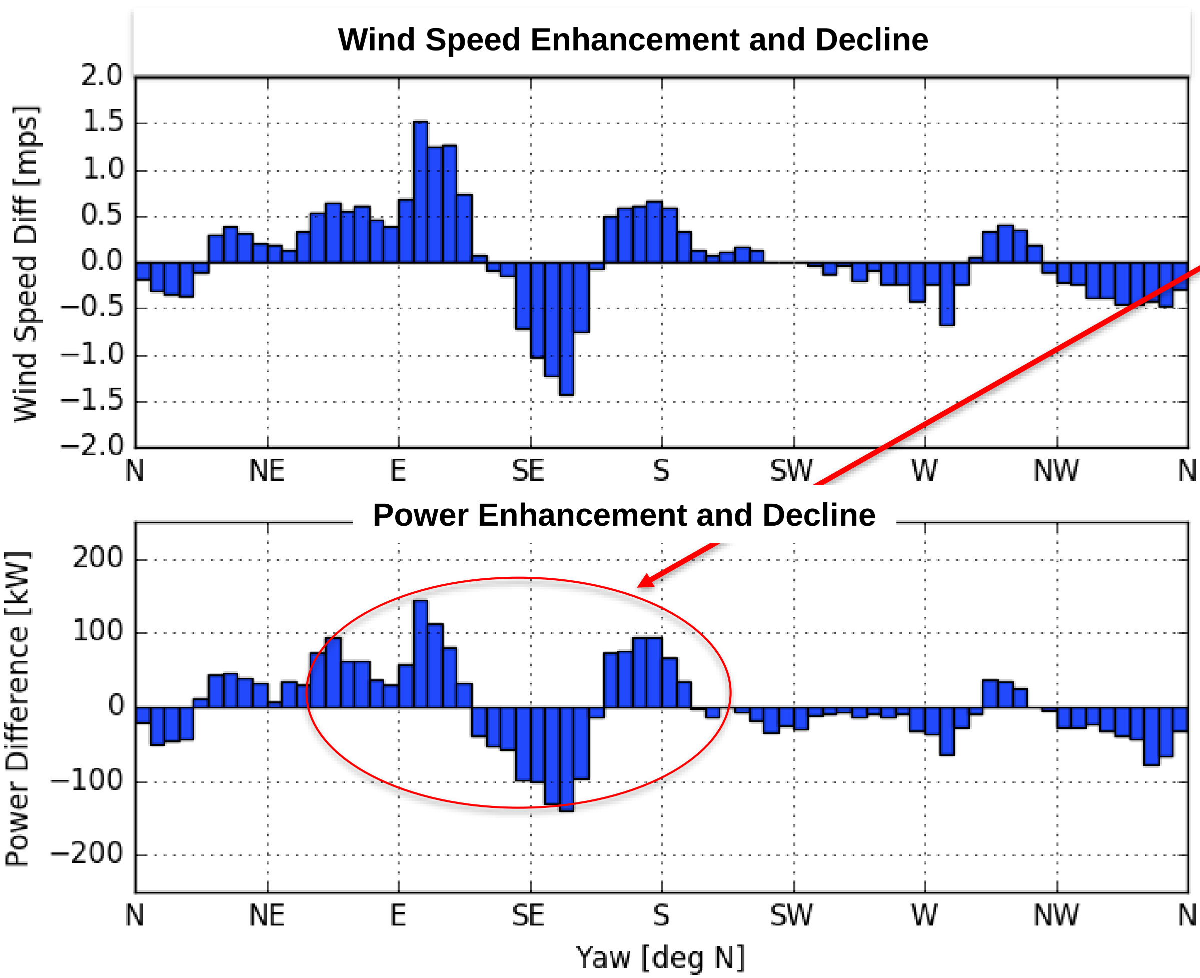
SCADA Diagnostic Tools:

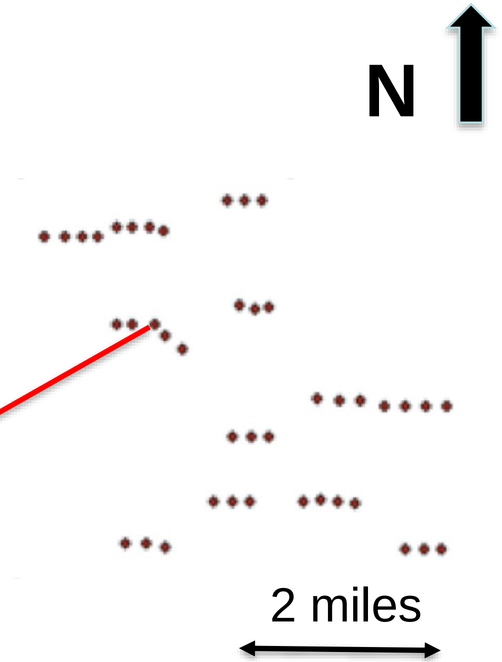
Directional Power visualization

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



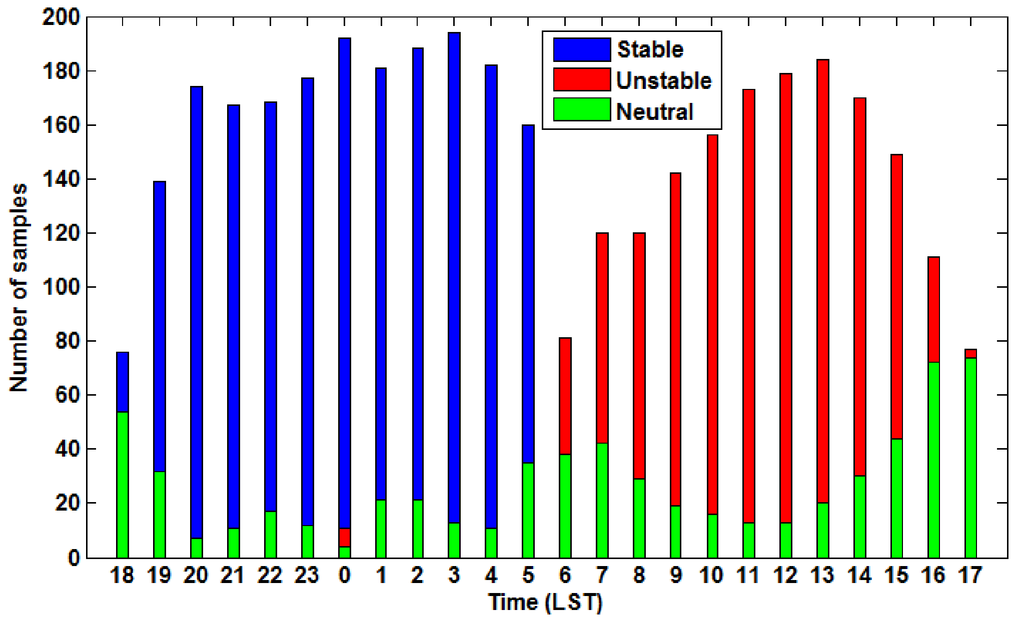


Stability and directional variability

Stability classification

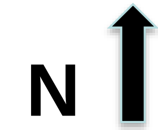
- Determine Obukhov length (L) from reference surface flux station **ISU 2** (south of reference turbine)
- Stability categories
  - **STABLE** 0 m<L<200m
  - **UNSTABLE** 0 m>L>-200 m
  - **NEUTRAL** |L|≥200 m

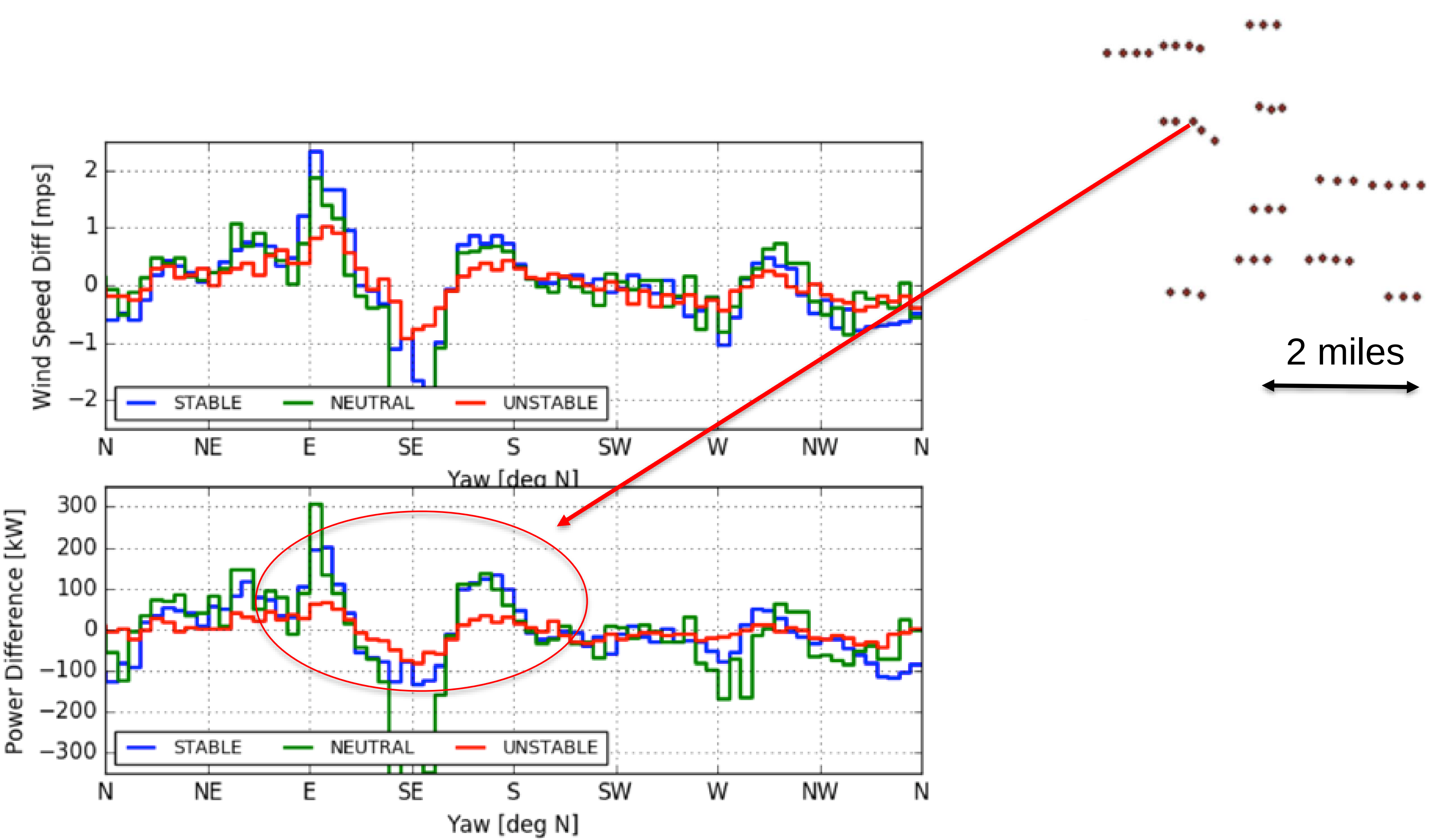
Diurnal distribution of stability



Distribution of stability class for cases when the reference flux station was not influenced by turbine wakes (verified by CU lidar) and passed quality control and, concurrently, P > 100 kW at 7 nearby turbines.

SCADA Diagnostic Tools:
Directional power evaluation



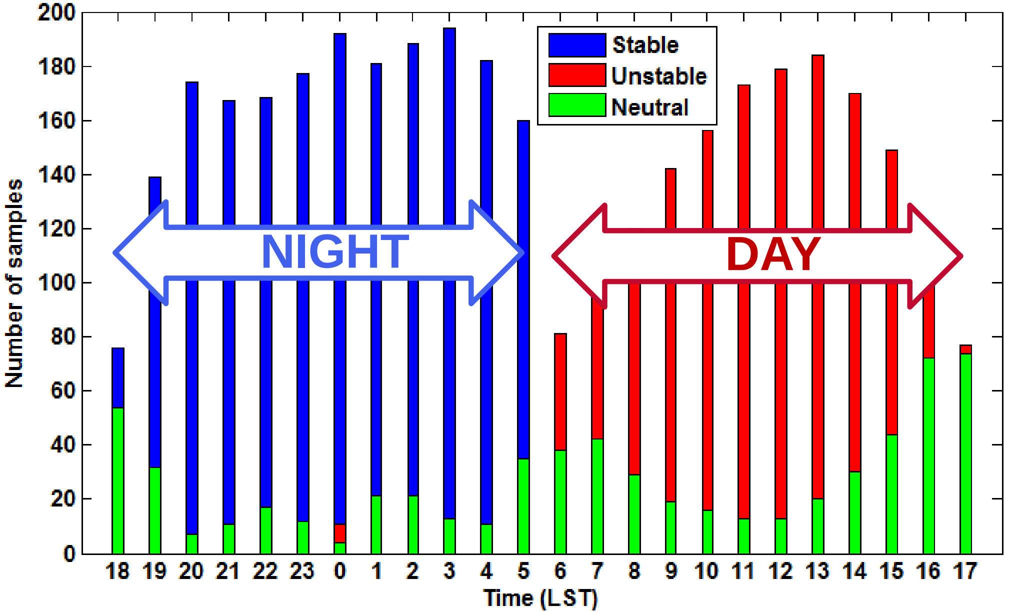


Stability and directional variability

Stability classification

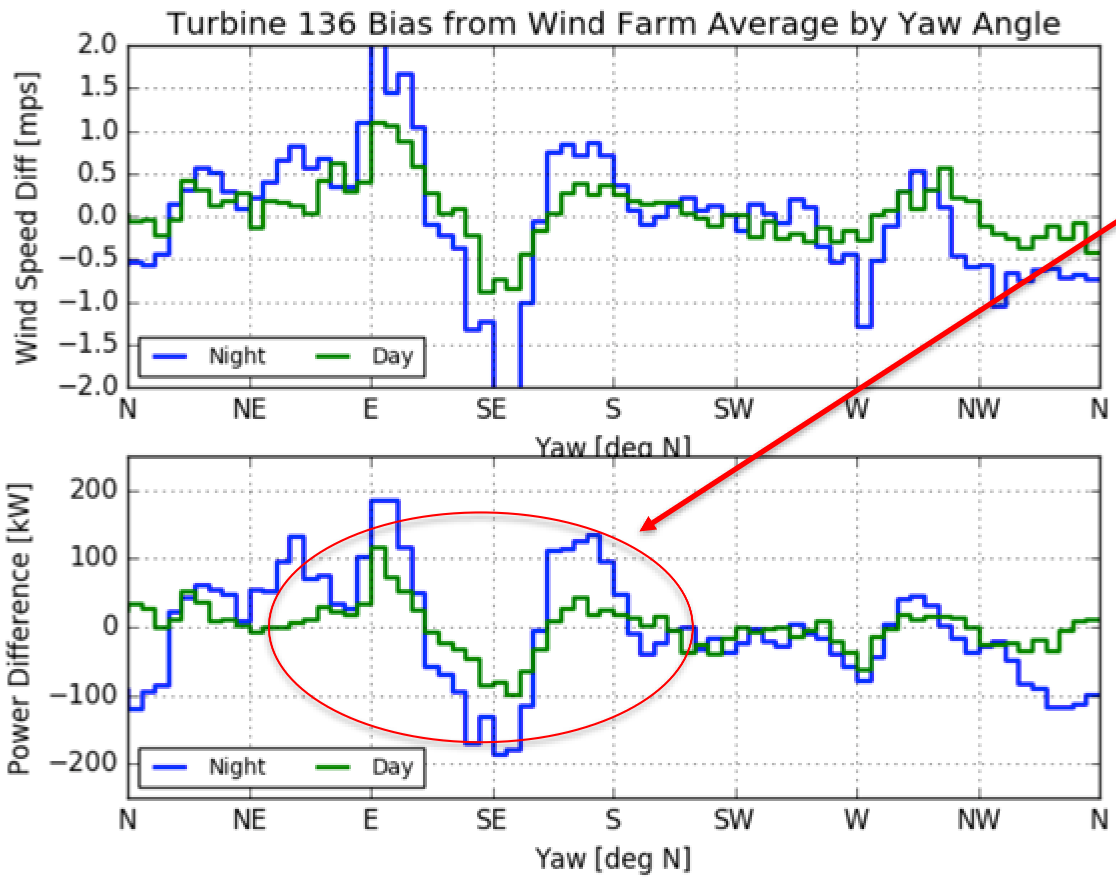
- Determine Obukhov length (L) from reference surface flux station **ISU 2** (south of reference turbine)
- Stability categories
  - **STABLE** 0 m<L<200m
  - **UNSTABLE** 0 m>L>-200 m
  - **NEUTRAL** |L|≥200 m

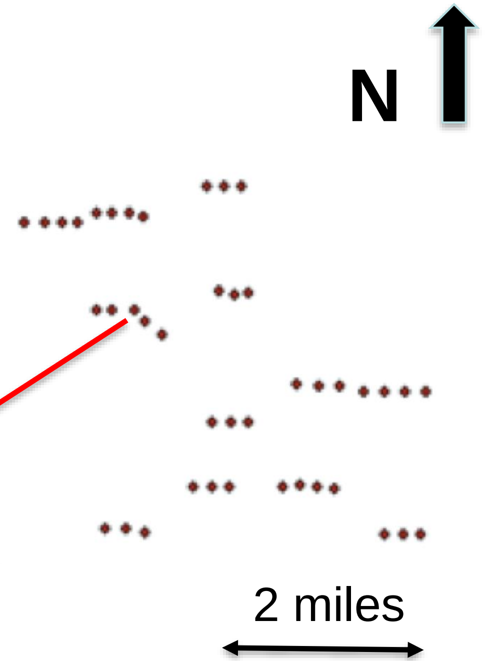
Diurnal distribution of stability



Distribution of stability class for cases when the reference flux station was not influenced by turbine wakes (verified by CU lidar) and passed quality control and, concurrently, P > 100 kW at 7 nearby turbines.

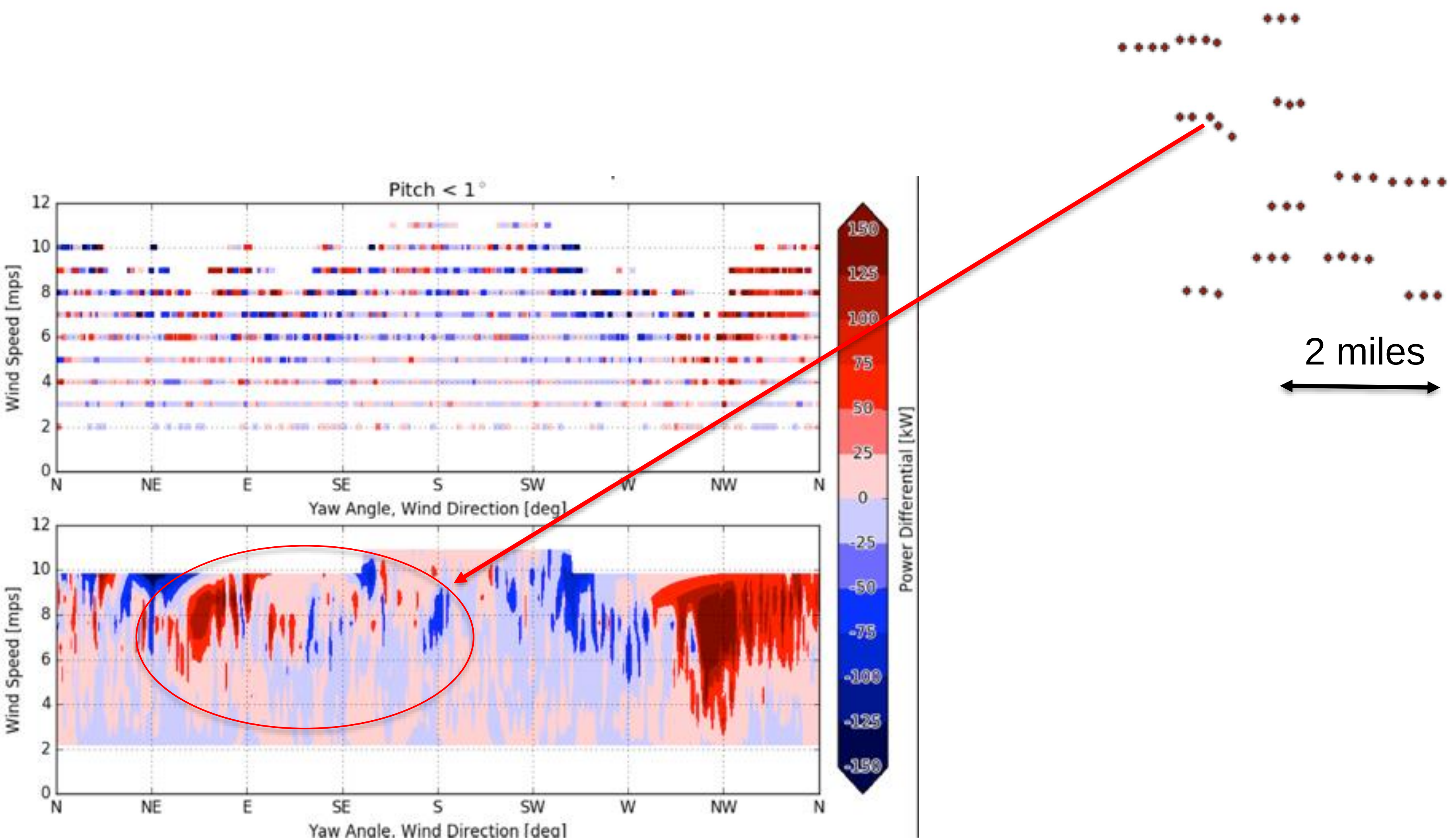
SCADA Diagnostic Tools:
Directional power evaluation



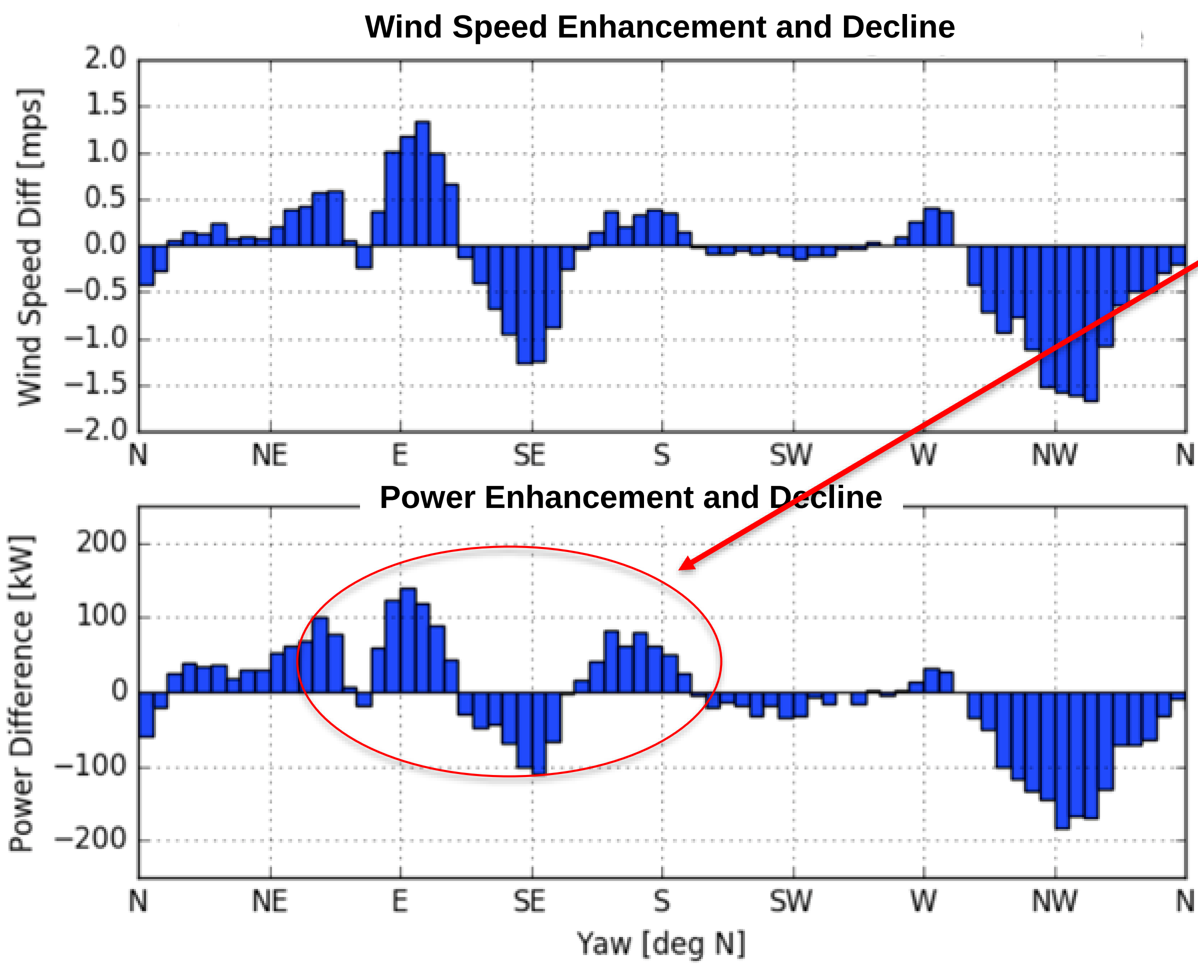


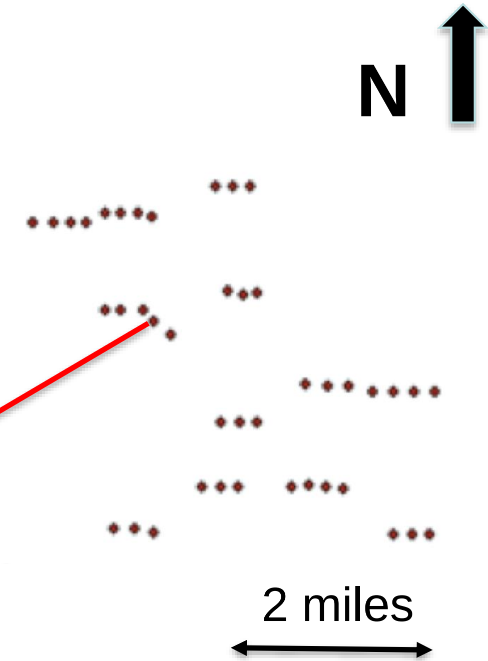
SCADA Diagnostic Tools:
Directional power evaluation

N

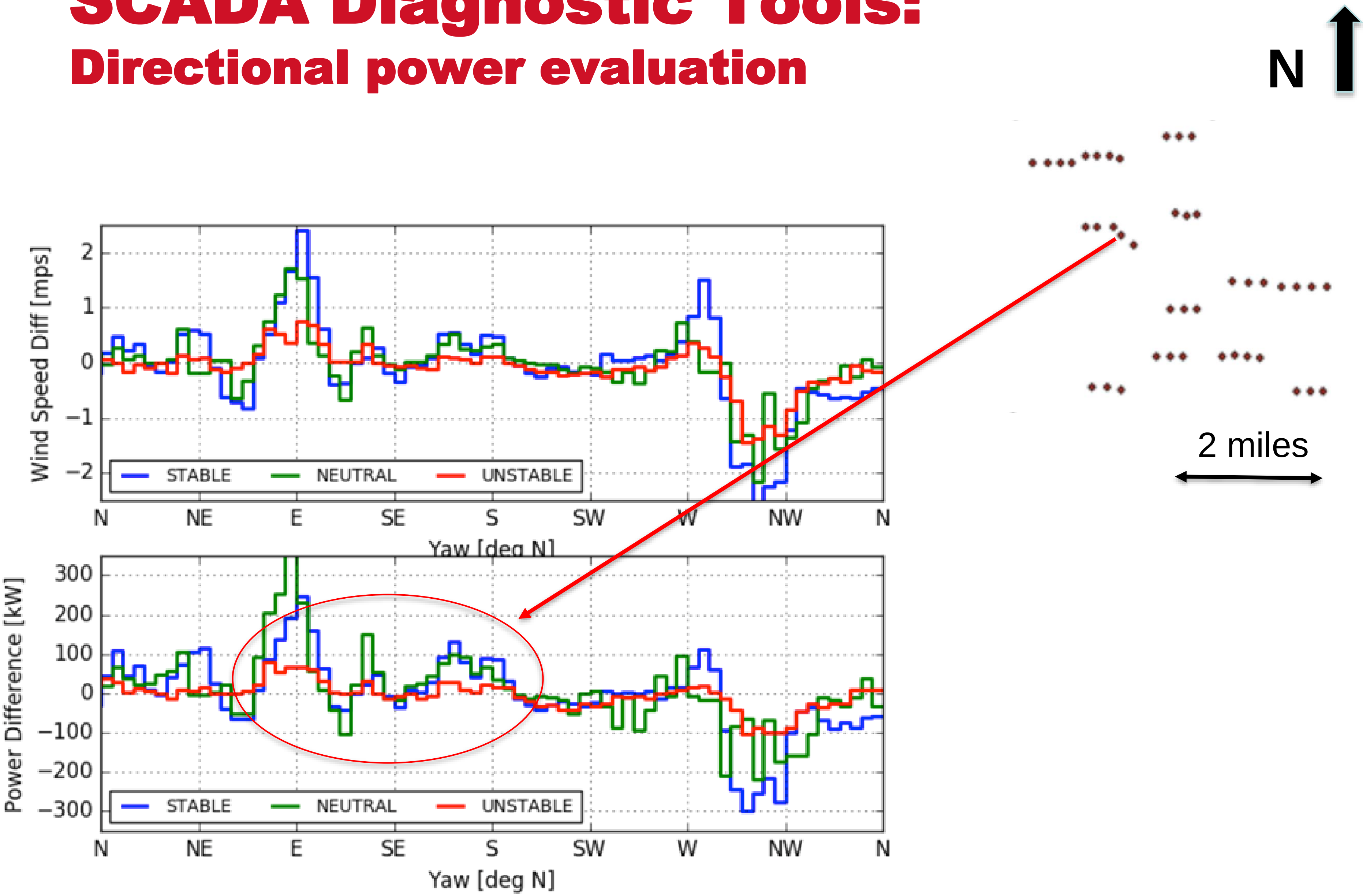


SCADA Diagnostic Tools:
Directional power evaluation

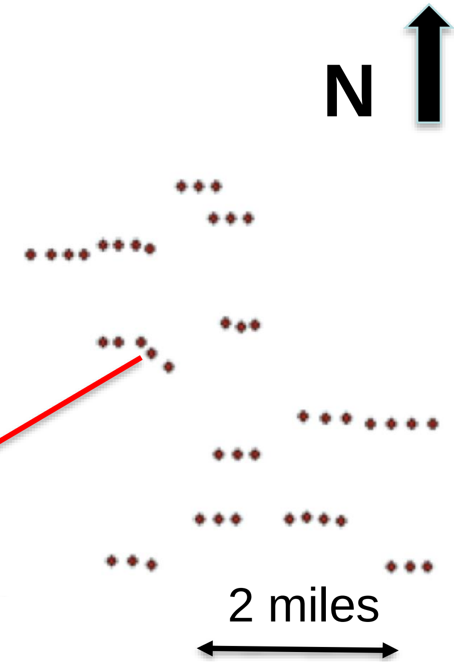


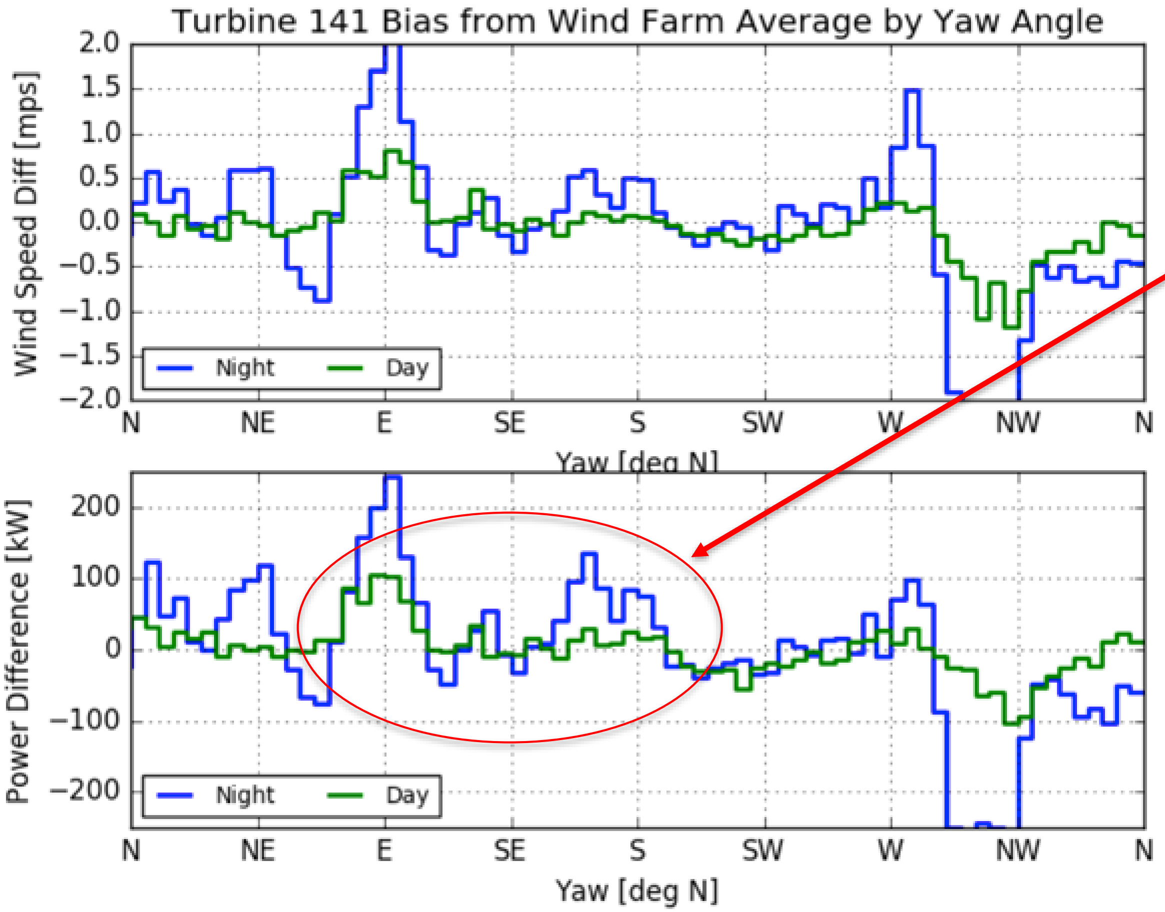


SCADA Diagnostic Tools:
Directional power evaluation

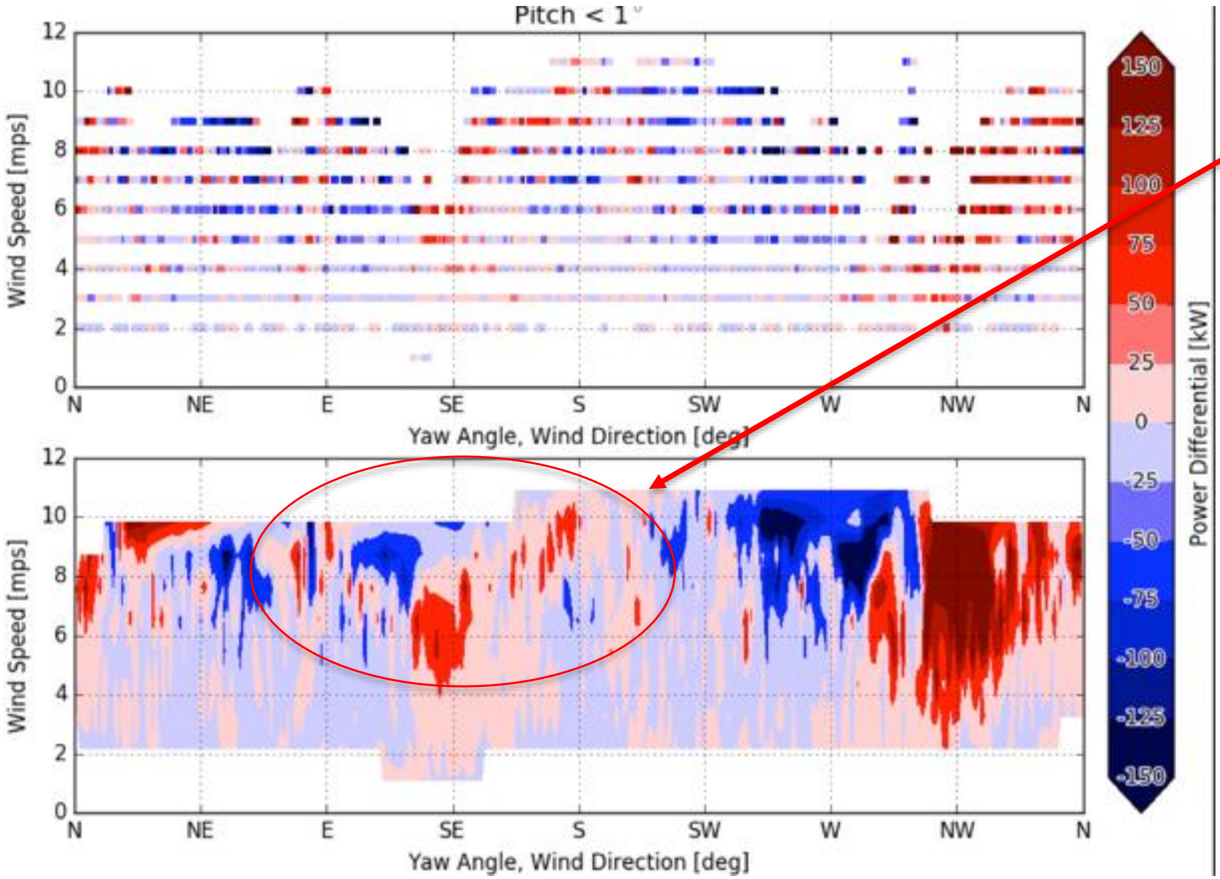


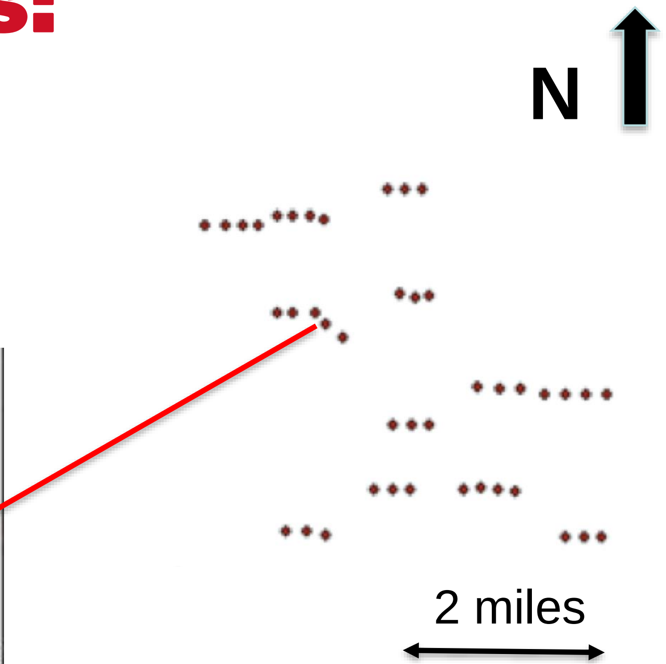
SCADA Diagnostic Tools:
Directional power evaluation



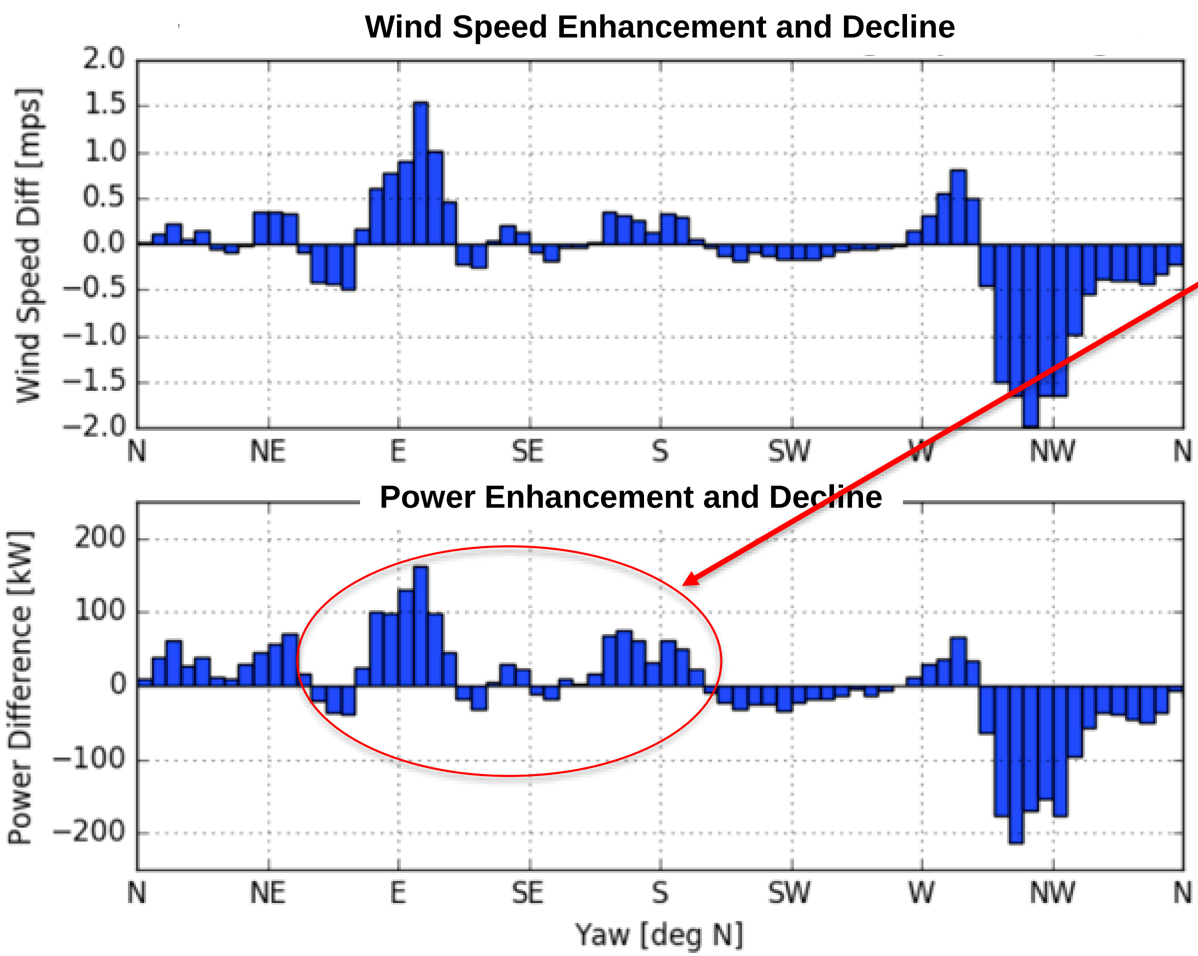


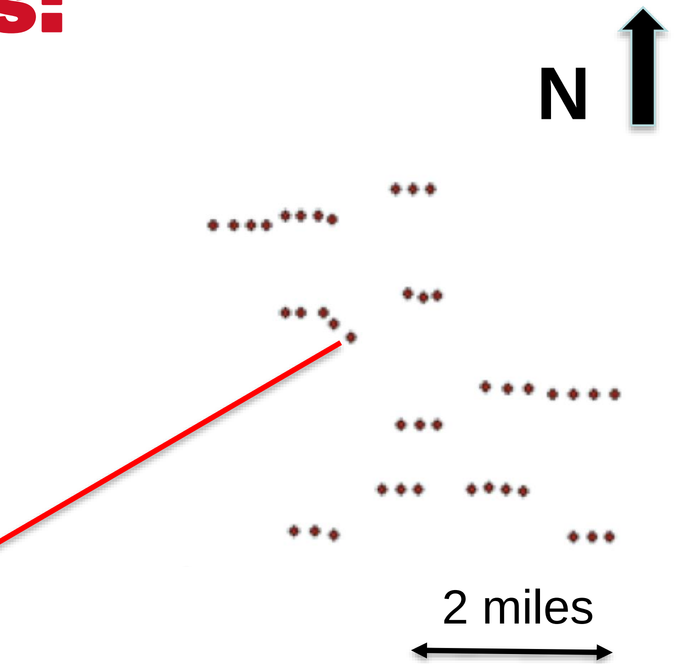
SCADA Diagnostic Tools:
Directional power evaluation





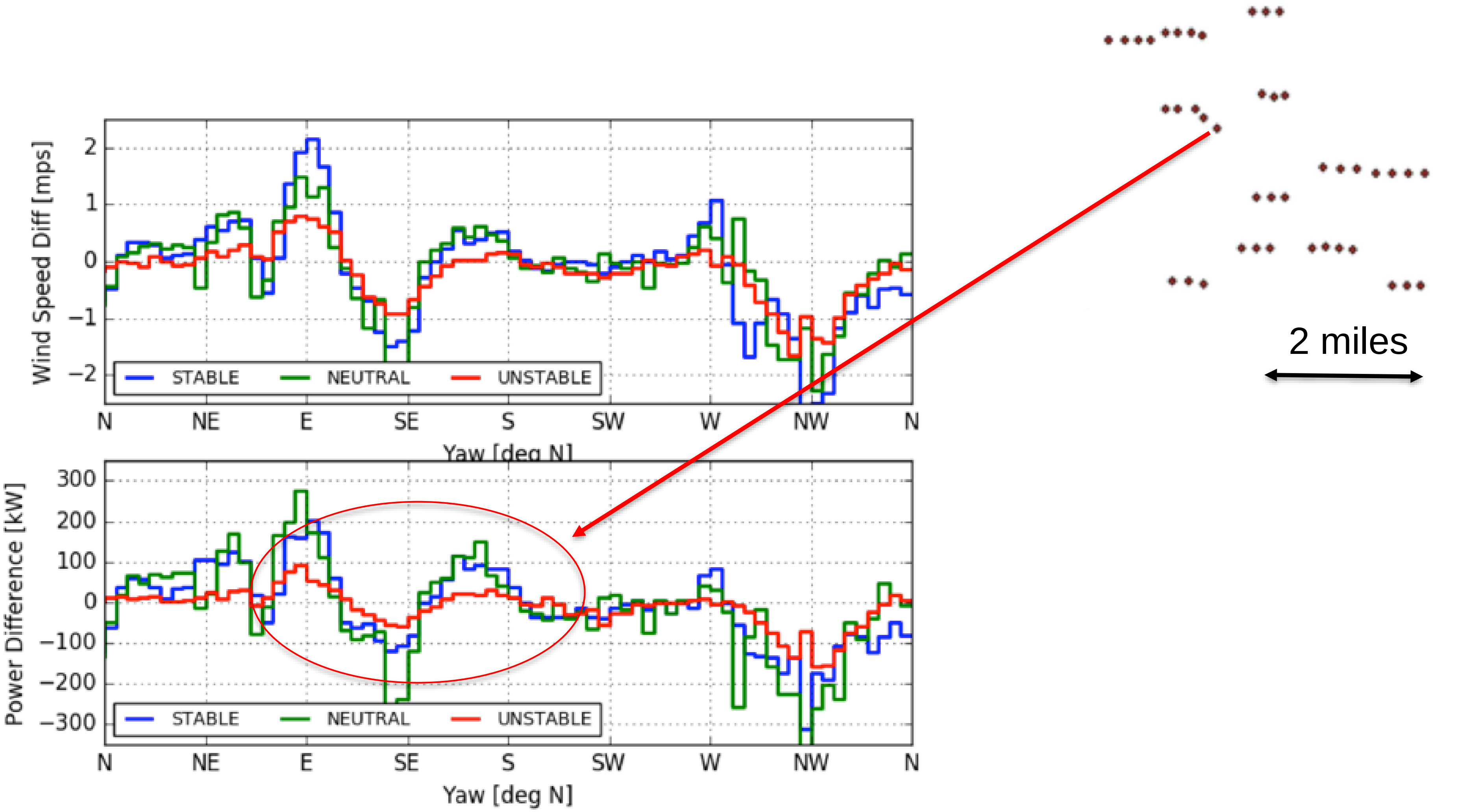
SCADA Diagnostic Tools:
Directional power evaluation



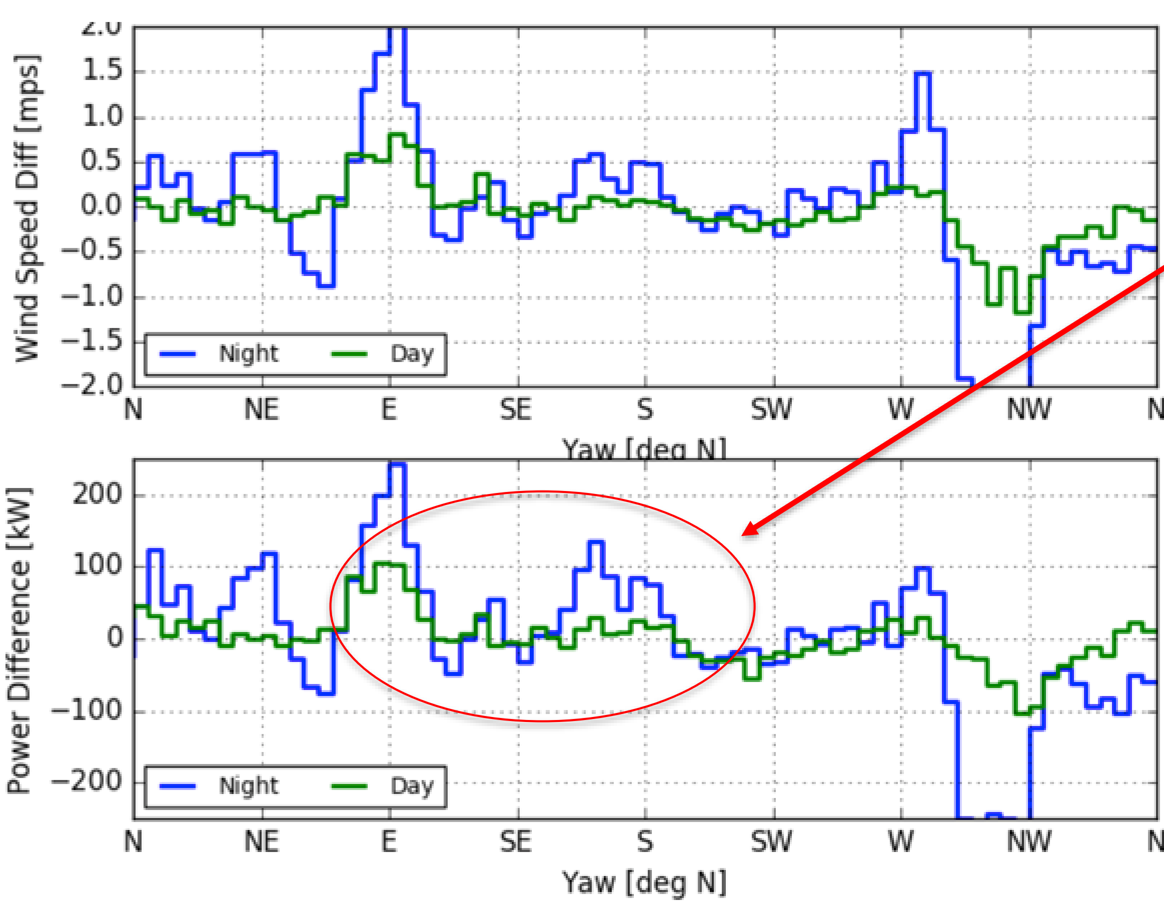


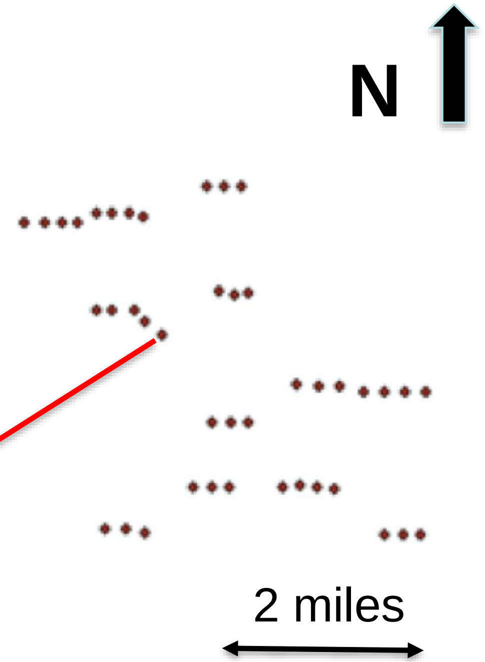
SCADA Diagnostic Tools:
Directional power evaluation

N

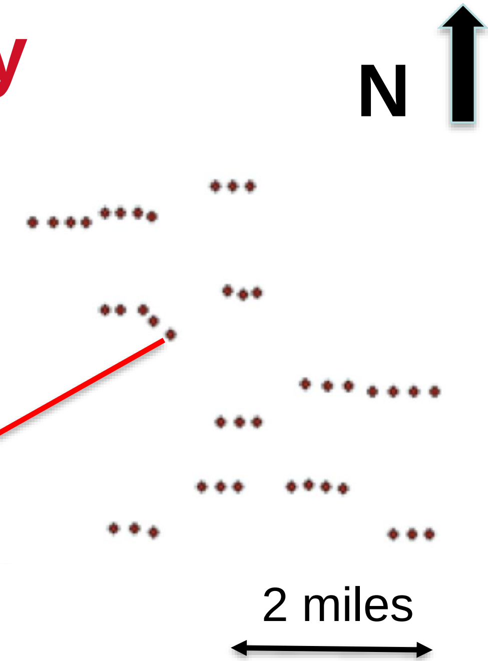


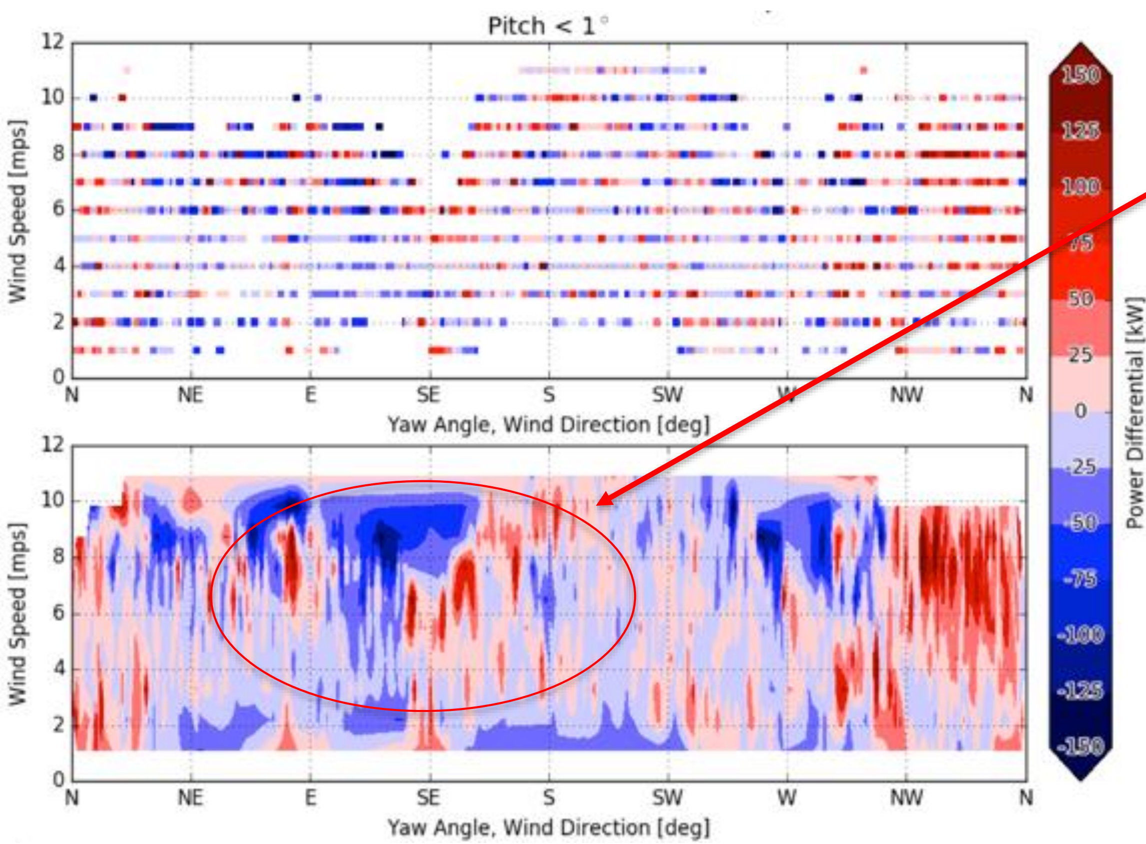
SCADA Diagnostic Tools:
Directional power evaluation





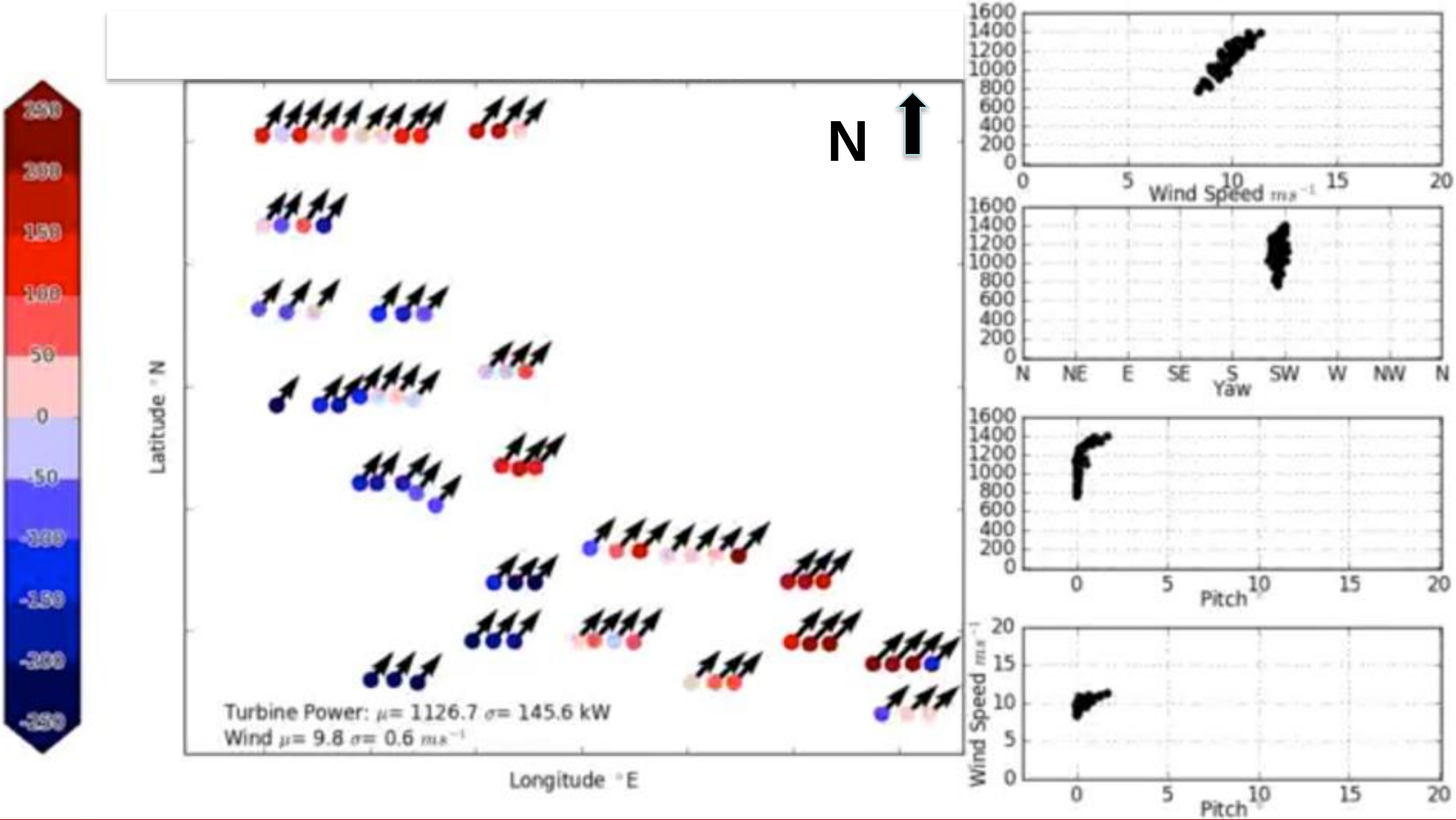
Stability and directional variability
Wake Concept Tool





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]

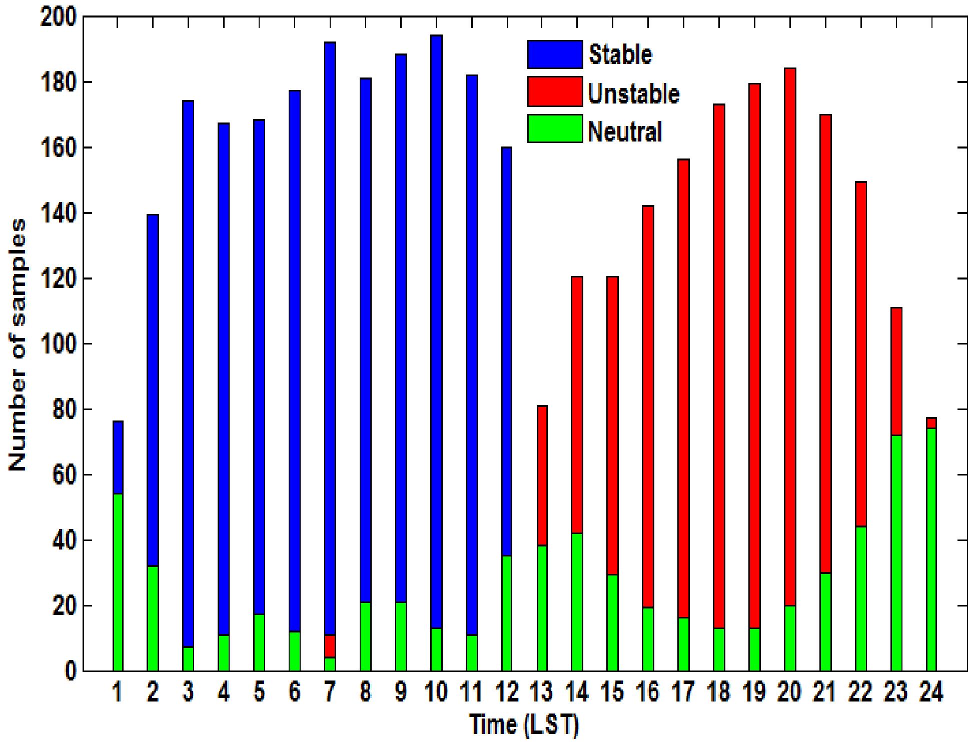
- SCADA power (10-minute resolution) from owner of wind farm

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 m<L<200m
  - **UNSTABLE** 0 m>L>-200 m
  - **NEUTRAL** |L|≥200 m

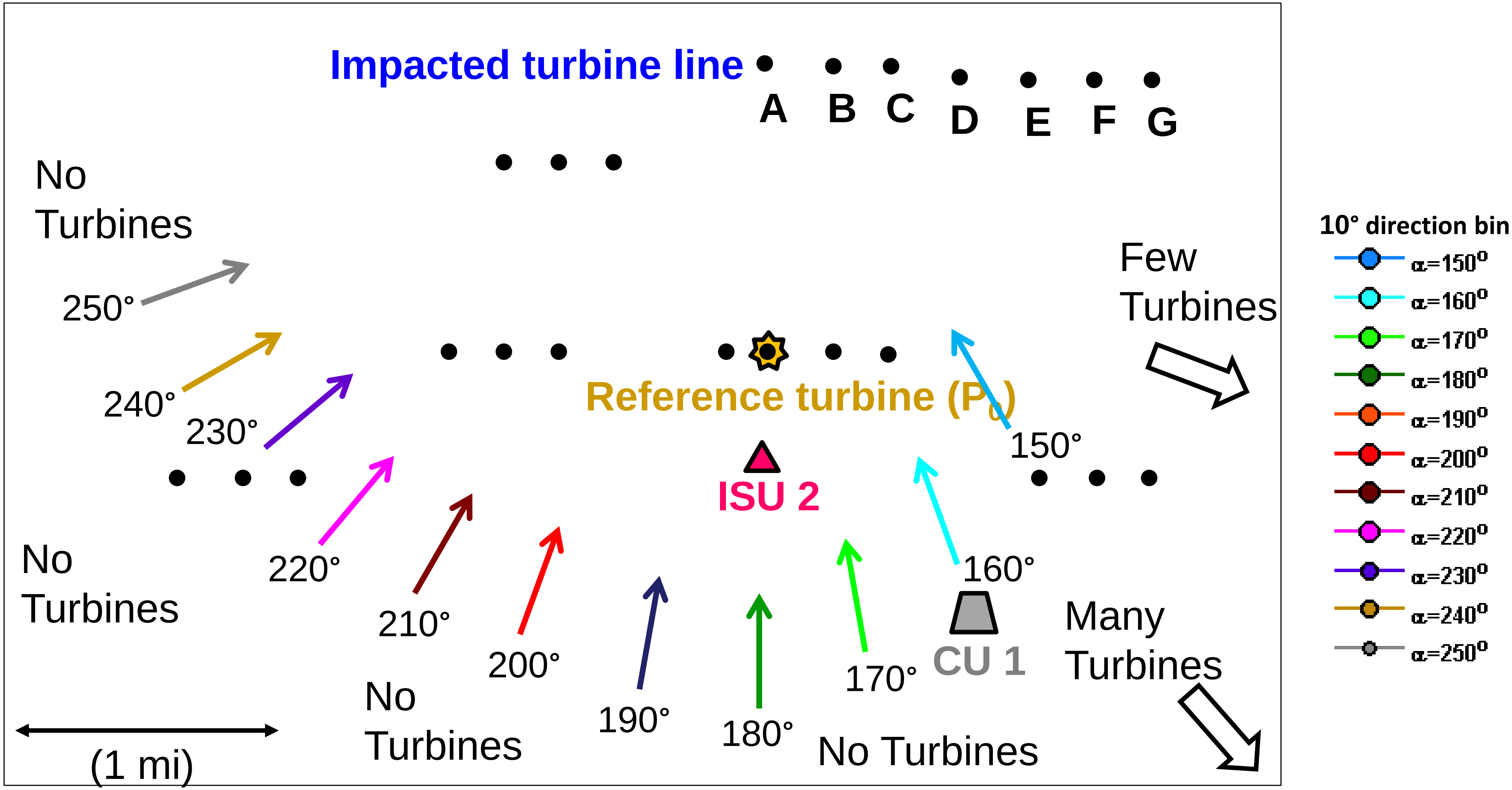
Diurnal distribution of stability for non-waked upwind directions



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

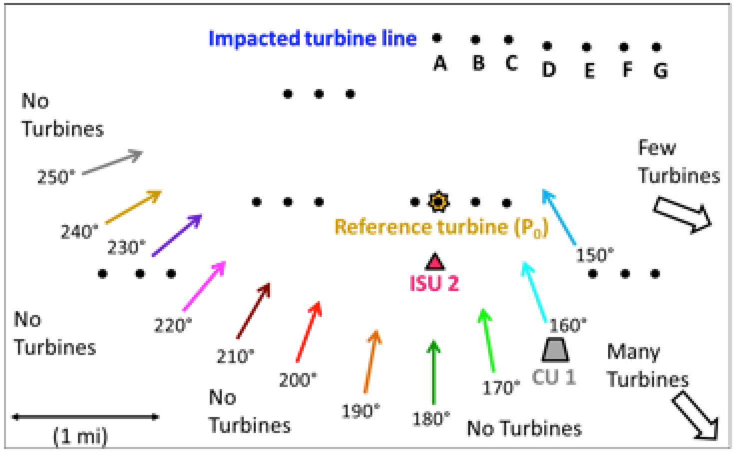
Stability and directional variability
Wake Concept Tool

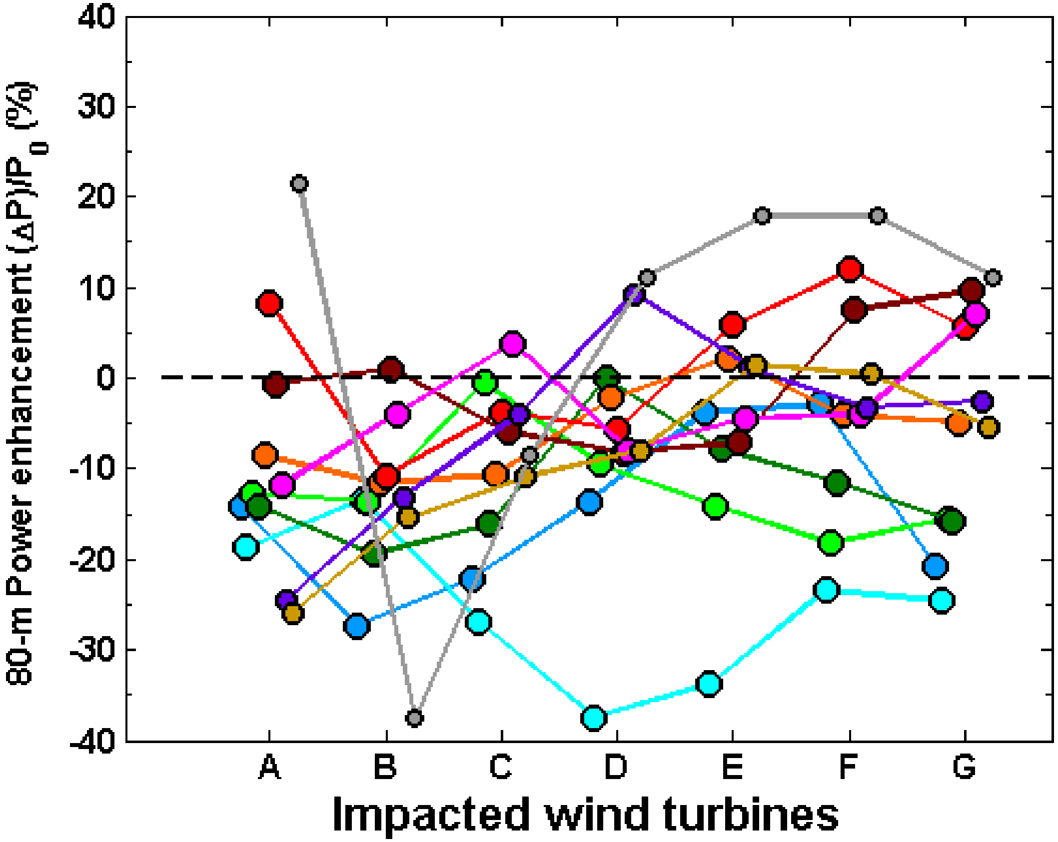
Layout: sorting by wake-distance categories



Stability and directional variability
Wake Concept Tool

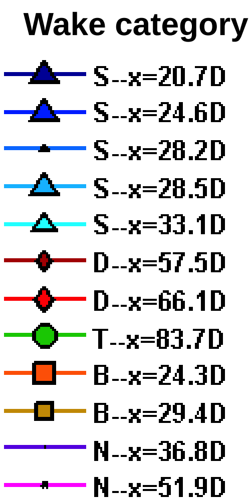
Stable stratification



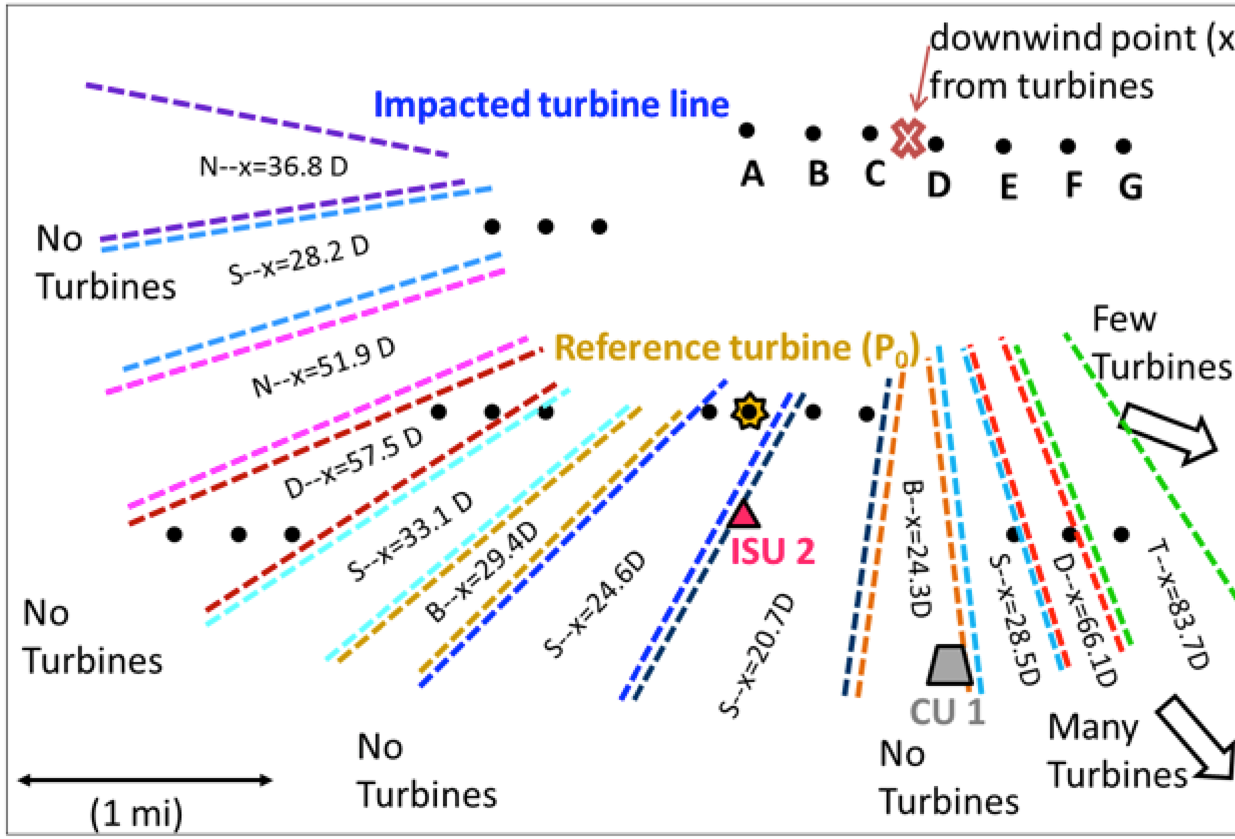


Stability and directional variability Wake Concept Tool

Layout: sorting by wake-distance categories

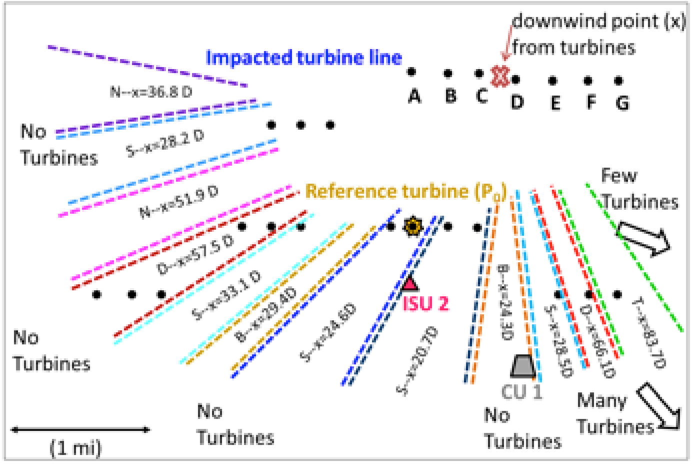


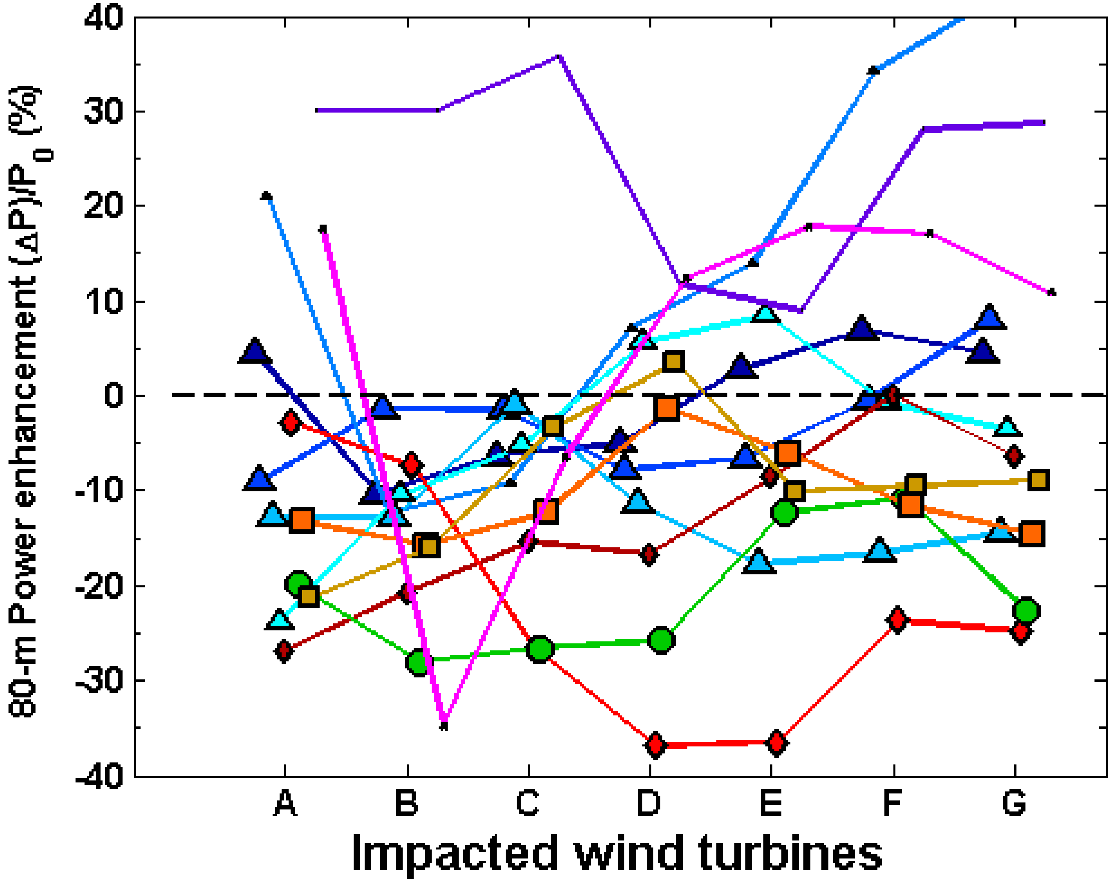
S—single
D—double
T—triple
B—between wakes
N—no wake



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 impact on turbine power variation:
  - 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

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