PO. ID 049

In situ and remotely-sensed mean and turbulence characteristics of wind turbine wakes

Julie K. Lundquist[1,2], Ludovic Bariteau[3], Matthieu Boquet[4], Michael E. Rhodes[1], Clara St. Martin[1]
(1) Dept. of Atmospheric and Oceanic Sciences (ATOC), University of Colorado at Boulder, (2) National Renewable Energy Laboratory, (3) Institute for Research in Environmental Sciences (CIRES), University of Colorado at Boulder, (4) Leosphere, Inc.

University of Colorado Boulder

rasei NREL Renewable & Sustainable Energy Institute

Abstract & Objectives

▪Accurate data on wind turbine wakes and their dissipation is required to optimize wind plant design

▪Total global wind power potential (Lu et al., 2010; Jacobson & Archer 2012) may depend on how the enhanced turbulence downwind of wind farms is dissipated

▪Wakes decay due to small-scale instabilities, so wakes may be best parameterized in terms of the turbulent kinetic energy dissipation rate ε (Frech 2007, Sarpkaya 2000, Holzapfel and Steen 2007)

▪Wake ε has not yet been measured

▪**OBJECTIVE:** collect *in situ* measurements of ε downwind of a multi-MW turbine for comparison to remotely-sensed quantities and improvement of turbine wake parameterizations

Methods: Remote Sensing

A scanning LIDAR (Fig.1, Leosphere WINDCUBE 100S,) measures the Doppler shift of particles moving with the flow. These "line-of-sight" (LOS) velocities from the LIDAR, when the LOS is aligned with flow, can:

•map and quantify wakes from individual or multiple turbines (Fig. 2),

•provide useful information regarding inhomogeneities & turbulence in the flow, and

•ensure accurate location of *in situ* instrumentation.

Fig. 1: LEOSPHERE WINDCUBE 100S LIDAR deployed during TODS

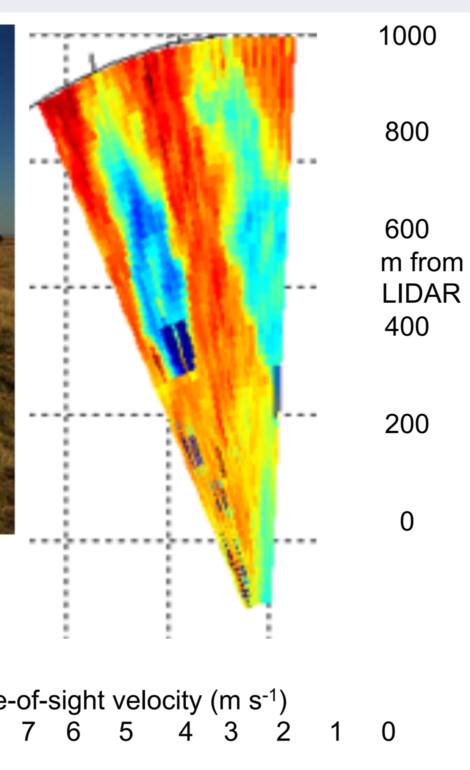


Fig. 2: Velocities observed by 100-S lidar, capturing wakes from two turbines at NREL's NWTC

Methods: *In situ*, Tethered Lifting System

The CIRES TLS is a robust, specialty-designed state-of-the art tethersonde, flown with a 21' blimp (Fig 3b) offering unique high resolution and highly sensitive *in situ* measurements, proven in rural (CASES-99) and urban (Pentagon Shield) experiments. Current payload capabilities (Fig. 3b) offer:

•Vertical resolution of 0.5m (depending on rate of ascent, see Table below)

•Temperature resolution finer than 1 deg C

•Velocity resolution ~ 1mm/s

•Fast turbulence measurements from 1.25mm length and 5 micron diameter Tungsten wire (hotwire and coldwire)

Sensor	Measurement	Sampling Rate
Hot wire anemometer	High frequency velocity	1 kHz
Cold wire sensor	High frequency temperature	1 kHz
Thermistors and solid-state sensor	Temperature and Humidity	100 Hz
Pitot tube and pressure sensor	Velocity, pressure	100 Hz
GPS	Latitude, Longitude, altitude, time	Every 6s
Compass	Pitch, Yaw, Roll	8Hz

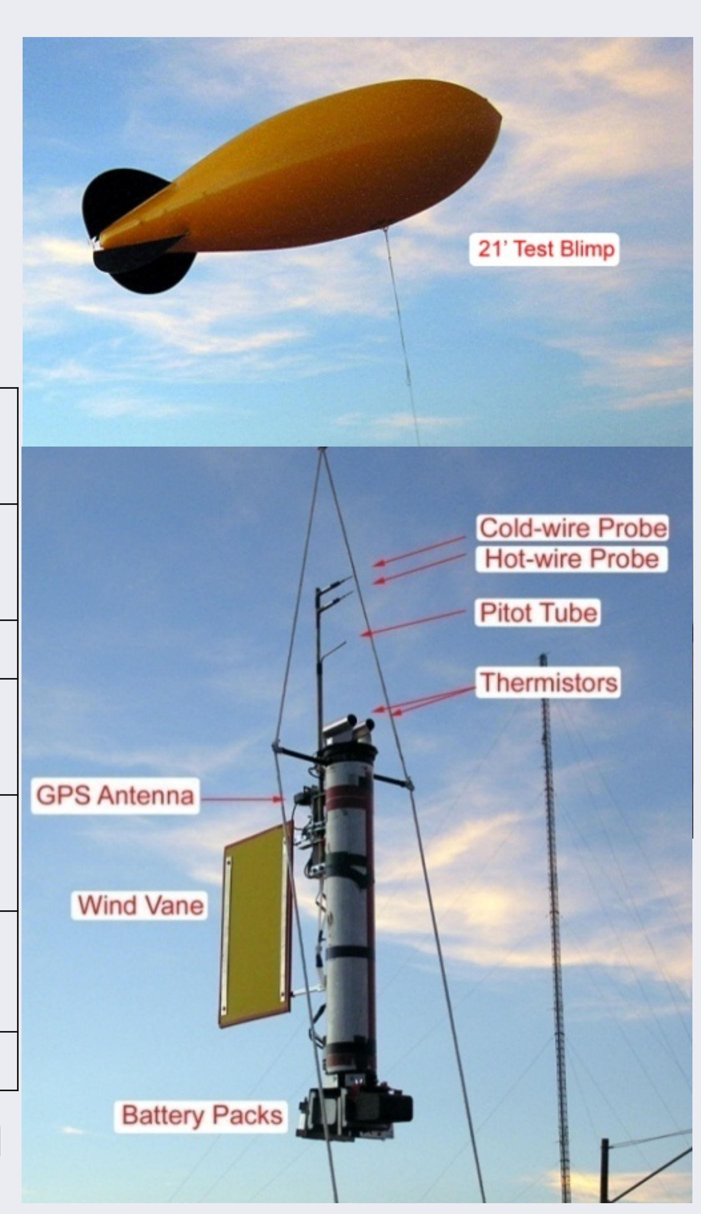


Fig. 3: TLS blimp ((a) top), and payload ((b), bottom)

Methods: Experimental Design

- Climatological data suggest the most frequent winds are from the west-northwest (Fig. 4)
- Frequent wakes are anticipated west of the DOE GE 1.5 MW turbine (red circle, Fig. 5)
- M5 met tower (135m, several levels of winds and temperatures) quantifies turbine inflow
- TLS systems located west of the turbine (Fig. 6)
- Scanning lidar located east of the turbine to scan towards east, sampling the TLS volume (Fig. 6)
- Radiometrics microwave radiometer to quantify temperature and humidity profiles (Fig. 6)
- Profiling lidar located east of turbine (Fig. 6)

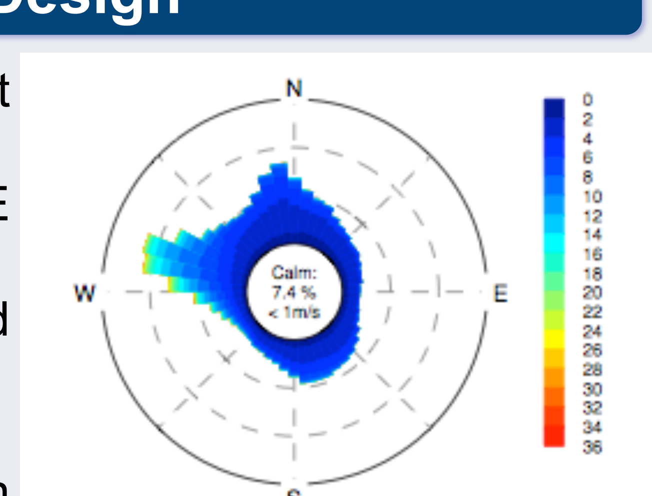


Fig. 4. Wind rose from NREL's NWTC (M2 tower) based on 80m measurements from several years. (From Clifton & Lundquist 2012)

Methods: Plan view of instrumentation

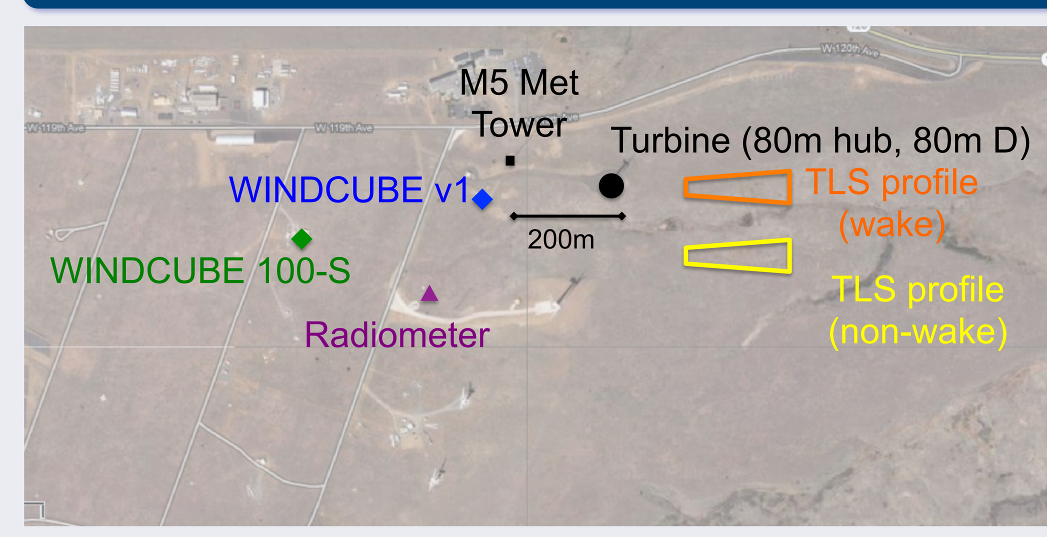


Fig. 6. Plan view of TODS instrumentation including the 135-m M5 met tower, a Radiometrics microwave radiometer for quantifying temperature and humidity profiles, a profiling WINDCUBE v1 LIDAR, a scanning WINDCUBE 100S LIDAR, and two TLS systems deployed in waked and non-waked locations east of the turbine.

Methods: ε and C_T^2 calculations from TLS data

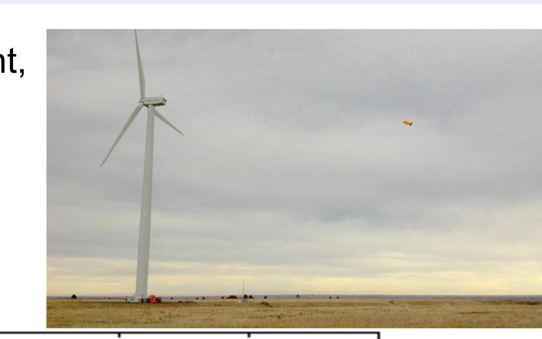
The energy dissipation rate ε and the temperature structure constant C_T^2 are estimated by fitting spectra to models accounting for the inertial range -5/3 power law, rollover at the Kolmogorov microscale (velocity), the temperature spectral peak, and instrumental noise floor (following Frehlich et al., 2003).

Results: initial estimates of ε

The TODS field campaign concluded at the end of November 2012. Initial analysis of the TLS data confirms that dissipation in the wake is typically two orders of magnitude larger than that in regions outside out of the wake:

- Out of wake
  - Wind speeds 1-6 ms^{-1}
  - ε ~ 10^{-4} m^{2}s^{-3}
- In wake
  - Wind speeds within wake 1-10 ms^{-1}
  - ε ~ 10^{-2} m^{2}s^{-3}

Fig. 8. TLS flight, 29 Oct 2012



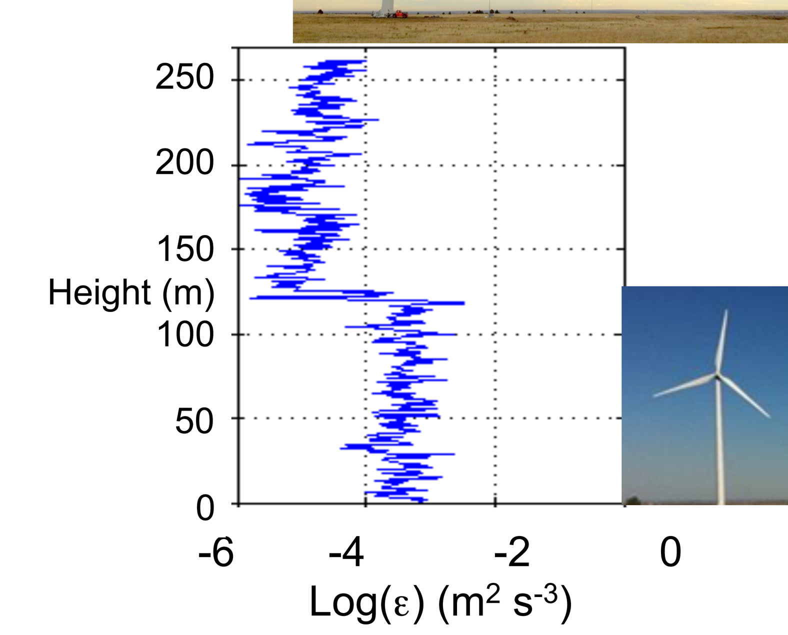


Fig. 9: profile of ε within and above wake

Ongoing Research Efforts

Ongoing efforts include:

•More extensive analysis of data collected during the field campaign

•Mesoscale modeling of the days in which TLS data were collected for provision of boundary conditions to finer-scale simulations

•Computational fluid dynamics simulations of the wakes observed for comparison to the TLS *in situ* measurements

•Design and execution of similar experiments within operating wind farms – new collaborations are welcome

Acknowledgements

We express our appreciation for research funding from the Colorado Research and Education in Wind seed grant program. We gratefully acknowledge many staff at NREL's NWTC who coordinated other tests with our TLS flights. We also express appreciation to Yannick Meillier, Josh Aikens, Matthew Aitken, Ryan King, and Brian Vanderwende.

References

- Clifton, A and JK Lundquist, 2012, "Data Clustering Reveals Climate Impacts on Local Wind Phenomena" Journal of Applied Meteorology and Climatology, 51, 1547–1557 doi: http://dx.doi.org/10.1175/JAMC-D-11-0227.1
- Frech, M, 2007, "Estimating the turbulent energy dissipation rate in an airport environment," Boundary- Layer Meteorology, 123, 385-393
- Frehlich, R, Y Meillier, M Jensen & B Balsley, 2003, "Turbulence measurements with the CIRES tethered lifting system during CASES-99: Calibration and spectral analysis of temperature and velocity," Journal of the Atmospheric Sciences, 60, 2487-2495
- Holzapfel F and M Steen, 2007, "Aircraft wake-vortex evolution in ground proximity: analysis and parameterization" AIAA Journal 45 (1):218–227
- Jacobson, MZ and CL Archer, 2012, "Saturation wind power potential and its implications for wind energy" PNAS 2012 ; published ahead of print September 10, 2012, doi:10.1073/pnas.1208993109
- Lu, X, MB McElroy, J Kiviluoma, 2009, "Global potential for wind-generated electricity" PNAS 2009 106 (27) 10933-10938; published ahead of print June 22, 2009, doi:10.1073/pnas.0904101106
- Meillier YPM, Frehlich RG, 2011, "The CIRES TLS Tethersonde: Performances and Research applications" http://breeze.colorado.edu/Meillier_2011.pdf
- Sarpkaya T, 2000, "New model for vortex decay in the atmosphere" J Aircraft 37:53–61