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A New Framework for Quantifying Lidar Uncertainty

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Observational Needs in Wind Energy

Observational needs include:

- Temporal and spatial wind variability in turbine siting locations
- Wind speed and temperature data to validate numerical weather prediction models
- Wind observations from a wider range of heights.

Remote sensing is expected to play a key role in resource assessment and model validation.

Challenges include:

- Assessing wind variability on offshore, complex, or remote terrain
- Quantifying uncertainty of remote sensing devices.

Photo by Sonia Wharton, Lawrence Livermore National Laboratory

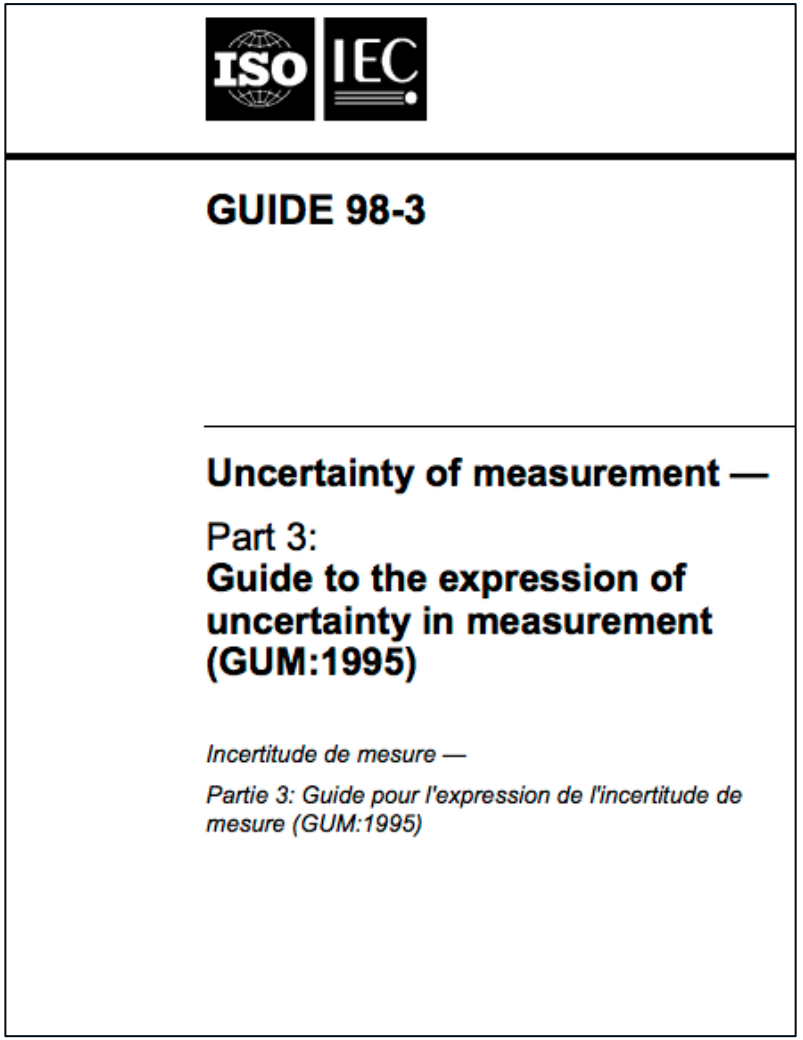
What Is Uncertainty?

Uncertainty is:

- A parameter that characterizes the spread of values that could be reasonably attributed to a measurand
- A measure of possible error in an estimated value
- A quantity characterizing the range of values within which the actual value of a measurand is expected to lie.

General definition:

Doubt about the validity of a measured quantity


ISO IEC

GUIDE 98-3

Uncertainty of measurement —

Part 3:
Guide to the expression of uncertainty in measurement (GUM:1995)

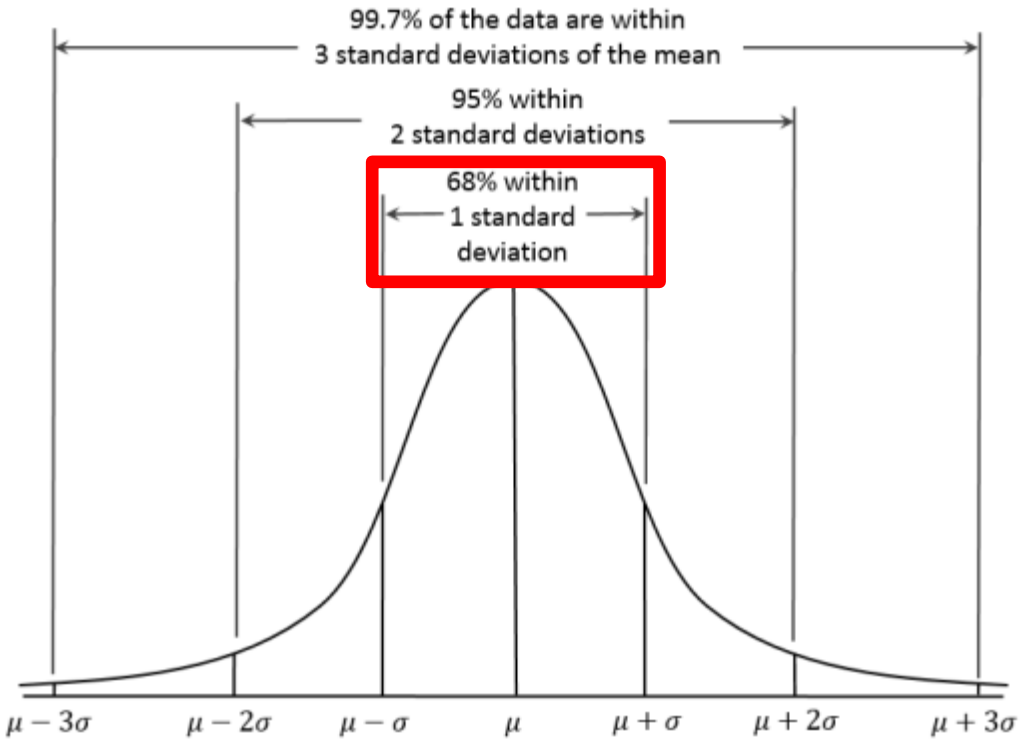
Incertitude de mesure —

Partie 3: Guide pour l'expression de l'incertitude de mesure (GUM:1995)

Reference: ISO/IEC GUIDE 98-3 ed1.0 (2008-09), *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement.* JCGM, 2008.

A Statistical Look at Uncertainty

The **uncertainty** is the range within which there is a certain probability that the true value lies.



Calculating uncertainty: The standard deviation of points around the best estimate of a measurand.

Uncertainty in practice: Under these conditions, we expect the true value to lie within this range.

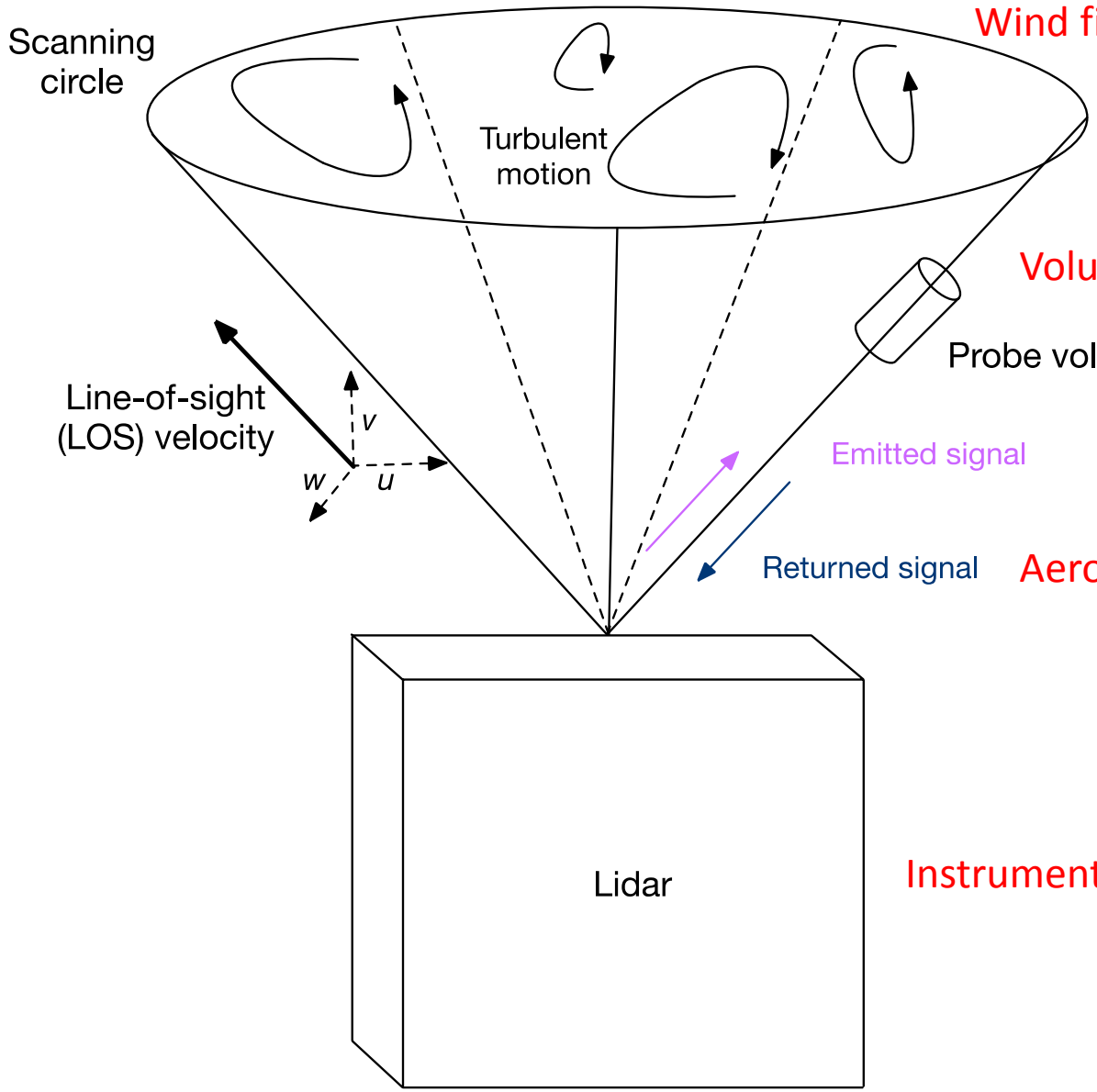
Illustration by Dan Kernler, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=36506025

What's an Uncertainty Framework?

- Assign all sources of uncertainties to clear categories
- Create models for each category
  - *Constants*
  - *Data-driven*
- Apply them to every 10-minute measurement from the lidar.

AXYS FLiDAR 6-meter (m) buoy. *Photo from Flickr, courtesy of Pacific Northwest National Laboratory*

Factors That Affect Uncertainty



Wind field reconstruction

Pointing accuracy

Volume averaging

Aerosol concentration

Instrument noise

Current Uncertainty Framework: International Electrotechnical Commission 61400-12-1

Estimate uncertainty resulting from:

- Calibration
- Classification
- Nonhomogeneous flow within probe volume
- Mounting effects
- Variation in flow across site.

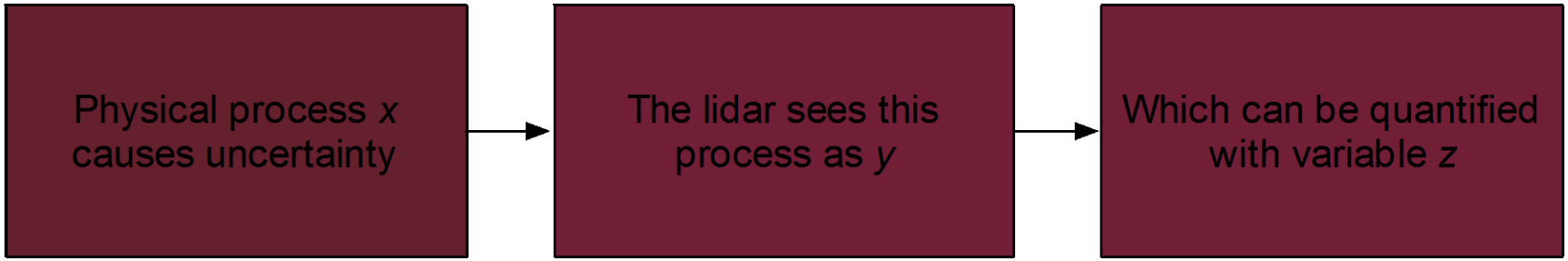
Limitations:

- Uncertainty depends only on mean wind speed
- Uncertainty is only calculated for horizontal wind speed, which is not directly measured by the lidar.

Photo by Andrew Clifton, NREL 24383

New Uncertainty Framework

- Uncertainty is *dynamic* and depends on current flow conditions during each 10-minute period.
- The framework relates what the lidar sees to physical processes and sources of error.



Sample Branch of Framework

This sample branch shows how lidar-measured variables relate to uncertainty due to aerosol distribution.

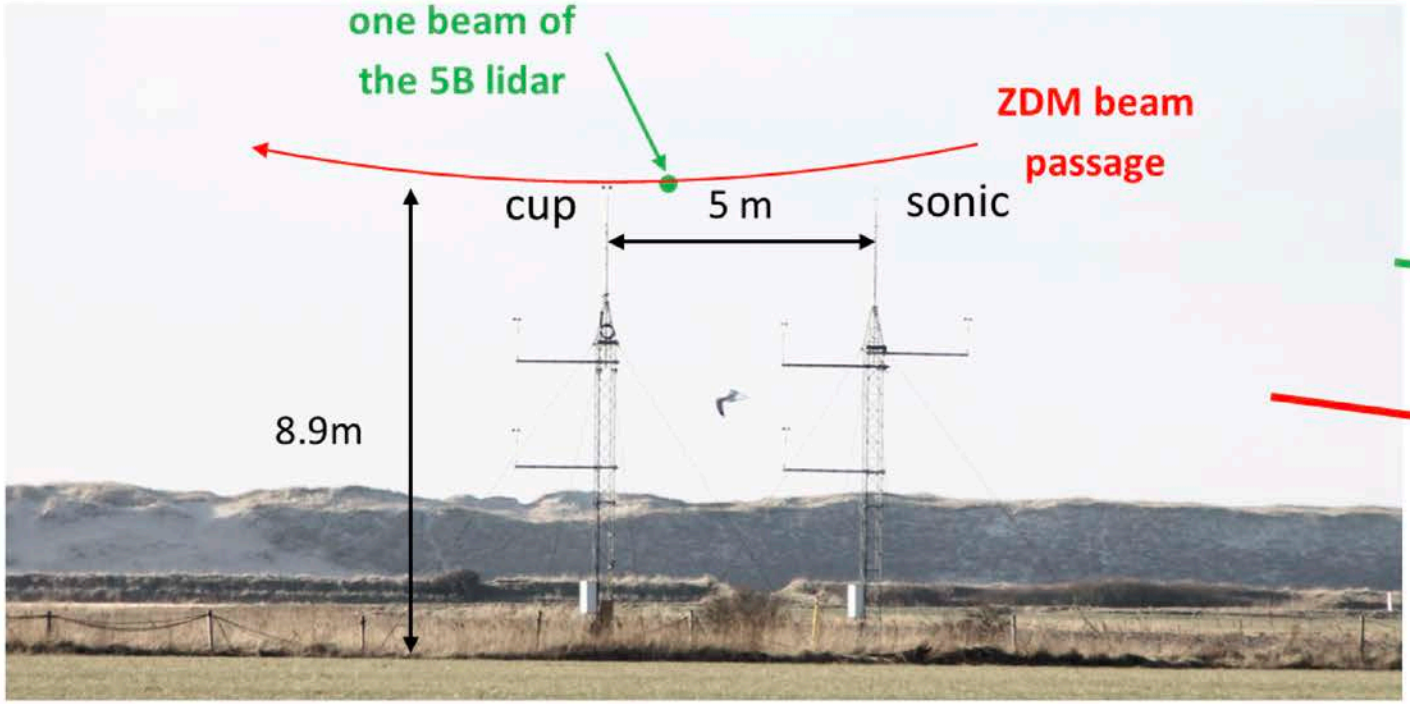
What causes deviations from the ideal case?	Backscattered signal strength	Category in framework
What is the physical basis of these effects?	Aerosol distribution	Physical process
How does the lidar see these effects?	Atmospheric signal that is difficult to separate from noise	Manifestation of uncertainty
How can we quantify these effects?	Signal-to-noise ratio (SNR), range	Variables that can be used to quantify how the physical process induces uncertainty

Starting Point: Line-of-Sight Velocity Uncertainty Framework

Borraccino et al. (2016) pointed a ZephIR Dual-Mode (ZDM) and 5-beam Avent Demonstrator (5B) lidar in the direction of two meteorological towers. Uncertainty was calculated for the line-of-sight (LOS) velocity.

Estimate uncertainty due to:

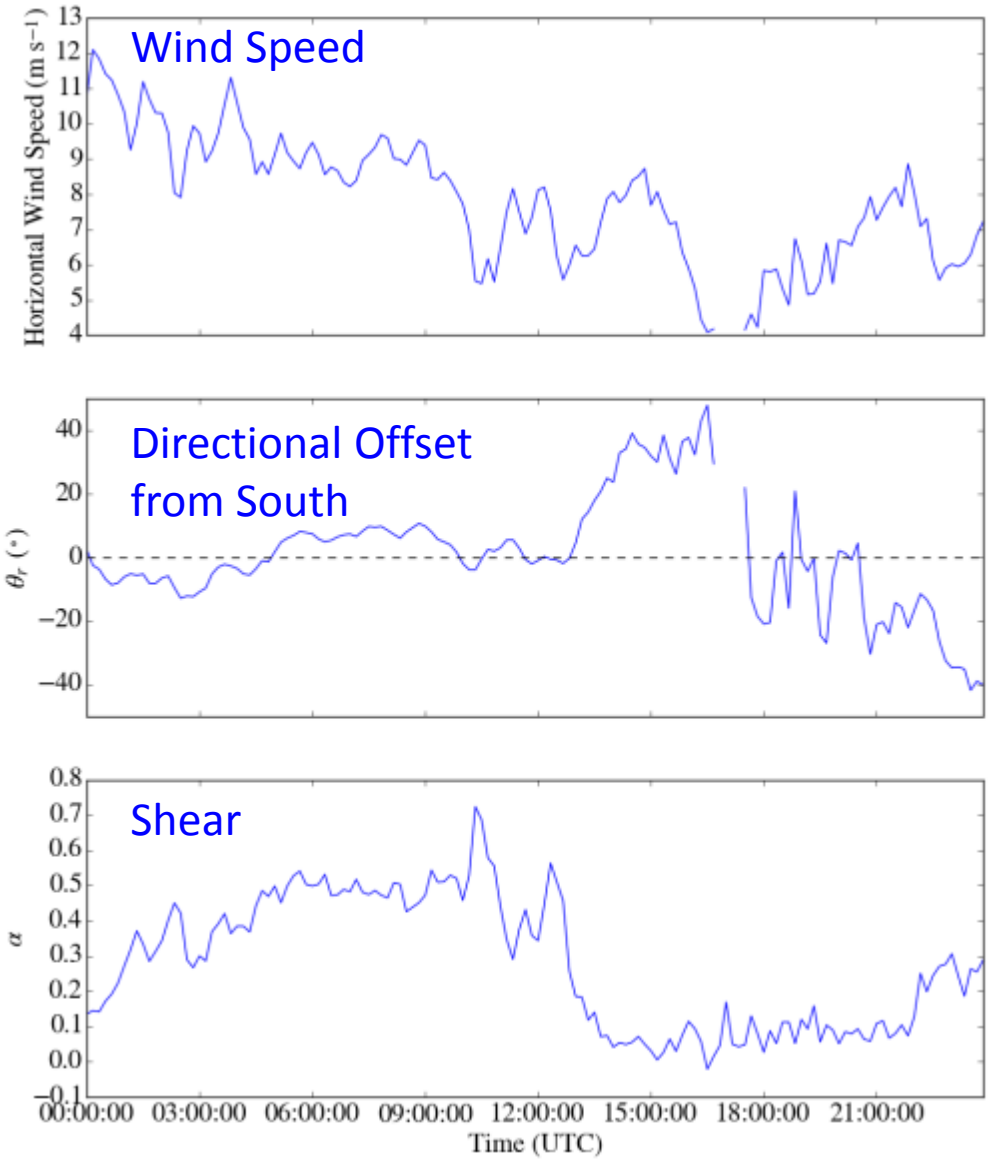
- Shear
- Horizontal wind speed
- Difference between lidar LOS and prevailing wind direction (θ_r).



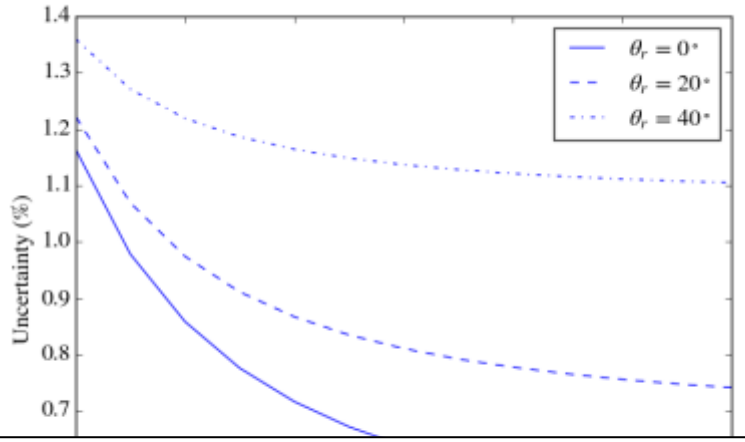
Source: Borraccino, A., M. Courtney, and R. Wagner, 2016: Generic methodology for field calibration of nacelle-based wind lidars. *Remote Sens.*, **8**, 907.

Adding a Dynamic Element to Current Framework

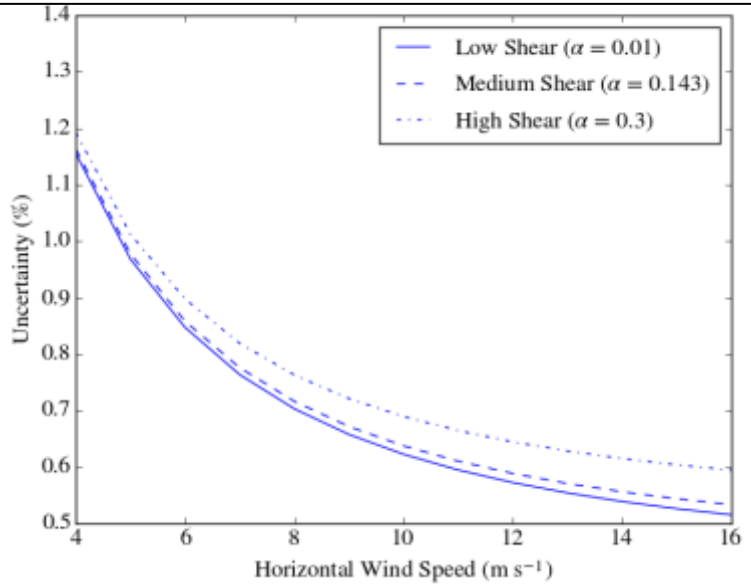
24 hours of data from Southern Plains wind farm



Changing conditions → changing uncertainty

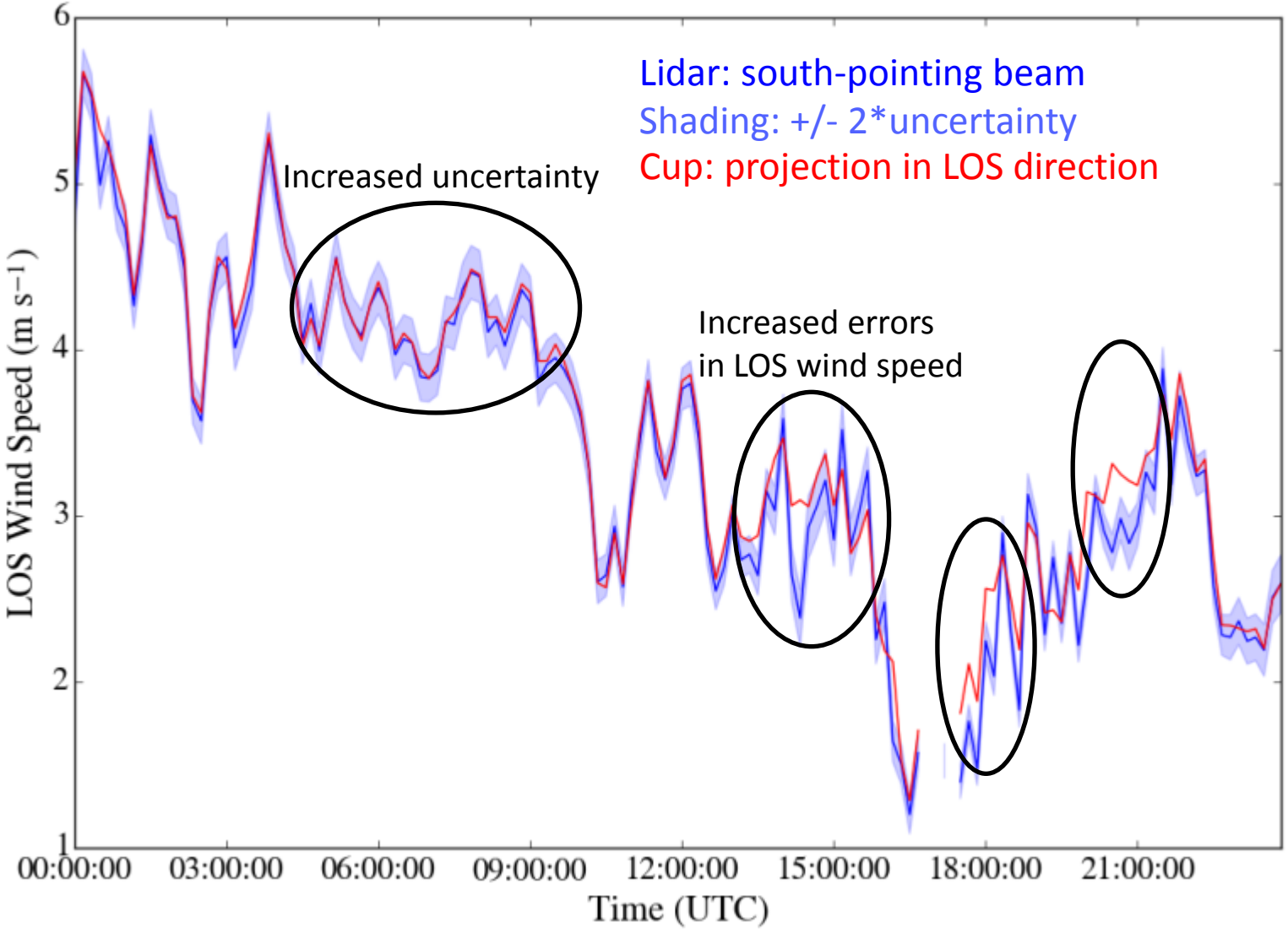


Worst case: low wind speed, high shear, large directional offset



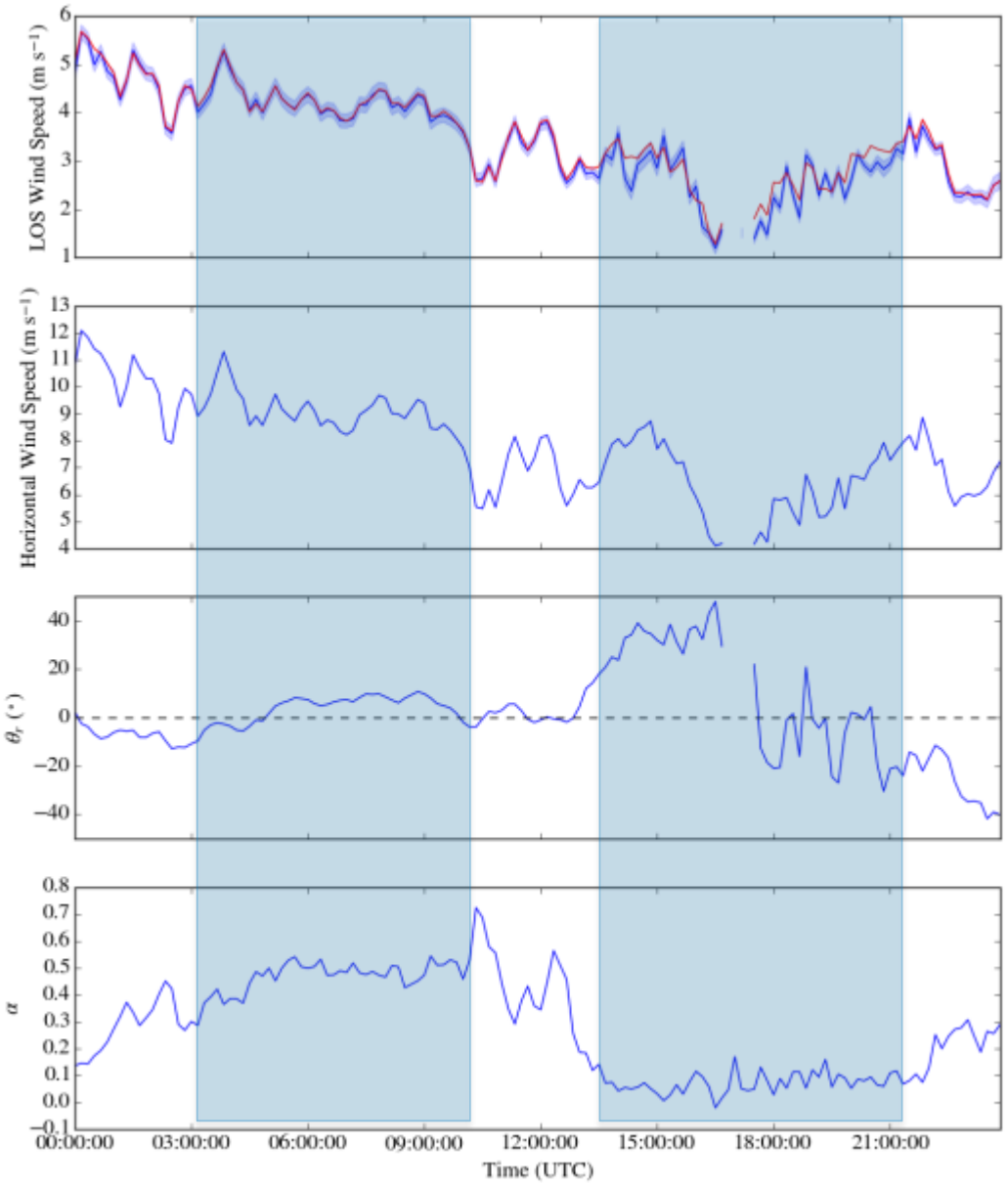
Dynamic Framework in Action

Shown below is the LOS wind speed from a 24-hour period at a Southern Plains wind farm where a WINDCUBE lidar was co-located with a meteorological tower.



Primary Sources of Uncertainty

Increased uncertainty as a result of averaging within probe volume



Increased uncertainty because of wind direction

Not all sources of uncertainty are taken into account

A New Way to Estimate Uncertainty

- The atmosphere and ocean are constantly changing, so lidar uncertainty is also constantly changing.
- Terms in an uncertainty framework should relate lidar measurements to physical processes.
- Physical models and results from lidar simulations can be used to quantify terms in the framework.

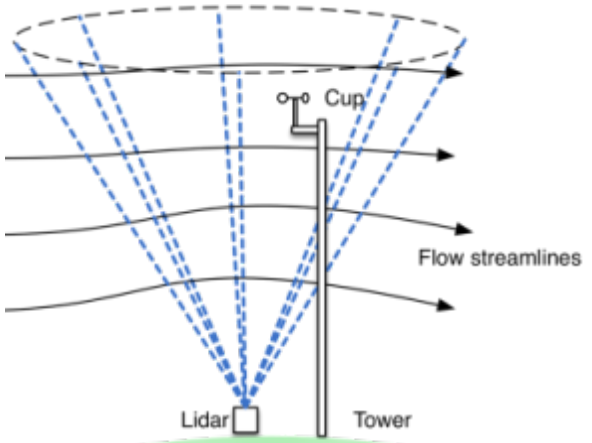


Illustration by Andy Clifton, NREL

Thank you to the Southern Plains wind farm for supplying the meteorological tower data.

Let's talk!

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Photo by Sonia Wharton