Development of a Dynamic Lidar Uncertainty Framework

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Factors That Affect Uncertainty

- Instrument noise
- Aerosol concentration
- Volume averaging
- Wind field reconstruction
- Pointing accuracy
- Line-of-sight (LOS) velocity
- Scanning circle
- Turbulent motion
- Probe volume
- Emitted signal
- Returned signal
- Lidar
- Pointing accuracy
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
A new uncertainty framework is being developed that introduces the following concepts:

- Uncertainty is *dynamic* and depends on current flow conditions during each 10-minute period.
- Framework should relate what the lidar sees to physical processes and sources of error.
Lidar Data for Framework Development

- Data used from two campaigns: Lidar Uncertainty Measurement Experiment (LUMEX; summer 2014) and eXperimental Planetary boundary layer Instrumentation Assessment (XPIA; spring 2015)

Lidar Data for Framework Development

- Three Leosphere 200S scanning lidars used:
  - One owned by University of Maryland, Baltimore County (UMBC)
  - Two owned by the National Oceanic and Atmospheric Administration’s Earth System Research Laboratory (referred to as Daleks).

- Lidars conducted a variety of scans during field experiments

- Focused on two types of scans:
  - Vertical stares (noise estimation)
  - Tower stares (comparison with sonic).
First Step: Estimate Uncertainty in LOS Wind Speed

• Measurement equation for LOS velocity (after Frehlich 2001)

\[ v_{LOS}(r, t) = v_{wgt}(r, t) + \epsilon(r, t) + b(r, t) \]

- Volume-averaged velocity
- Random error
- Systematic error (bias)

- Shear
- Carrier-to-Noise Ratio (CNR)

• Two ways to estimate uncertainty:
  – Physical models (based on theories and equations)
  – Data-derived models (based on observations from real data or simulations).

• Assuming a stationary time series with zero mean, the autocovariance function (ACVF) at lag 0 can be modeled as the following (Lenschow et al. 2000):

\[ M_{11}(0) = \bar{q}^2 + \bar{e}^2 \]

Variance of atmospheric signal  Variance due to noise

• The true atmospheric variance can be estimated by extrapolating ACVF to lag 0

Noise Uncertainty as a Function of CNR

Uncertainty Due to Noise (m s⁻¹) vs CNR (dB)

- XPIA: Dalek 1
- XPIA: Dalek 2
- LUMEX: UMBC
Noise Uncertainty as a Function of CNR

Uncertainty Due to Noise (m s$^{-1}$)

- XPIA: Dalek1. $y = 0.00064 \times \exp(-0.24 \times x)$
- XPIA: Dalek2. $y = 0.00029 \times \exp(-0.27 \times x)$
- LUMEX: UMBC. $y = 0.00066 \times \exp(-0.23 \times x)$

CNR (dB)
Data-Driven Model: Uncertainty Due to Volume Averaging

- Simulate wind field using the National Renewable Energy Laboratory’s Simulator for Wind Farm Applications (SOWFA)
- Sample wind field with virtual lidar
- Calculate difference between LES (large-eddy simulation) velocity at the center of range gate and range-weighted velocity
- Determine flow-field characteristics that relate to this velocity difference
- Find proxies for these characteristics that can be measured by a real lidar
Simplified Shear Model

• Describe 10-minute mean velocity within a range gate as a piecewise linear function with different values of shear for top and bottom of range gate

\[
\text{shear}_t = \frac{V(r_t) - V_0}{r_t - r_0}
\]

\[
\text{shear}_b = \frac{V_0 - V(r_b)}{r_0 - r_b}
\]
How Do Changes in Shear Relate to Volume Averaging Error?

40-meter (m) range gate with 5-m spacing in LES

Analytical expression (assuming uniform range-weighting)

\[ V_0 - V_{avg} = -5.556(\text{shear}_t - \text{shear}_b) \]

Actual data from neutral and unstable LES runs
How Do Changes in Shear Relate to Volume Averaging Error?

50-m range gate with 5-m spacing in LES

Analytical expression (assuming uniform range-weighting)

\[ V_0 - V_{avg} = -6.818(shear_t - shear_b) \]

Actual data from neutral and unstable LES runs
Shear between range gates is a decent approximation for neutral and unstable conditions, but this relation still needs to be tested on stable conditions.
Applying Framework to XPIA Data

Leosphere 200S lidars conducted coordinated and uncoordinated tower stare scans.

From Lundquist et al. (2017)
Estimating Combined Uncertainty

Use measurement equations with Guide to the Expression of Uncertainty in Measurement (GUM) method to combine uncertainty.

- Measurement equation for LOS velocity:

\[ v_{LOS}(r, t) = v_{wgt}(r, t) + \epsilon(r, t) + b(r, t) \]

  - Analytical approach using shear between range gates
  - Fit from Lenschow method
  - Mean error from large sample of data

- Measurement equation for reference velocity:

\[ v_{ref} = u \cos \phi \sin \theta + v \cos \phi \cos \theta + w \sin \phi \]

  - Uncertainty in azimuth and elevation angle from lidar
  - Uncertainty in sonic anemometer measurements
LOS wind speed from a 24-hour period during XPIA

Lidar LOS velocity
Shading: +/- 2\times\text{uncertainty}
Sonic projection in LOS direction
Shading: +/- 2\times\text{uncertainty}
Primary Sources of Uncertainty

- Increased reference uncertainty due to large wind direction offset
- Increased lidar uncertainty due to decrease in CNR
- Increased reference uncertainty due to large wind direction offset

CNR

Shear difference

Wind direction offset
Summary: A New Way to Estimate Uncertainty

• The atmosphere is 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.

• Next step: Quantify uncertainty due to wind field reconstruction.
Thank You!
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