Moving Beyond 2% Uncertainty:  
A New Framework for Quantifying Lidar Uncertainty  

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IEA Wind Task 32 Workshop #4  
Glasgow, Scotland  
December 14, 2016  

NREL/PR-5000-67642
What is Uncertainty?

- Parameter that characterizes the spread of values that could be reasonably attributed to a measurand
- Measure of possible error in an estimated value
- Quantity characterizing 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.*

How Do We Quantify Uncertainty?

• Lots of different ways!

• In this presentation, we define uncertainty as the *standard deviation of the normalized error* about the best-fit line.
A Statistical Look at Uncertainty

• Assume the wind speed errors in each bin follow a Gaussian distribution

• The uncertainty gives us an idea of the range of true wind speed values that are associated with our estimate.

Source: Dan Kernler - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=36506025
Example of Lidar Wind Speed Uncertainty

- For wind speeds > 8 meters per second (m/s), uncertainty is close to 2%
- Uncertainty increases rapidly for lower wind speeds

Data from 60 m above ground level (AGL) at Southern Great Plains ARM site
Example of Lidar Wind Speed Uncertainty

Data from 60 m AGL at Southern Great Plains ARM site

Stability matters!
Current Uncertainty Framework: International Electrotechnical Commission (IEC) 61400-12-1

- Estimate uncertainty due to:
  - Calibration
  - Classification
  - Nonhomogeneous flow within probe volume
  - Mounting effects
  - Variation in flow across site

- Assume that:
  - Uncertainty components are independent of one another
  - Components can be added in quadrature
  - **Total uncertainty is a single, climatological value.**
• From Annex L: Classification of remote sensing devices

• Bin input data and calculate regression line for binned data vs. % difference between remote sensing device (RSD) and reference cup

• **Sensitivity:** Product of slope of regression line and standard deviation of input variable

• Sensitivity is used to identify significant variables and calculate RSD accuracy class.

Data from 80 m AGL at Southern Plains wind farm
Limitations of Current Framework

- Sensitivity analysis assumes linear relation between external variables and RSD error.
- Physical processes that cause these errors are not considered.

**Example:** At this site and measurement height, relation between shear and RSD error is not strictly linear.

But shear could be related to physical processes in the atmosphere that increase uncertainty in RSD measurements.

Data from 80 m AGL at Southern Plains wind farm
### Brainstorming an Uncertainty Framework

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Predictand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti (corrected)</td>
<td>Ti</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$\frac{\Sigma W}{U}$</td>
</tr>
<tr>
<td>SNR</td>
<td>$L_T^{-2}$</td>
</tr>
<tr>
<td>$\frac{(\sigma W)^2}{L_T^{-2}}$</td>
<td>$L_T^{-1}$</td>
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<tr>
<td>Spectral Broadening</td>
<td>Internal temp</td>
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<tr>
<td>Off-Wind Pitch Angle</td>
<td>Scanning circle $\varnothing$</td>
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</tbody>
</table>

**Characteristic Scales**

- Time scale $= \varnothing / U$
- Variance $= \frac{\sigma^2 W}{T_i}$
- Off-Wind Pitch Angle
- Internal Temp
- Spectral Broadening

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**Additional Notes**

- Integral
- Integral over time
- Probe length
- Heat
- Characteristic Scale

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**System Parameters**

- SNR
- Internal Temp

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**Stairs Diagram**

- Long scale
- Integral
- Integral over time
- Off-Wind Angle
- Characteristic Scale
Brainstorming an Uncertainty Framework

- Range of motion
- Capacity for motion compensation
- Vertical variability
- Horizontal variability
- Viewing angle

- Lidar Motion
- Windfield Reconstruction

- Lidar Uncertainty Framework
- Internal temperature
  - Signal to noise ratio
  - Radio-frequency noise

- Lidar Conditions
- Atmospheric Conditions
  - Wind shear
    - Turbulence
  - Horizontal variability
  - Precipitation
  - Cloudiness
  - Aerosol concentration
Brainstorming an Uncertainty Framework
### Brainstorming an Uncertainty Framework

<table>
<thead>
<tr>
<th>High Level Category</th>
<th>Proposal Bases</th>
<th>Uncertainty Framework</th>
<th>Observation</th>
<th>Proof</th>
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</thead>
<tbody>
<tr>
<td>LOS</td>
<td>Delayed correction</td>
<td>LIDAR, Atmosphere</td>
<td>FWHM(%)</td>
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<td></td>
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<td>SNR</td>
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<td>Motion</td>
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<td></td>
<td></td>
<td>Atmospheric dispersion</td>
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<td>LIDAR Range</td>
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<td></td>
<td>Mast distortion</td>
<td>Assumed homogeneity</td>
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<td>flow direction</td>
<td>Assumed homogeneity</td>
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</table>

Possible uncertainty factors:
- LOS = LIDAR correction
- Delayed correction
- LIDAR, Atmosphere
- FWHM(%)
What’s an Uncertainty Framework?

• Assign all sources of uncertainties to clear categories
• Create models for each of them
  – Physics or data-driven
• Apply them to every measurement.
Uncertainty is *dynamic* and depends on current flow conditions during each 10-minute period.

Relate what the lidar sees to physical processes and sources of error.

**Physical process x**
causes uncertainty

The lidar sees this process as *y*

Which can be quantified with variable *z*
Example: Wind Shear

Changes in wind speed within the probe volume cause uncertainty

The lidar sees this process as wind field heterogeneity in the line-of-sight (LOS) direction

Which can be quantified with lidar shear and turbulence measurements

The key of the framework is figuring out this relationship.
Factors That Affect Uncertainty

These factors can be broadly grouped into two categories: **line-of-sight wind speed** and **wind field reconstruction**.
What The Framework Might Look Like

What parameters do we need?

What measurements do we need?

How do we get these measurements from lidar?

What is the ideal measurement case?

What causes deviations from the ideal case?

What is the physical basis of these effects?

How does the lidar see these effects?

How can we quantify these effects?
Simplified Framework

What parameters do we need?

Horizontal wind speed

Accurate u, v, and w wind components

What measurements do we need?

Estimates of LOS wind speed

Application of wind field reconstruction algorithm

How do we get these measurements from lidar?

- Sources of uncertainty

What is the physical basis of these effects?

Atmospheric processes

Lidar operating conditions

Additional sources of uncertainty for floating lidar systems

Ocean conditions
What’s an Uncertainty Framework?

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AXYS FLiDAR 6-m buoy. Photo from AXYS Technologies
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AXYS FLiDAR 6-m buoy. Photo from AXYS Technologies
Workflow: Framework Development

- Start with the ideal measurement case
- Consider factors that cause deviations from the ideal case
- Identify the physical basis of these effects
- Determine how the lidar sees these effects
- Identify proxies for these effects
Workflow: Framework Development

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Diagram:
- Dirac delta in Doppler spectrum
- Spectral broadening
Workflow: Framework Development

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Spectral broadening
Workflow: Framework Development

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Heterogeneity in wind field
Workflow: Framework Development

- Start with the ideal measurement case
- Consider factors that cause deviations from the ideal case
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Heterogeneity along LOS direction
Workflow: Framework Development

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- Consider factors that cause deviations from the ideal case
- Identify the physical basis of these effects
- Determine how the lidar sees these effects
- Identify proxies for these effects

Lidar measurements of vertical wind shear
Workflow: Framework Application

• Lidar collects data during a 10-minute period

• Data are used to characterize atmospheric conditions and lidar performance during that 10-minute period

• Parameters are used as input to uncertainty framework

• Uncertainty caused by different effects is estimated
How to Move Beyond Climatic Uncertainty Values

Develop an Uncertainty Model

• “White box” uncertainty models for every 10-min. measurement for LOS and windfield reconstruction
  o Use knowledge of lidar measurement process
  o Use physics first, then correlations from observations, then informed estimates
• Include random “noise” as well (unresolved physics)
• **Need a low-uncertainty reference, not just a cup on a tower.**

Apply the Model

• No extra data required (based on measurements made by the lidar)
• Calculated online or afterward.

Questions and comments to:
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A multimegawatt wind turbine and 1-megawatt photovoltaic field at the National Wind Technology Center at the National Renewable Energy Laboratory. Image by Dennis Schroeder, NREL