NATIONAL RENEWABLE ENERGY LABORATORY

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

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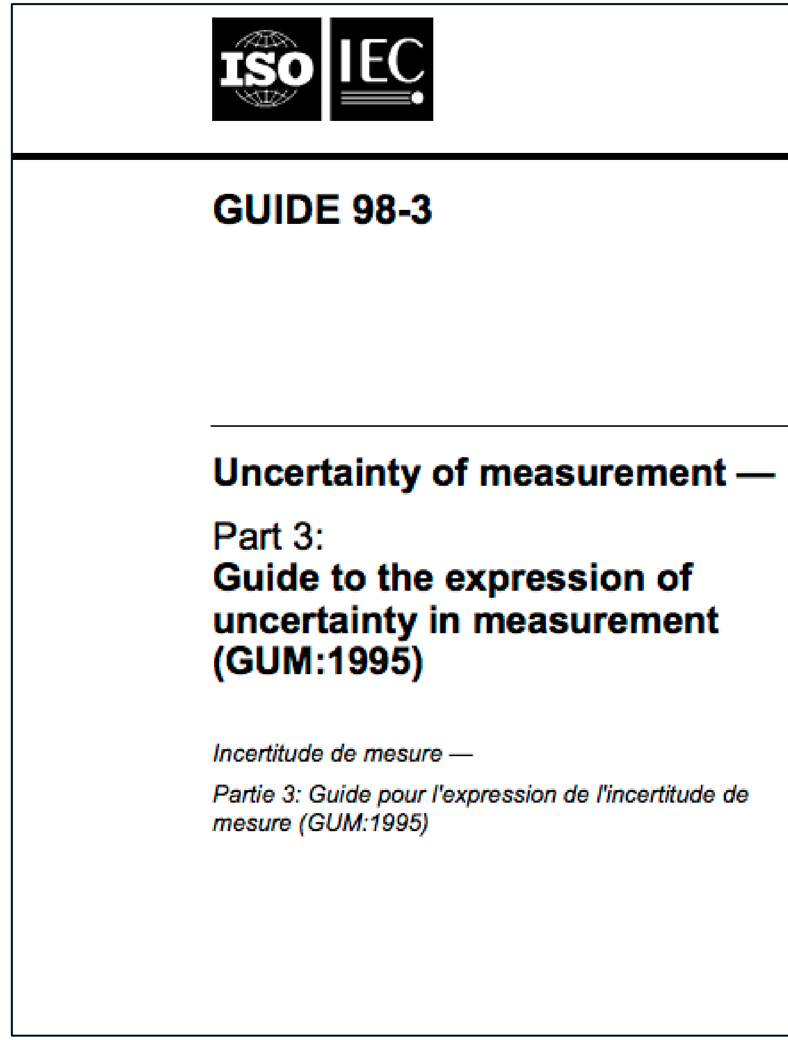
What is Uncertainty?

- 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.


ISO IEC

GUIDE 98-3

Uncertainty of measurement —

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

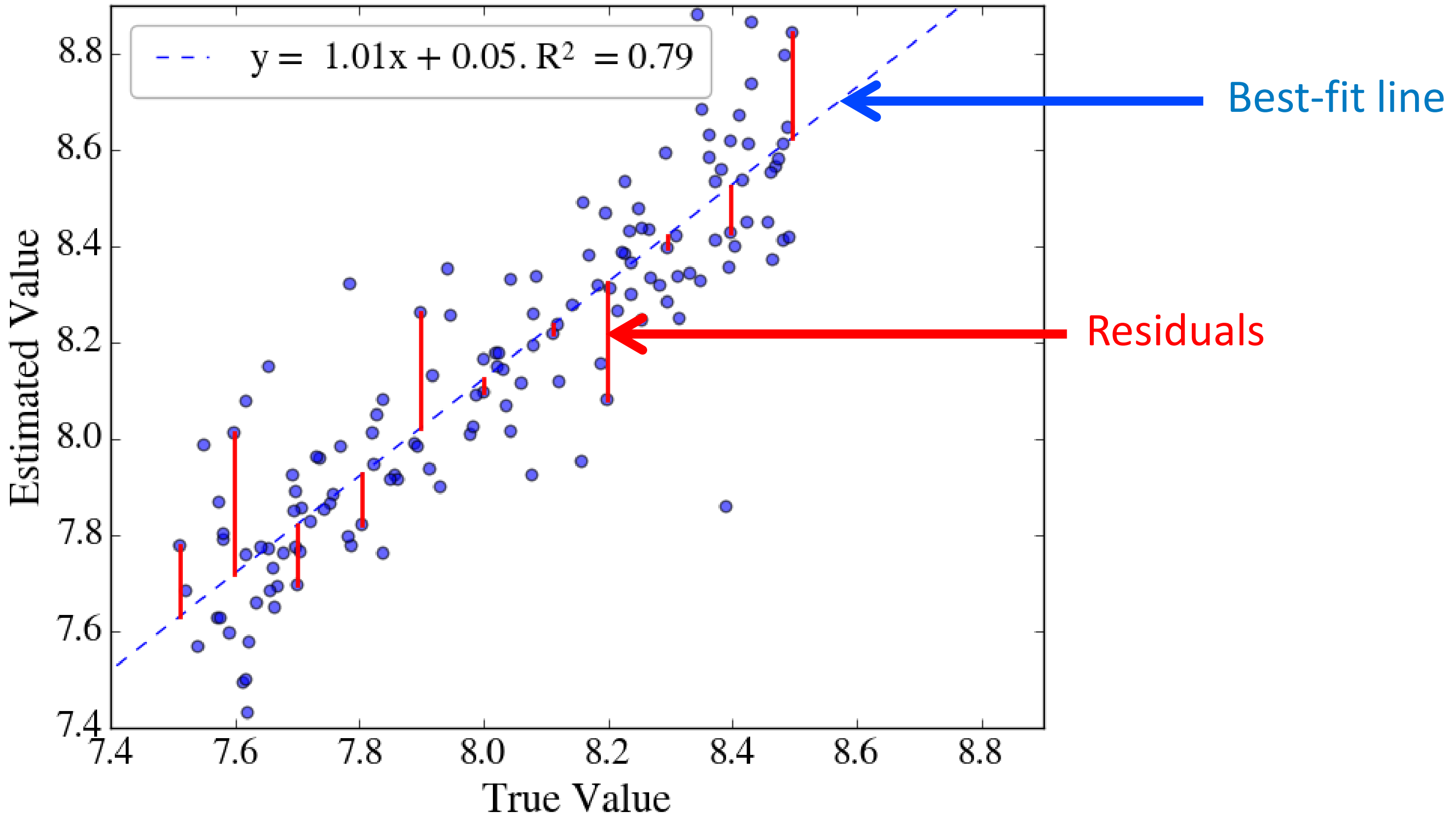
Incertitude de mesure —

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

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

How Do We Quantify Uncertainty?

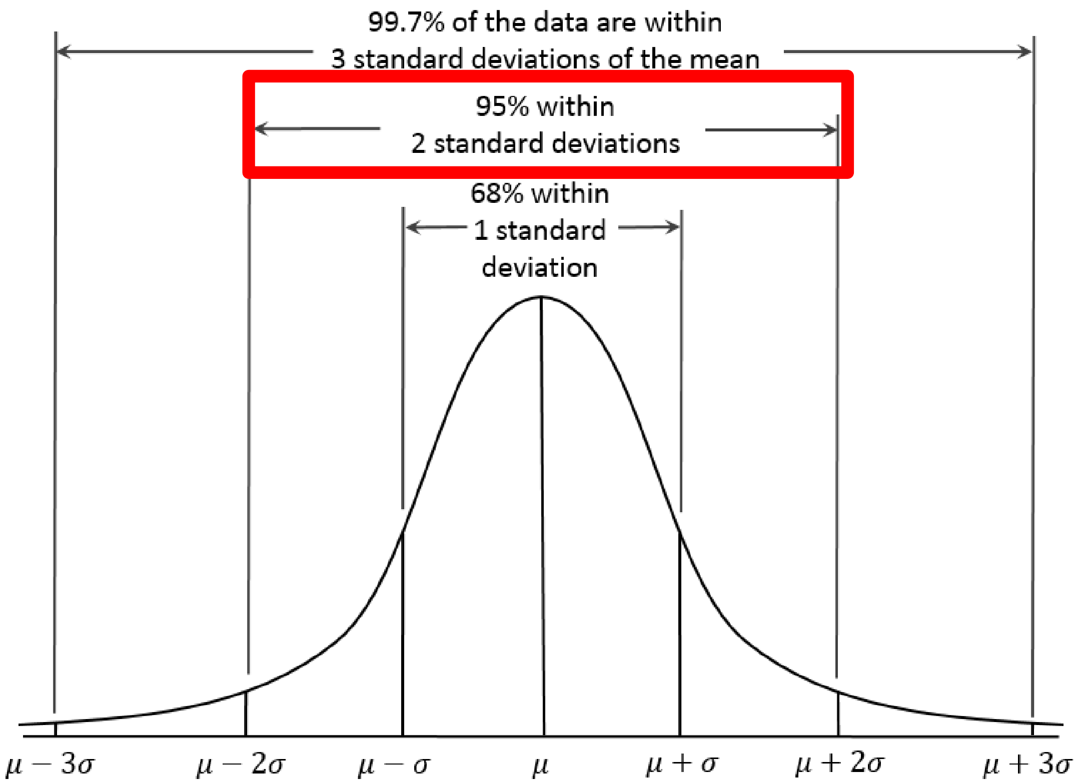
- Lots of different ways!
- In this presentation, we define uncertainty as the *standard deviation of the normalized error* about the best-fit line.



A Statistical Look at Uncertainty

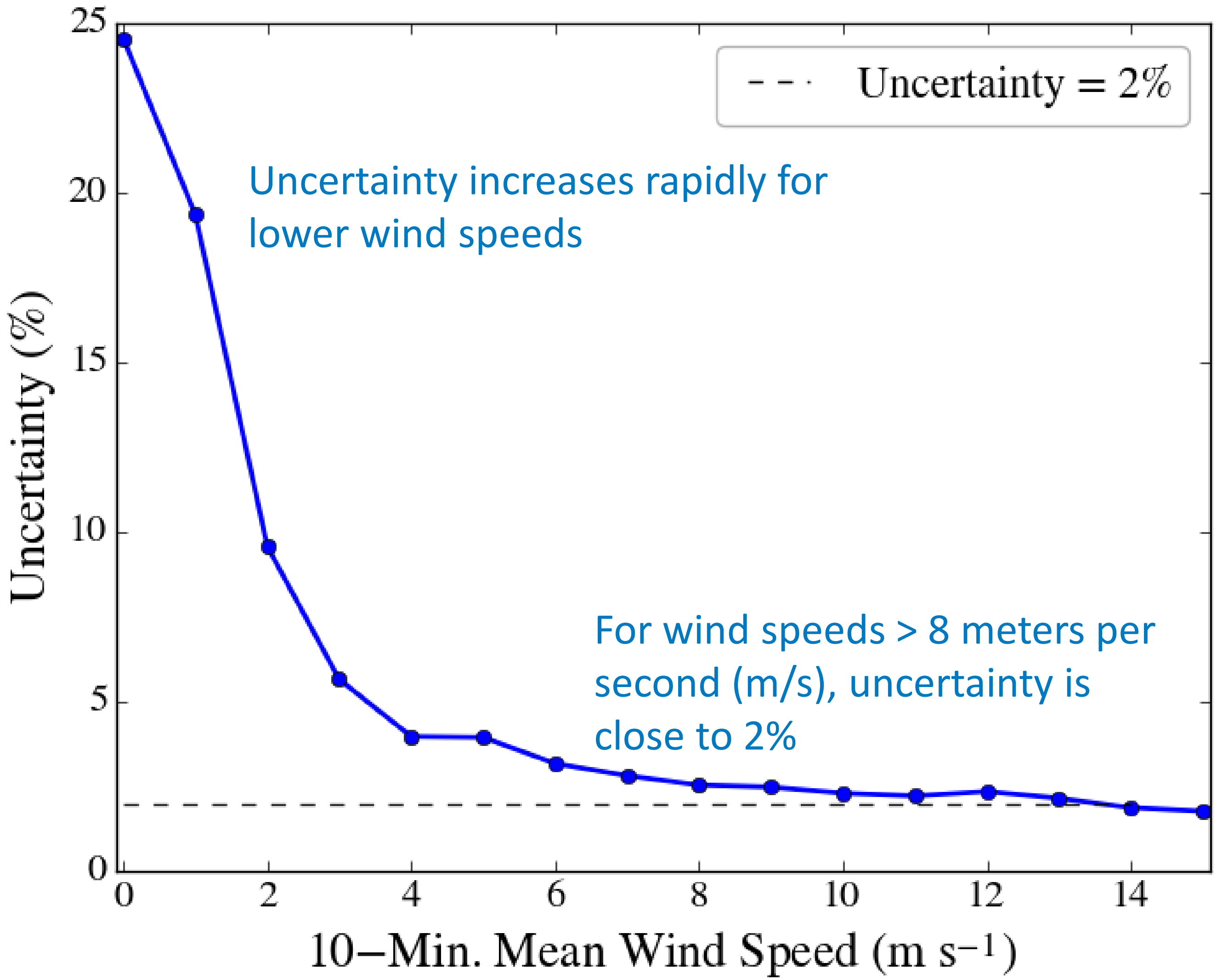
- Assume the wind speed errors in each bin follow a Gaussian distribution

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



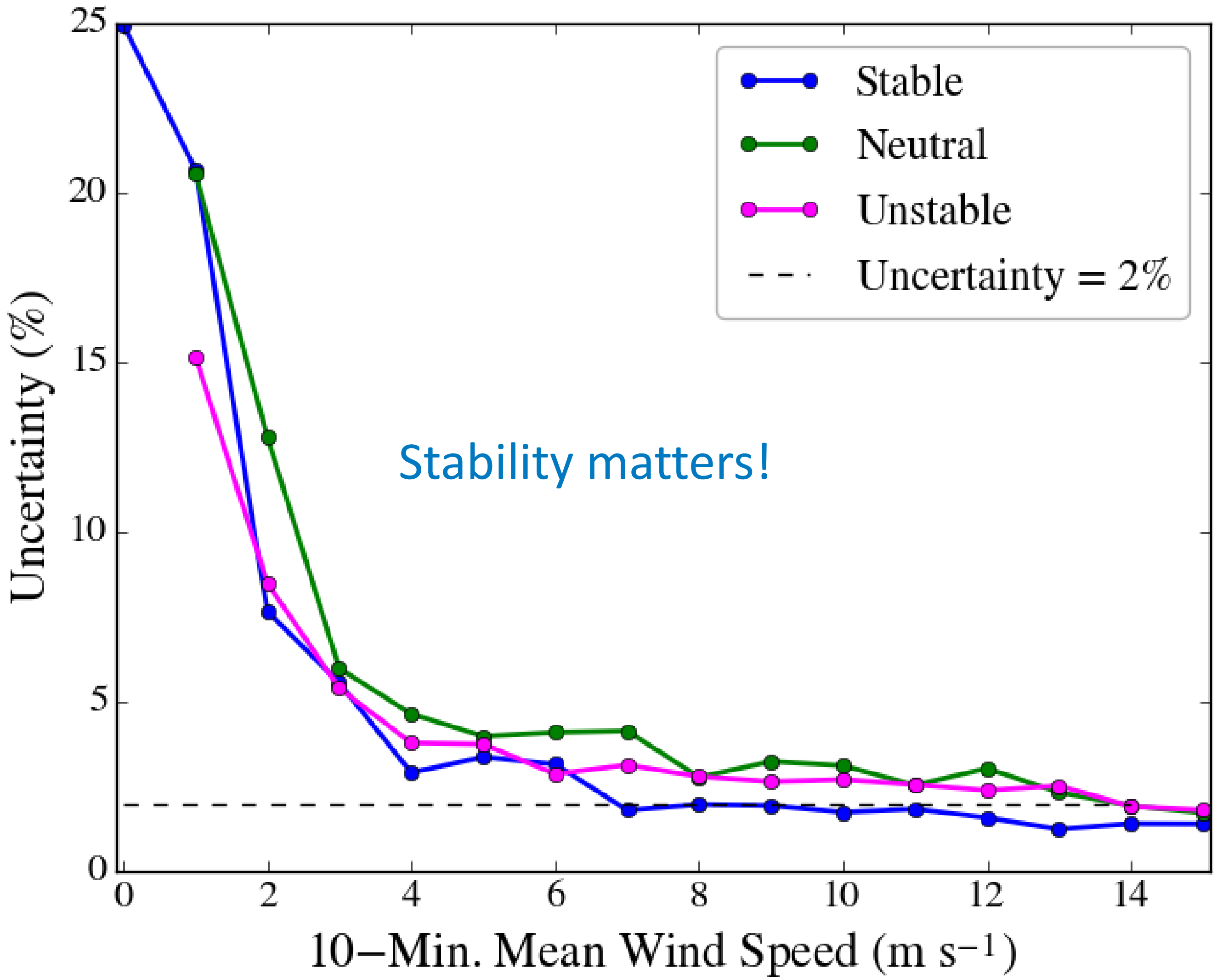
Source: Dan Kernler - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=36506025

Example of Lidar Wind Speed Uncertainty



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

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.**

Photo by Andrew Clifton, NREL 24383

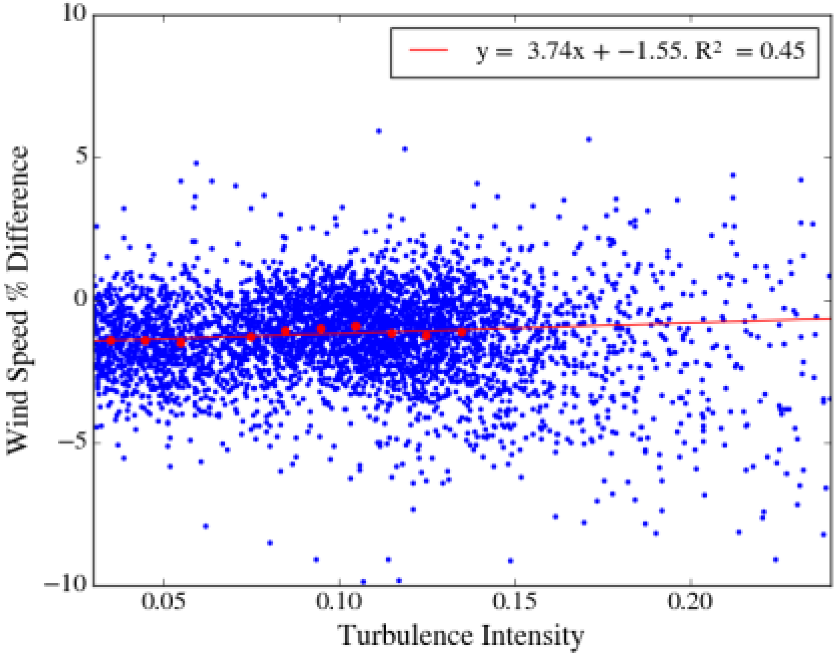
Sensitivity to External Parameters: IEC 61400-12-1

- 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.



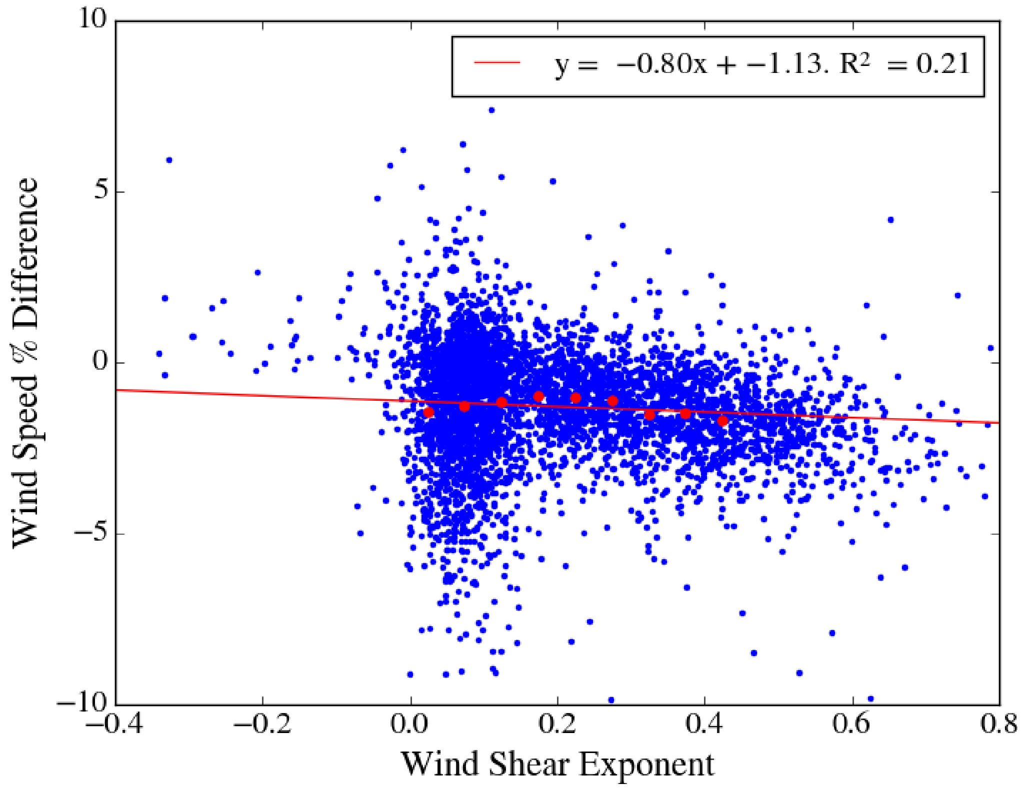
Data from 80 m AGL at Southern Plains wind farm

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.



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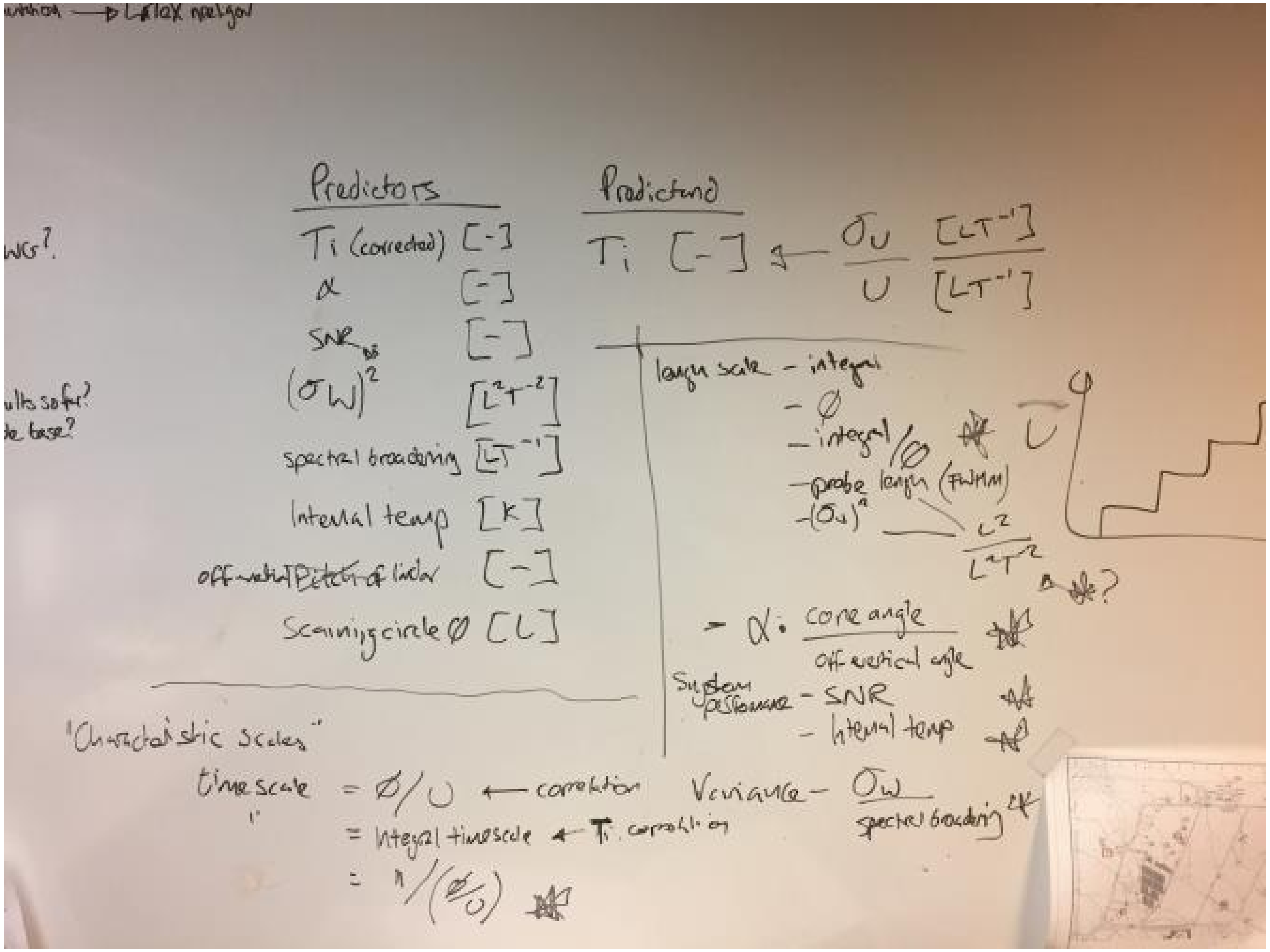
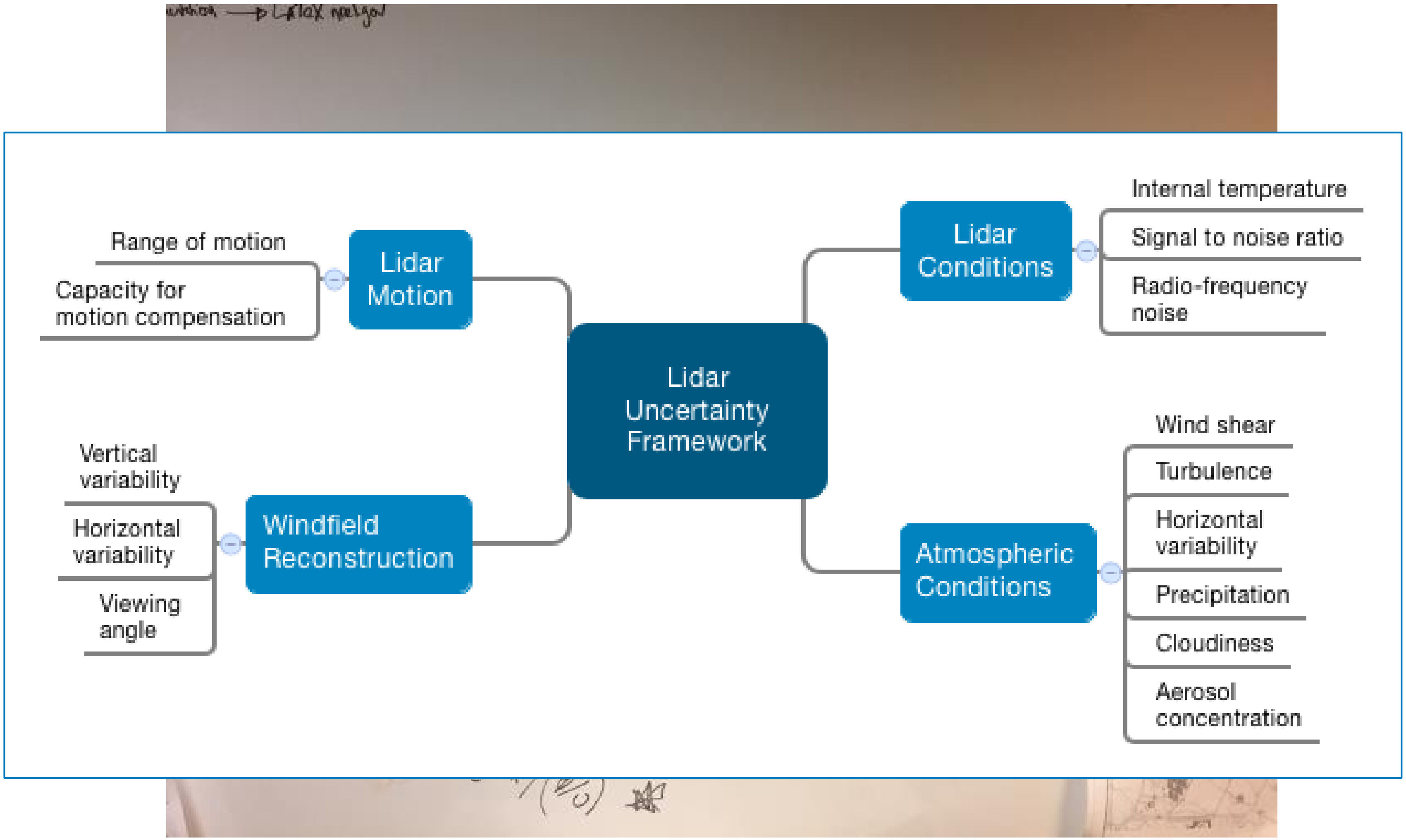
Brainstorming an Uncertainty Framework



Brainstorming an Uncertainty Framework



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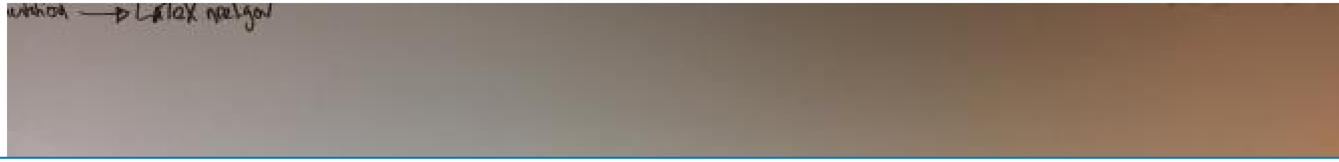

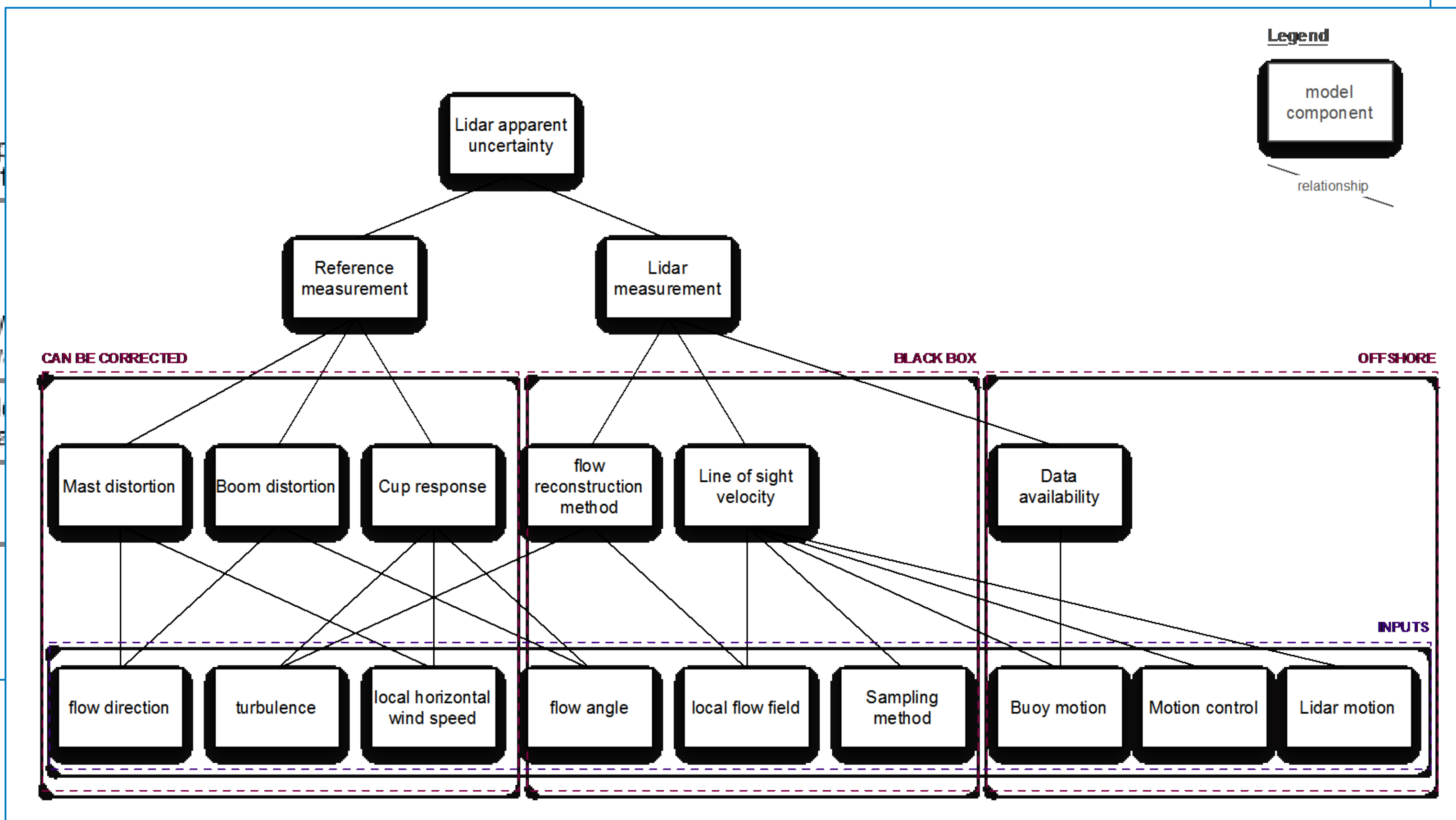

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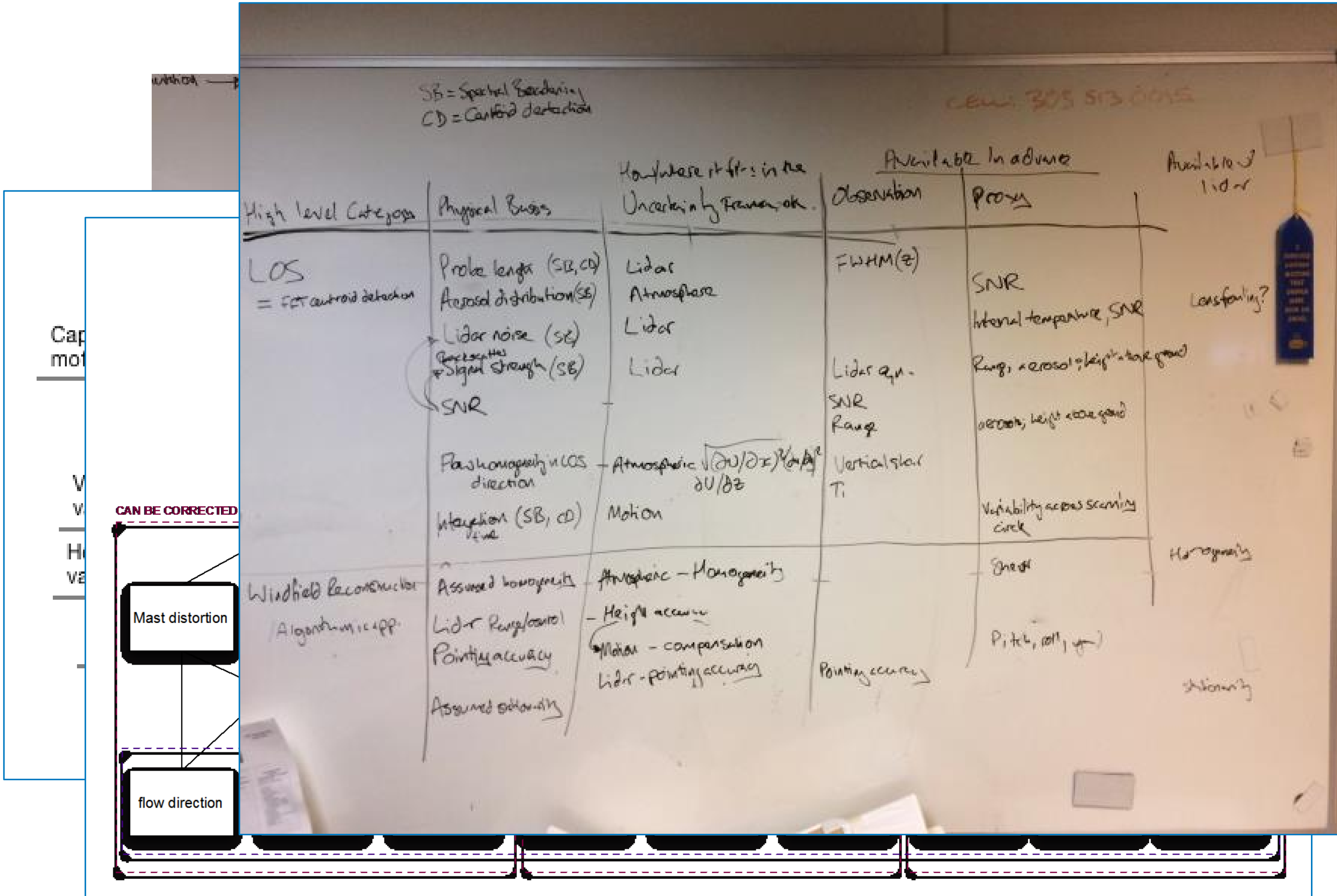
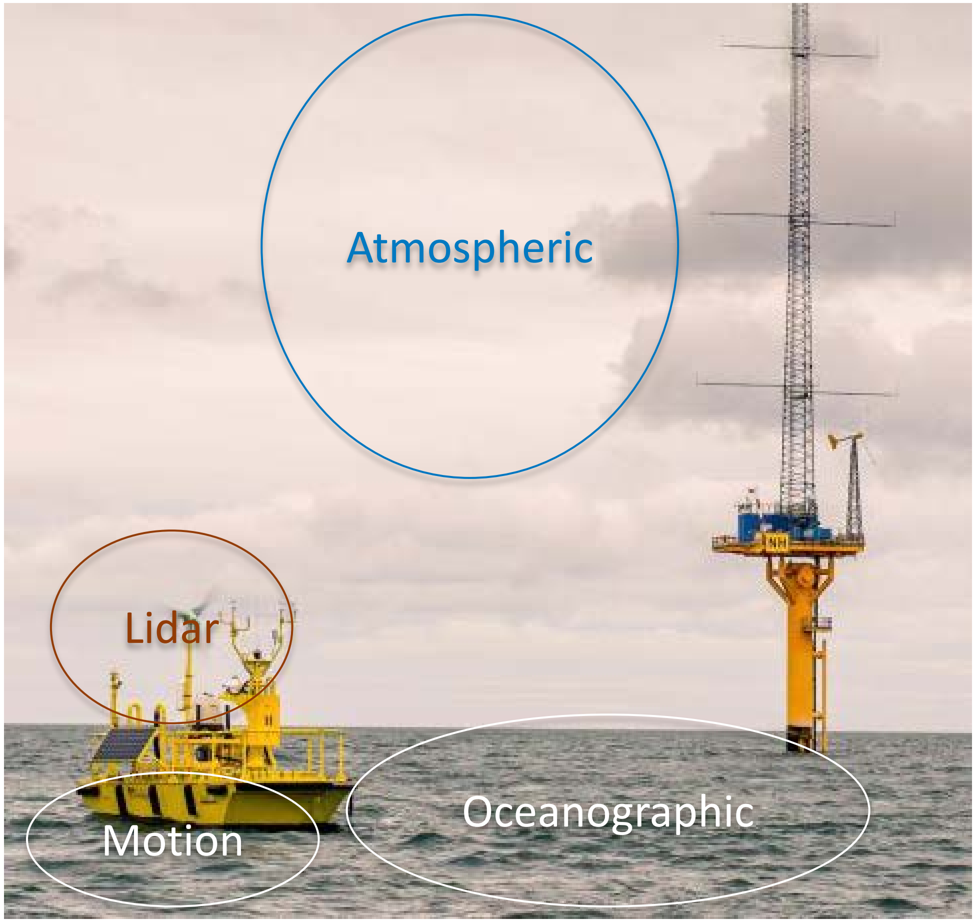


What's an Uncertainty Framework?

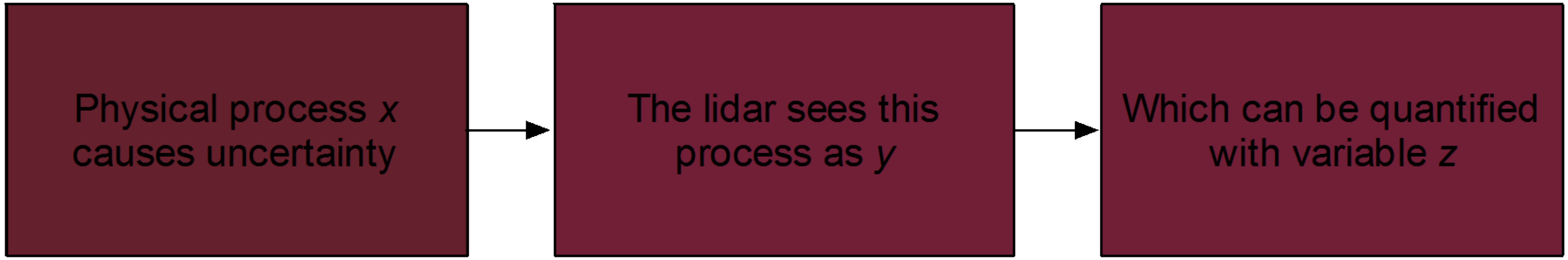
- Assign all sources of uncertainties to clear categories
- Create models for each of them
  - Physics or data-driven
- Apply them to every measurement.



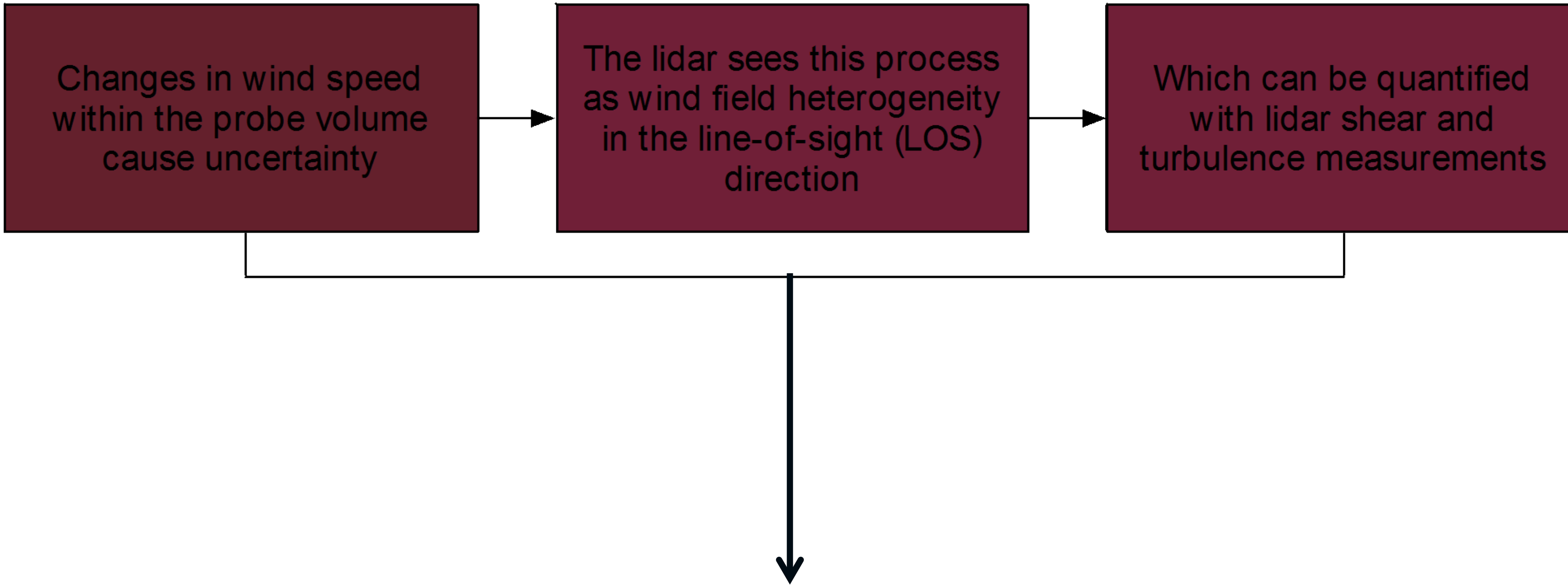
AXYS FLiDAR 6-meter buoy. *Photo from AXYS Technologies*

New Uncertainty Framework

- 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.

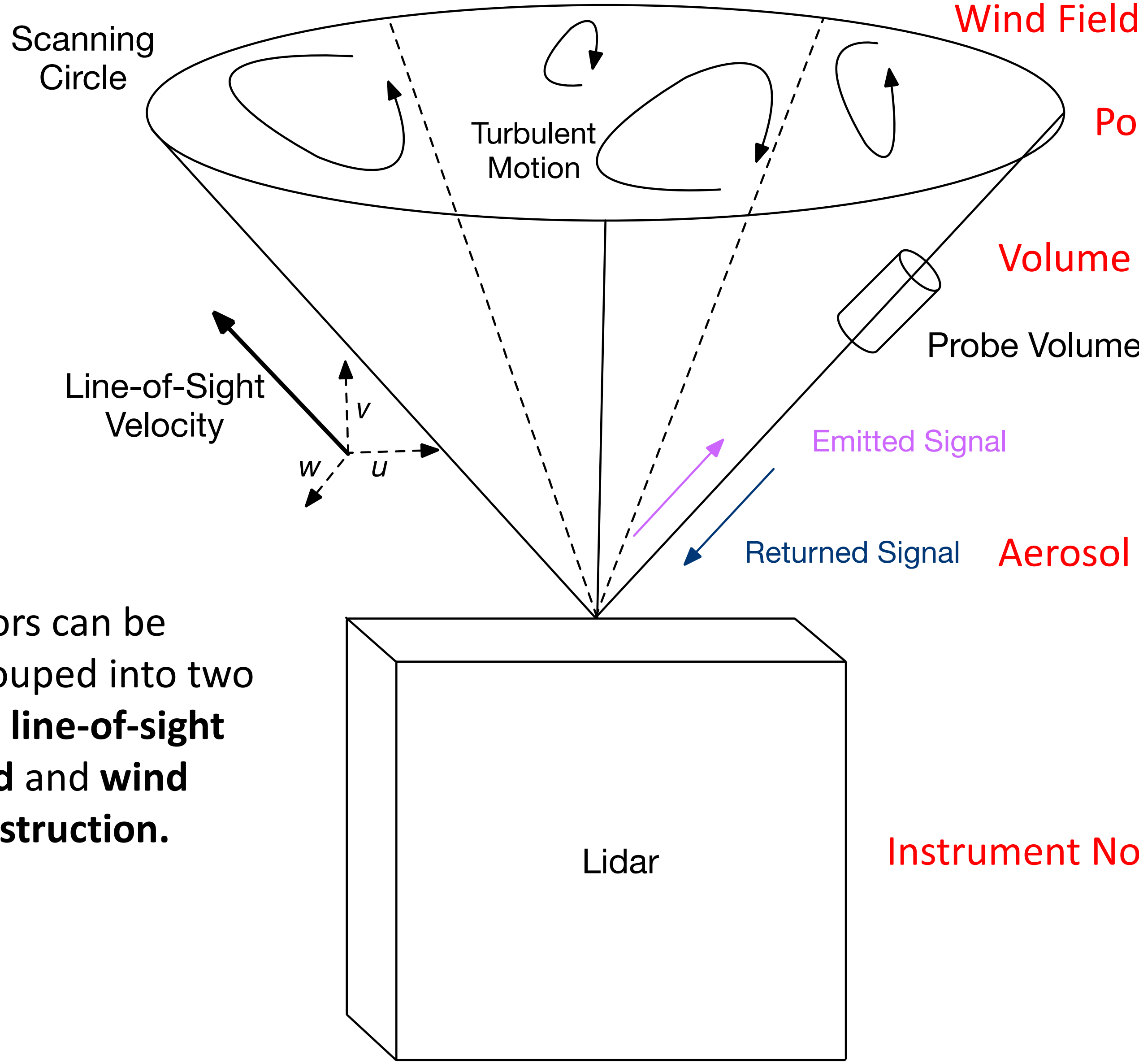


Example: Wind Shear



The key of the framework is figuring out this relationship.

Factors That Affect Uncertainty



Wind Field Reconstruction

Pointing Accuracy

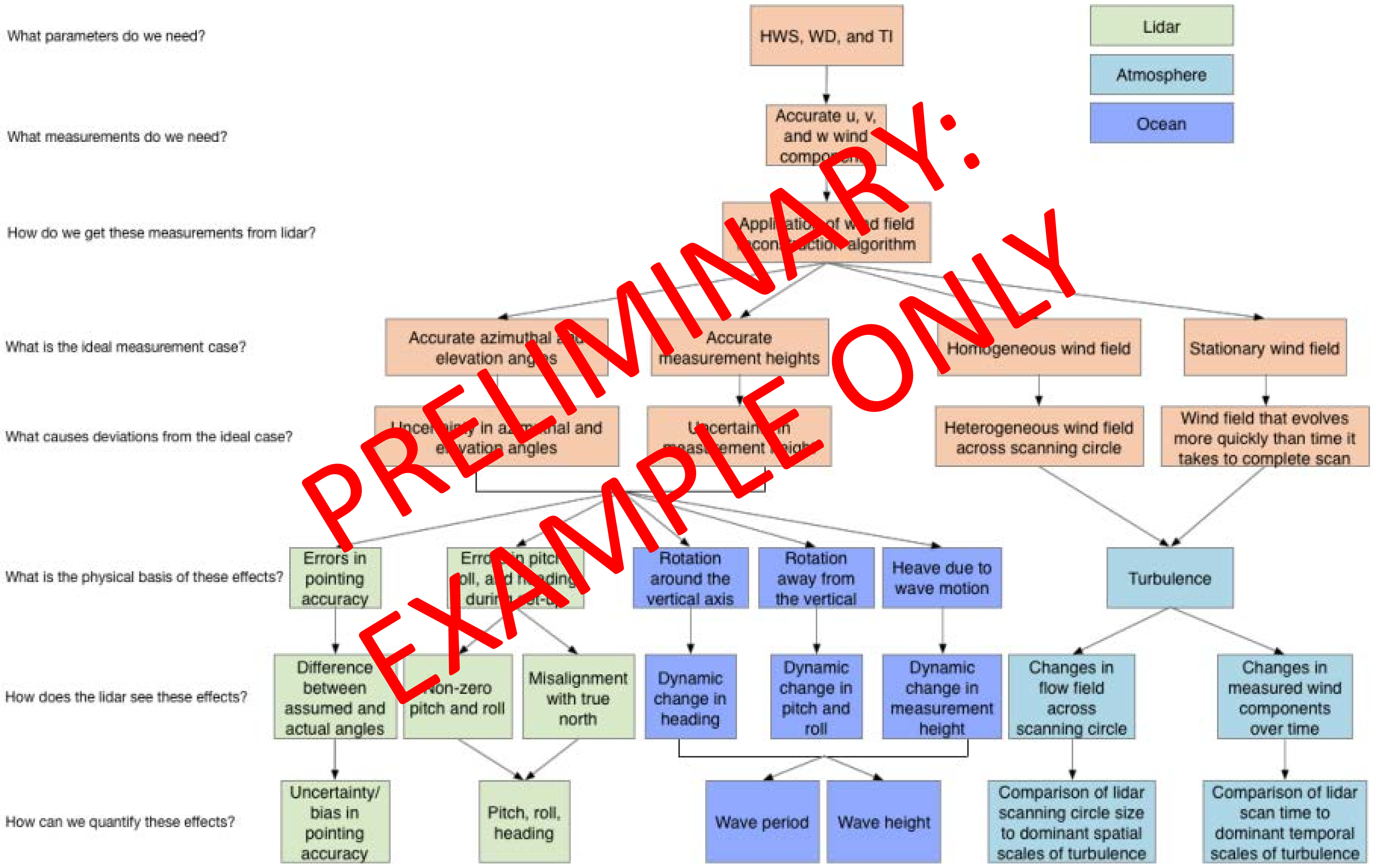
Volume Averaging

Aerosol Concentration

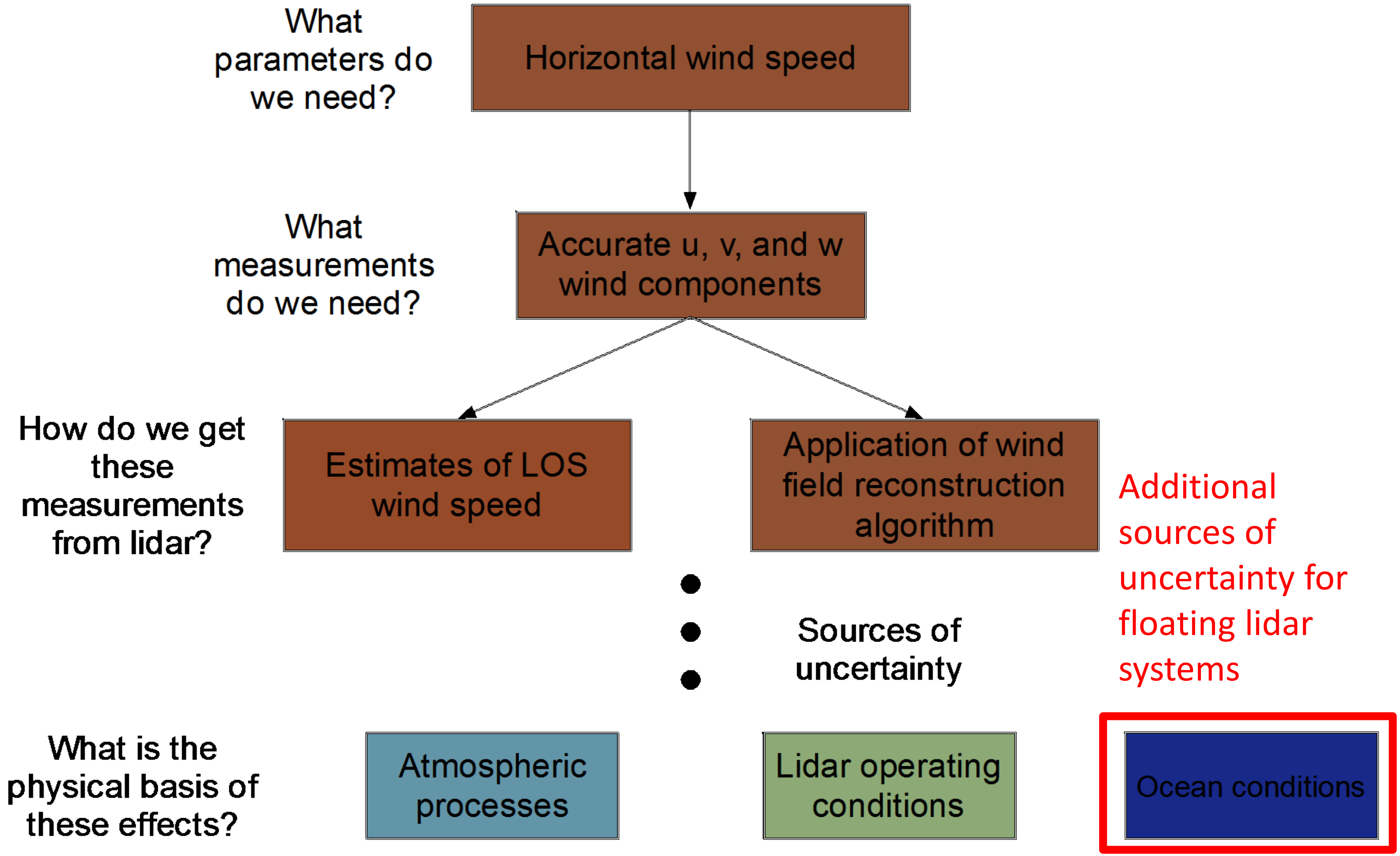
Instrument Noise

These factors can be broadly grouped into two categories: **line-of-sight wind speed** and **wind field reconstruction.**

What The Framework Might Look Like



Simplified Framework



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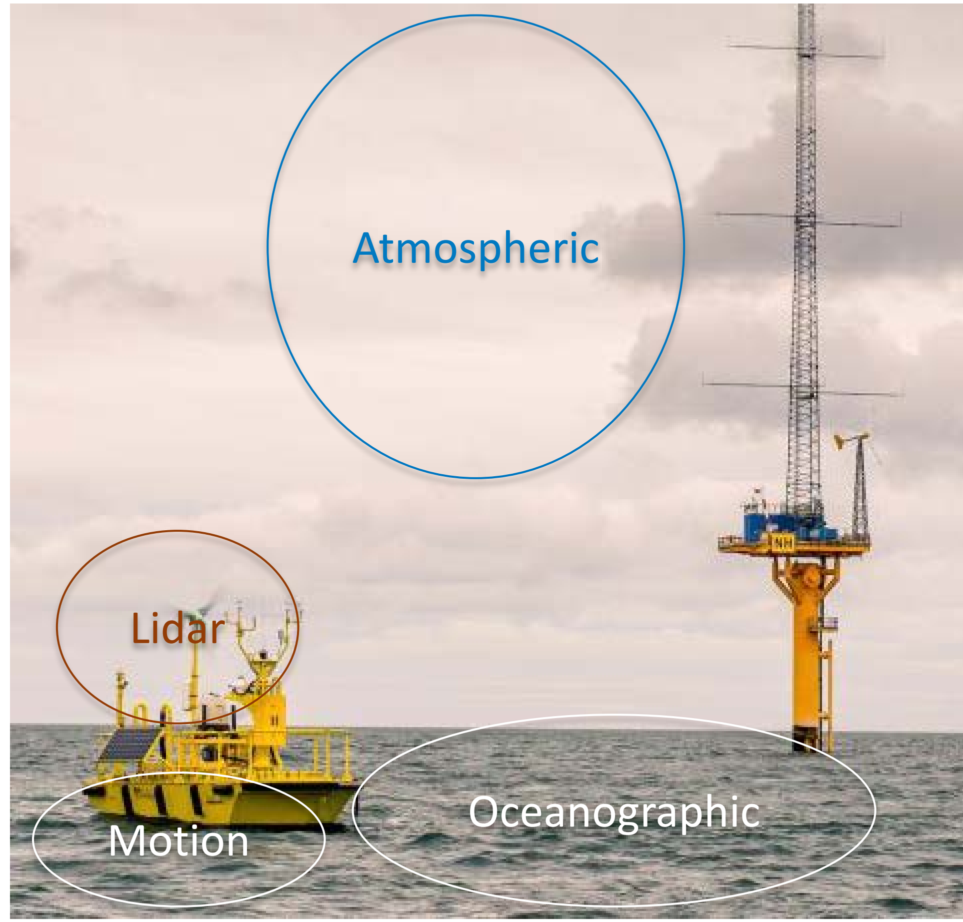

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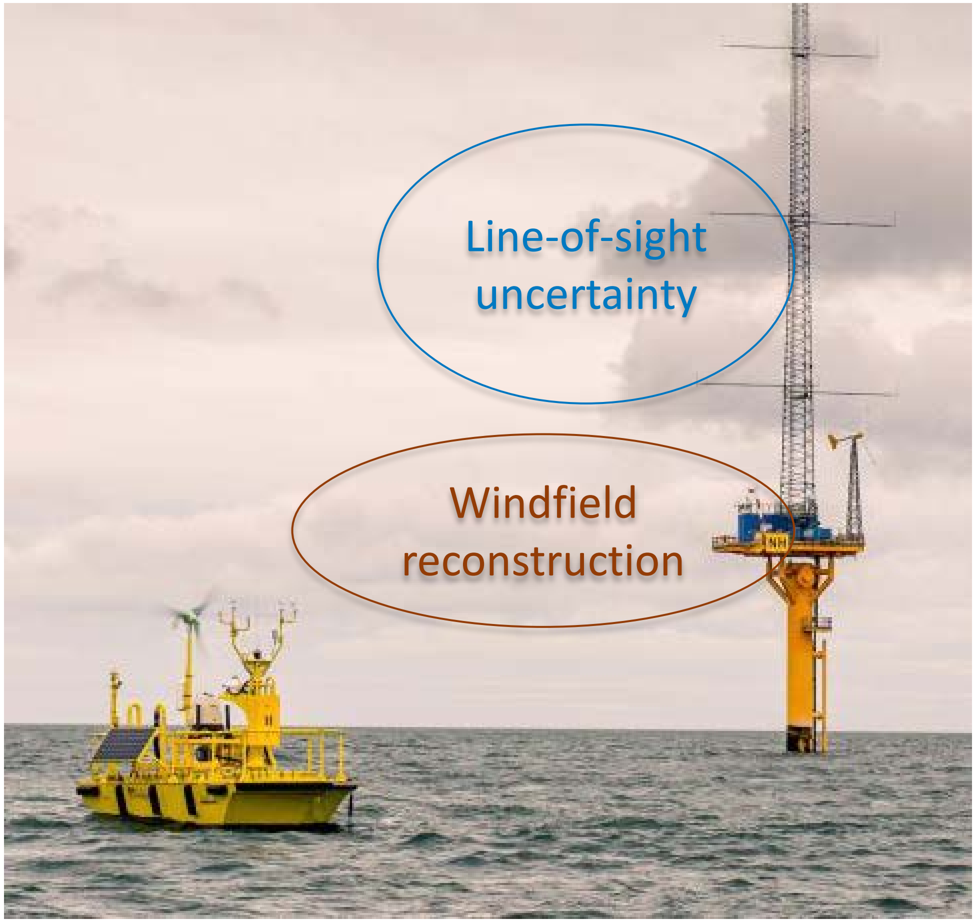

AXYS FLiDAR 6-m buoy. *Photo from AXYS Technologies*

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

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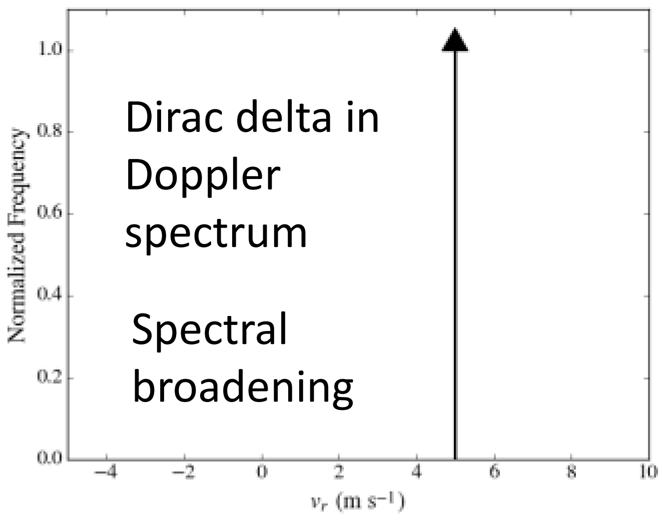

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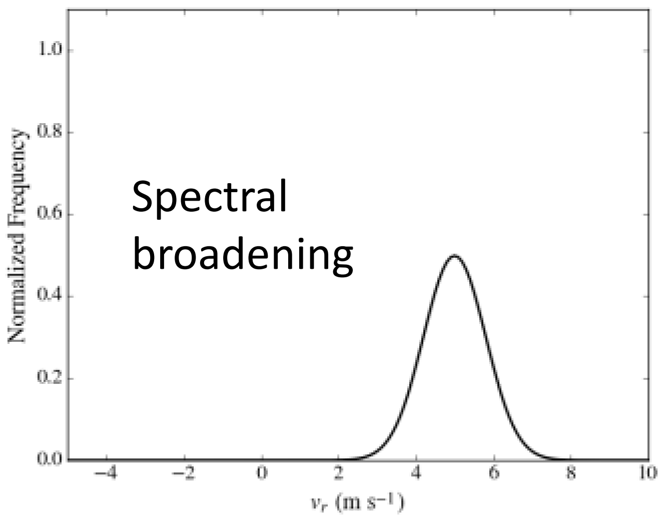

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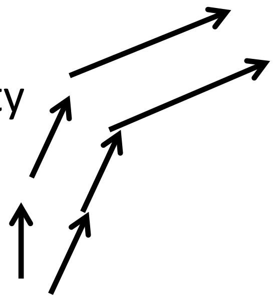
Heterogeneity in wind field



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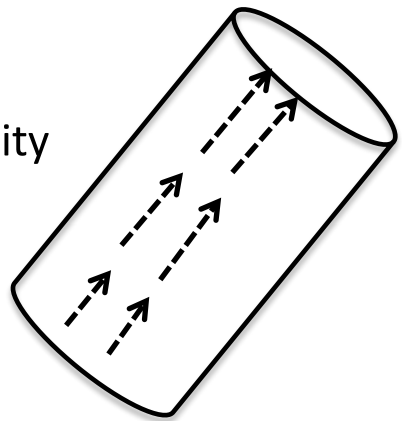
Heterogeneity along LOS direction



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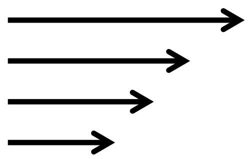
Lidar measurements of vertical wind shear



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
  - Use knowledge of lidar measurement process
  - 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.**

Questions and comments to:
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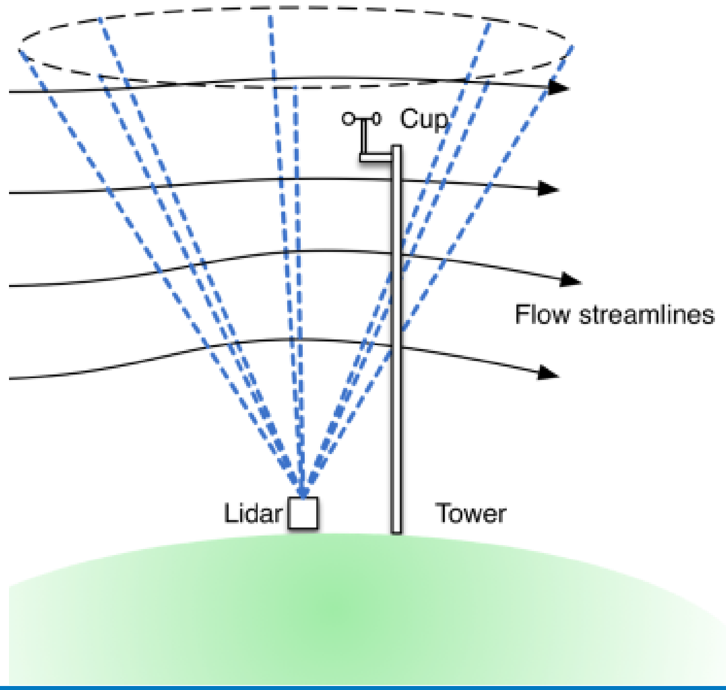
Andrew Clifton, andrew.clifton@nrel.gov

Apply the Model

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



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Let's talk!

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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*