



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

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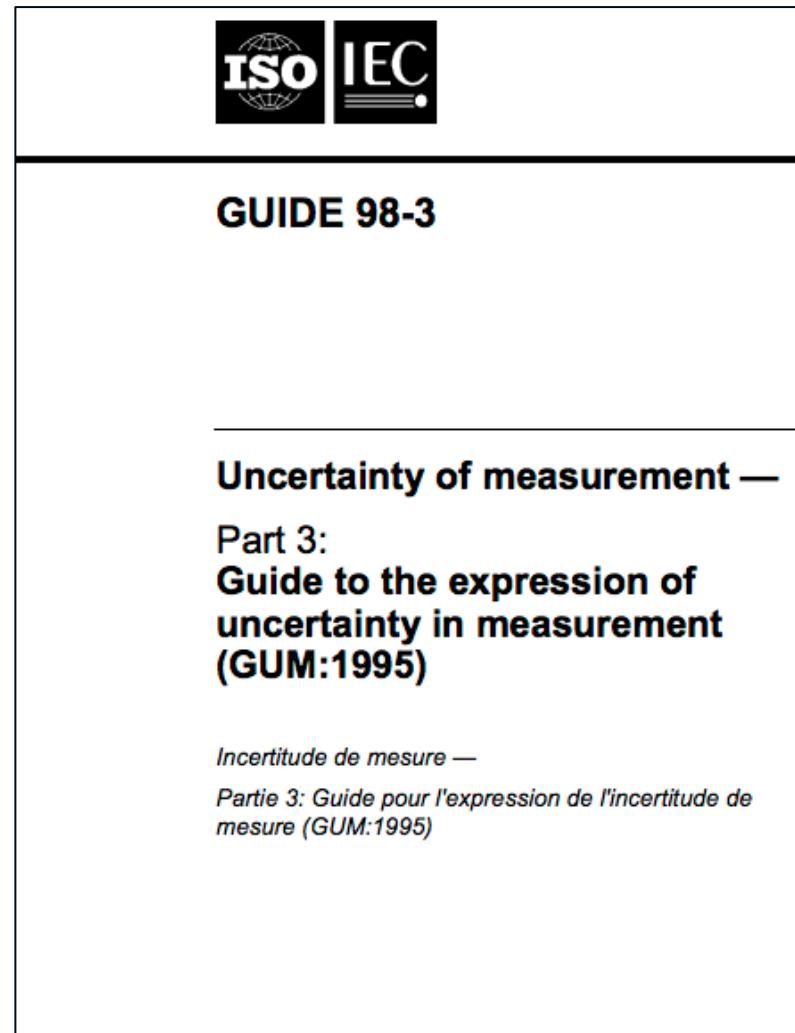
NREL/PR-5000-67642

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:

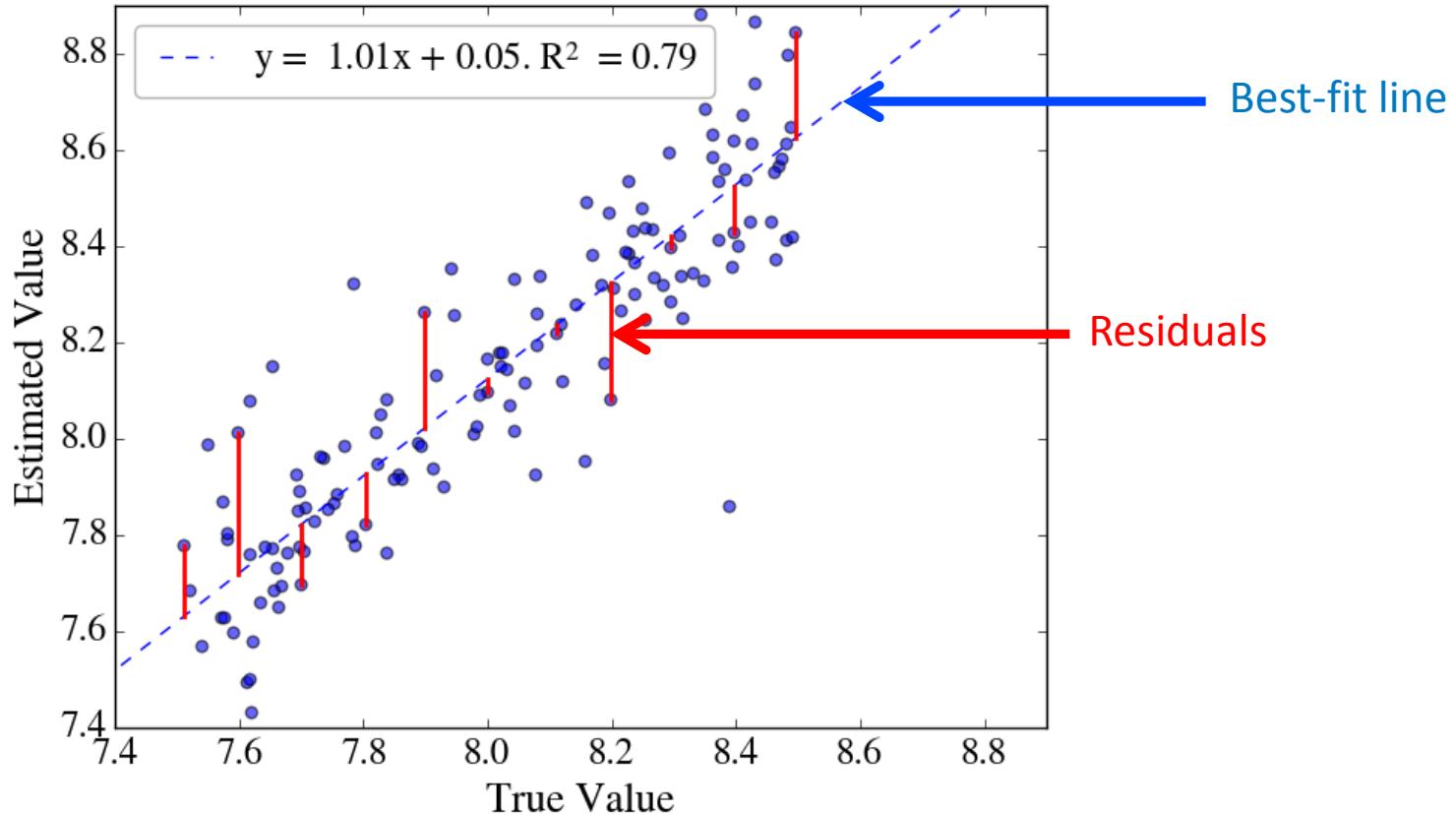
Doubt about the validity of a measured quantity.



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.

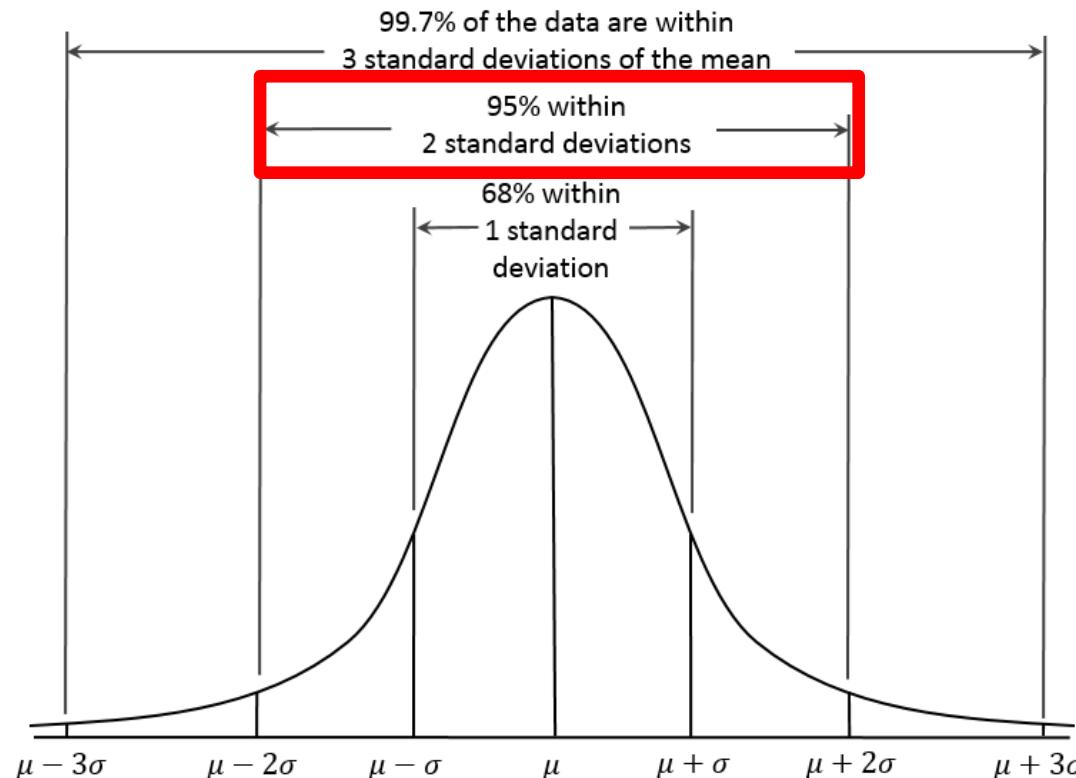
How Do We Quantify Uncertainty?

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



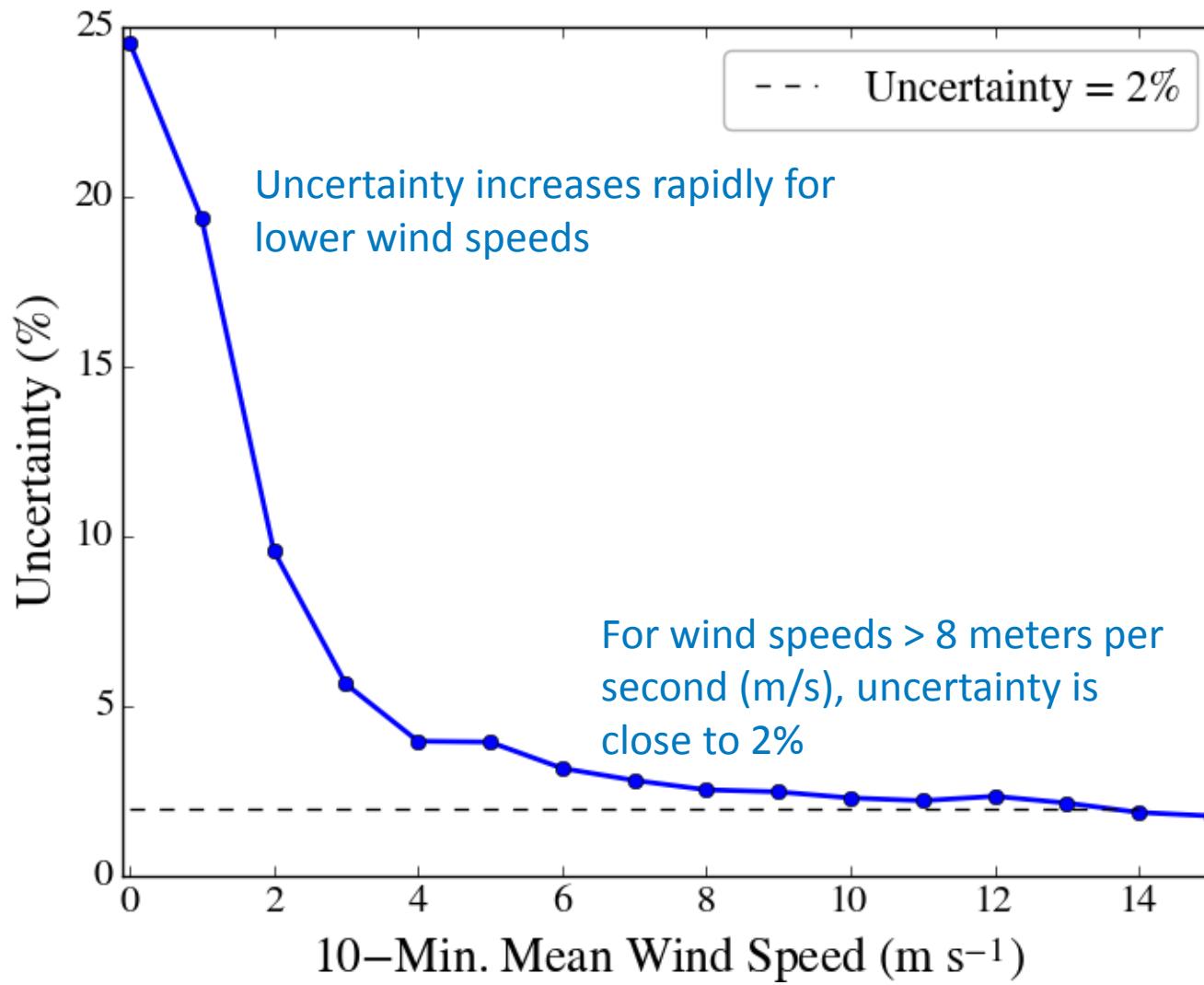
A Statistical Look at Uncertainty

- 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.



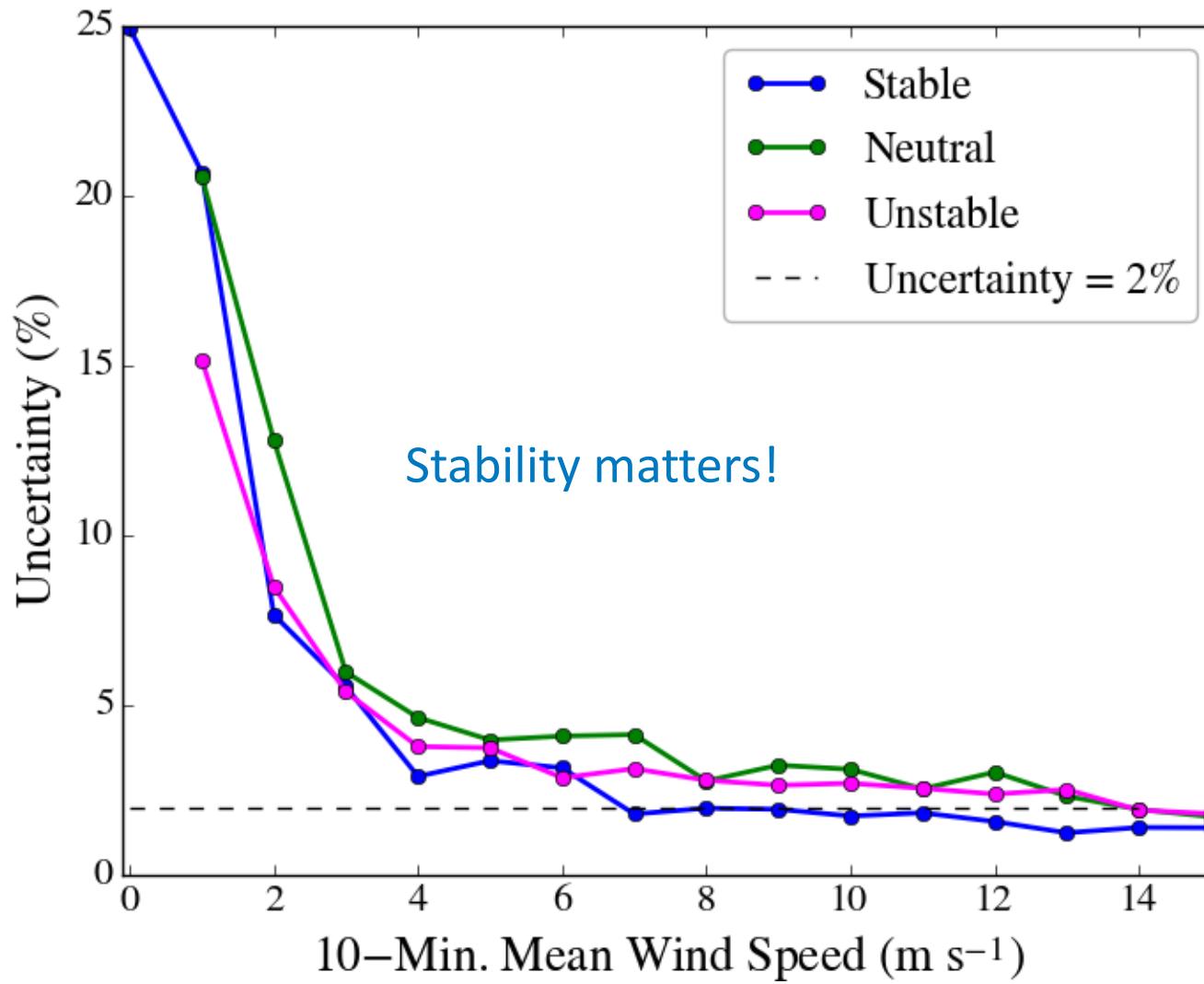
Source: Dan Kernler - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=36506025>

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

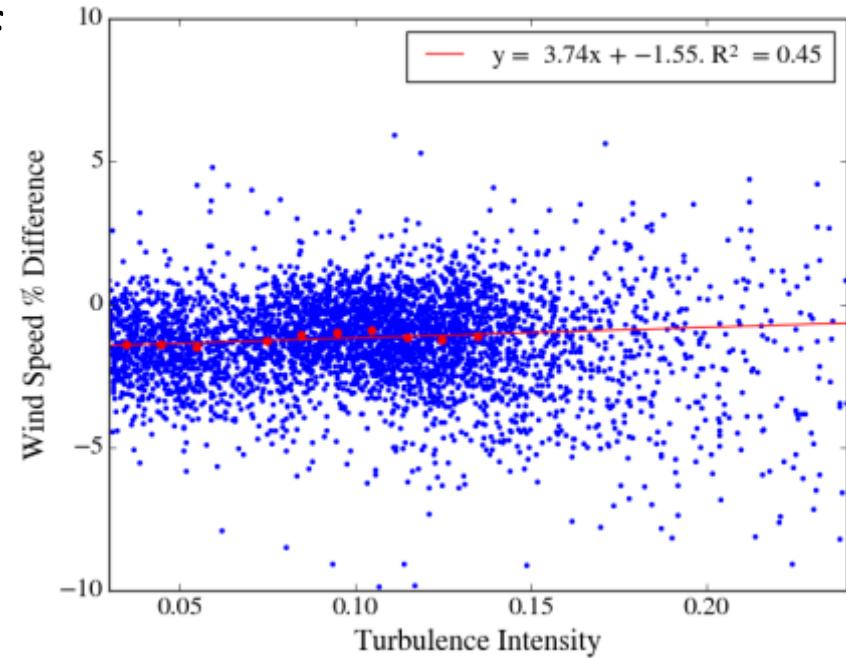
- Estimate uncertainty due to:
 - Calibration
 - Classification
 - Nonhomogeneous flow within probe volume
 - Mounting effects
 - Variation in flow across site
- Assume that:
 - Uncertainty components are independent of one another
 - Components can be added in quadrature
 - **Total uncertainty is a 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.



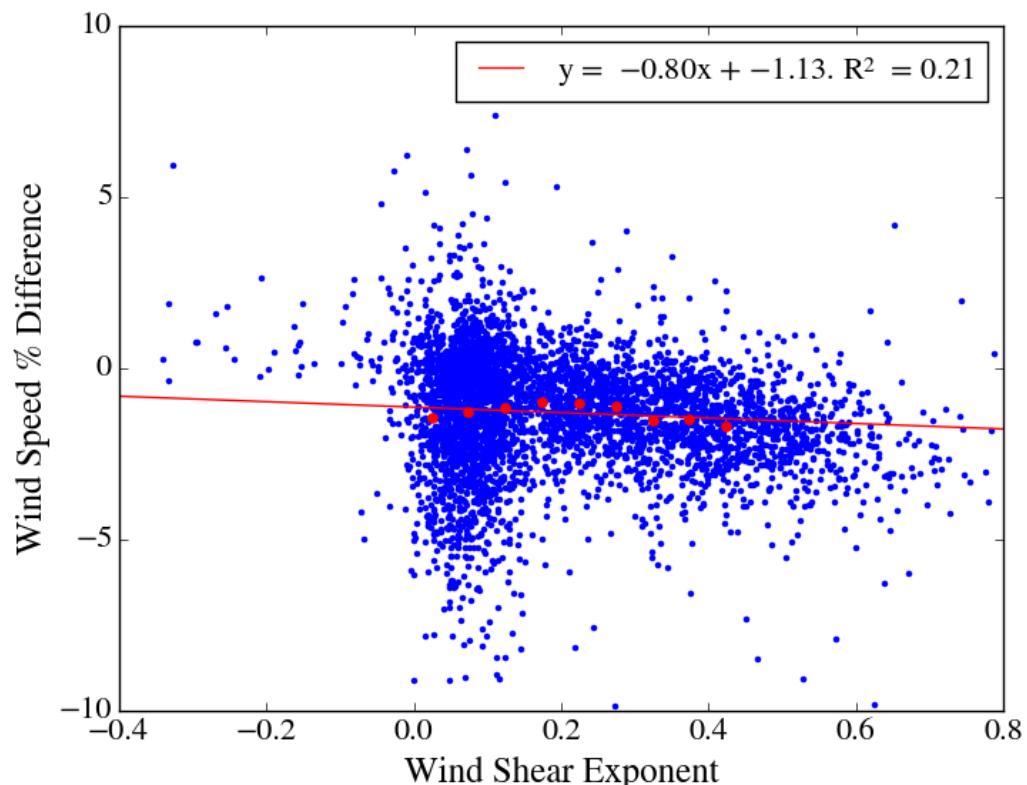
Data from 80 m AGL at Southern Plains wind farm

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.



Data from 80 m AGL at Southern Plains wind farm

Brainstorming an Uncertainty Framework

author → L10x merged

<u>Predictors</u>	<u>Predictand</u>
T_i (corrected) [-]	T_i [-] $\leftarrow \frac{\sigma_u}{\cup} \frac{[LT^{-1}]}{[LT^{-1}]}$
α [-]	
SNR_{ws} [-]	
$(\sigma_w)^2$ $[L^2 T^{-2}]$	
spectral broadening $[LT^{-1}]$	
internal temp [K]	
off-nadir pitch of lidar [-]	
Scanning circle ϕ [L]	

WGS?

ult. so far?
to base?

"Characteristic scales"

timescale = ϕ / \cup ← correlation
 " = integral timescale ← T_i correlation
 " = $1 / (\sigma_w)$

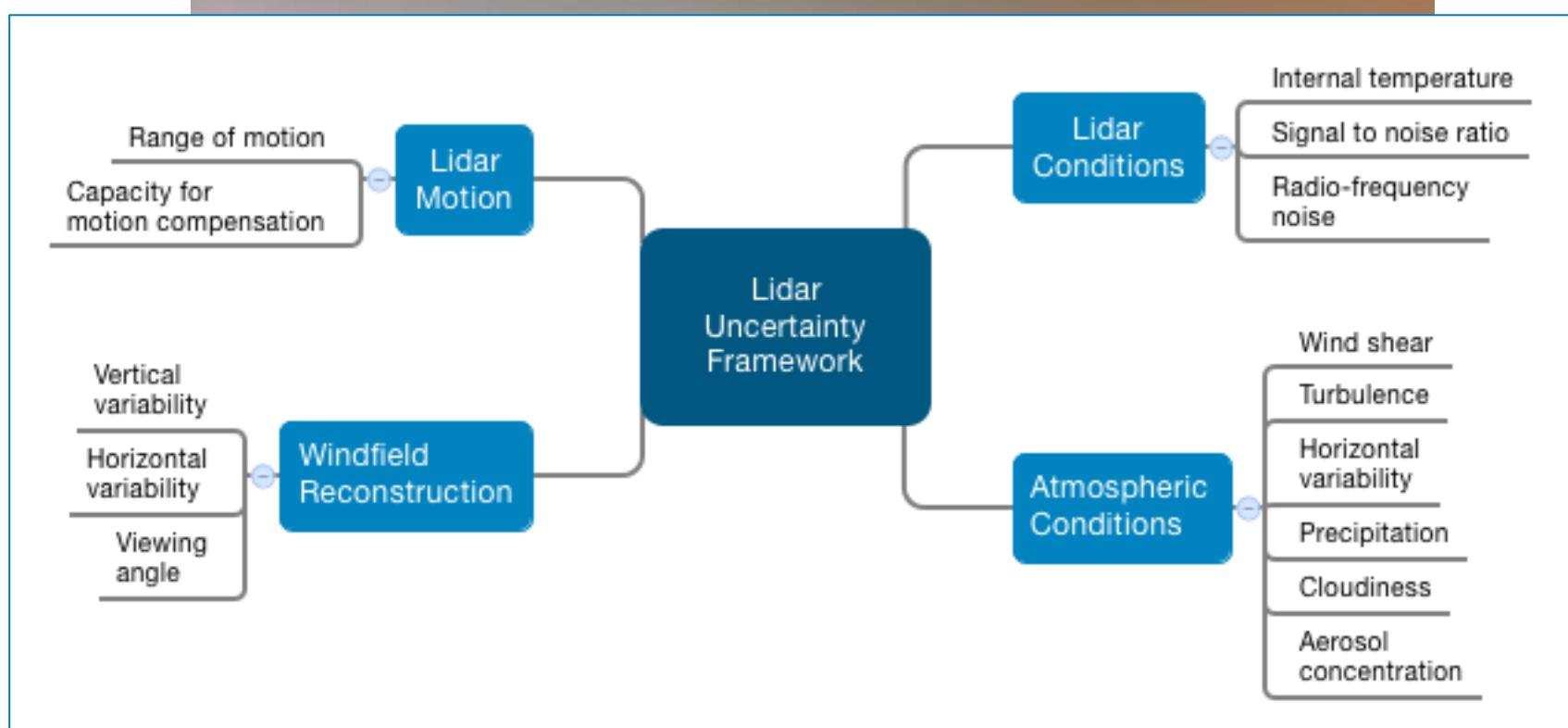
long scale - integral
 - ϕ
 - integral / ϕ
 - probe length (FWHM)
 $(\sigma_w)^2$ $\frac{L^2}{L^2 T^2}$

- α : core angle
 off-nadir angle

System performance - SNR
 - internal temp

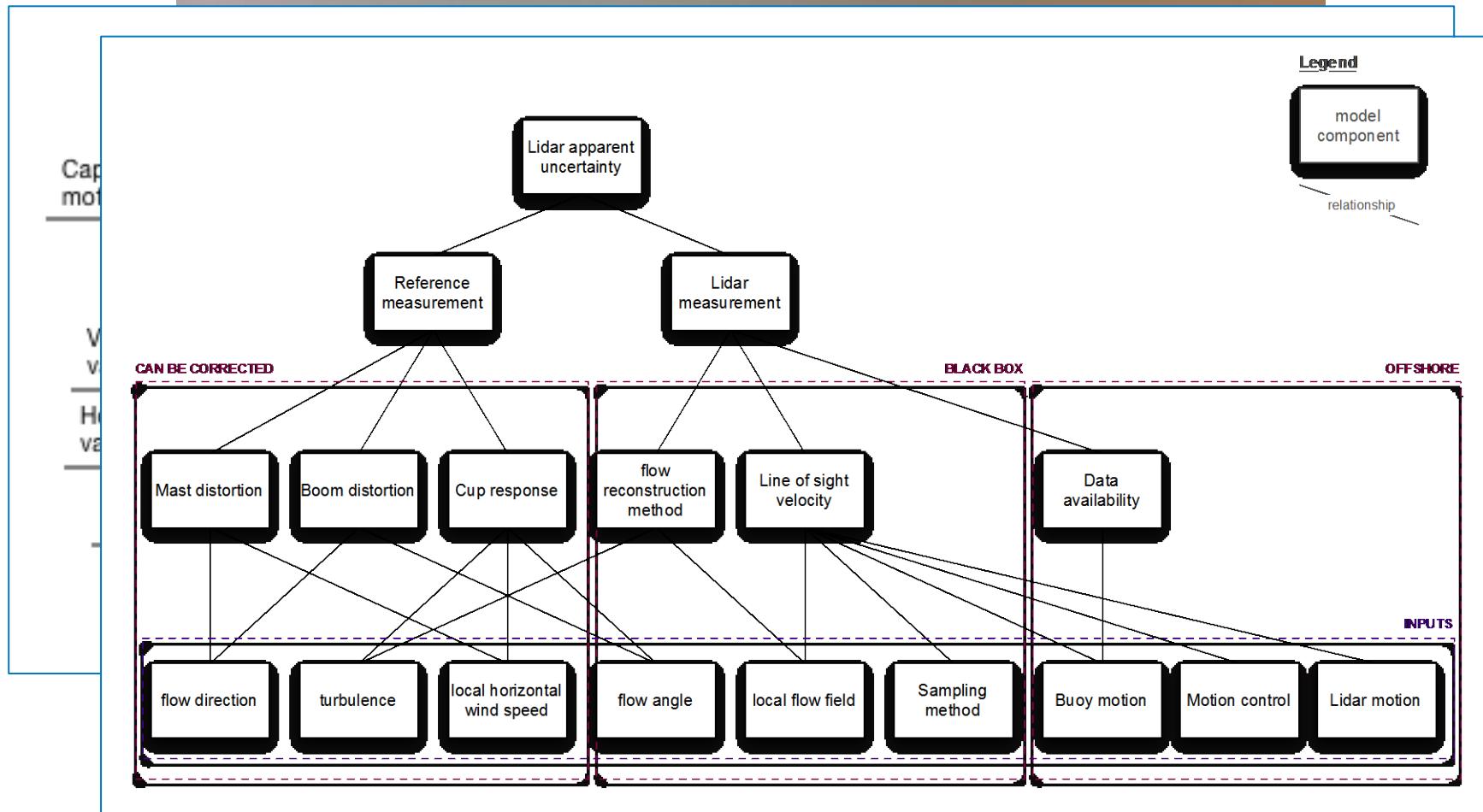
Variance - σ_w
 spectral broadening

Brainstorming an Uncertainty Framework



Brainstorming an Uncertainty Framework

Uncertainty → Lidar apparent uncertainty



Brainstorming an Uncertainty Framework

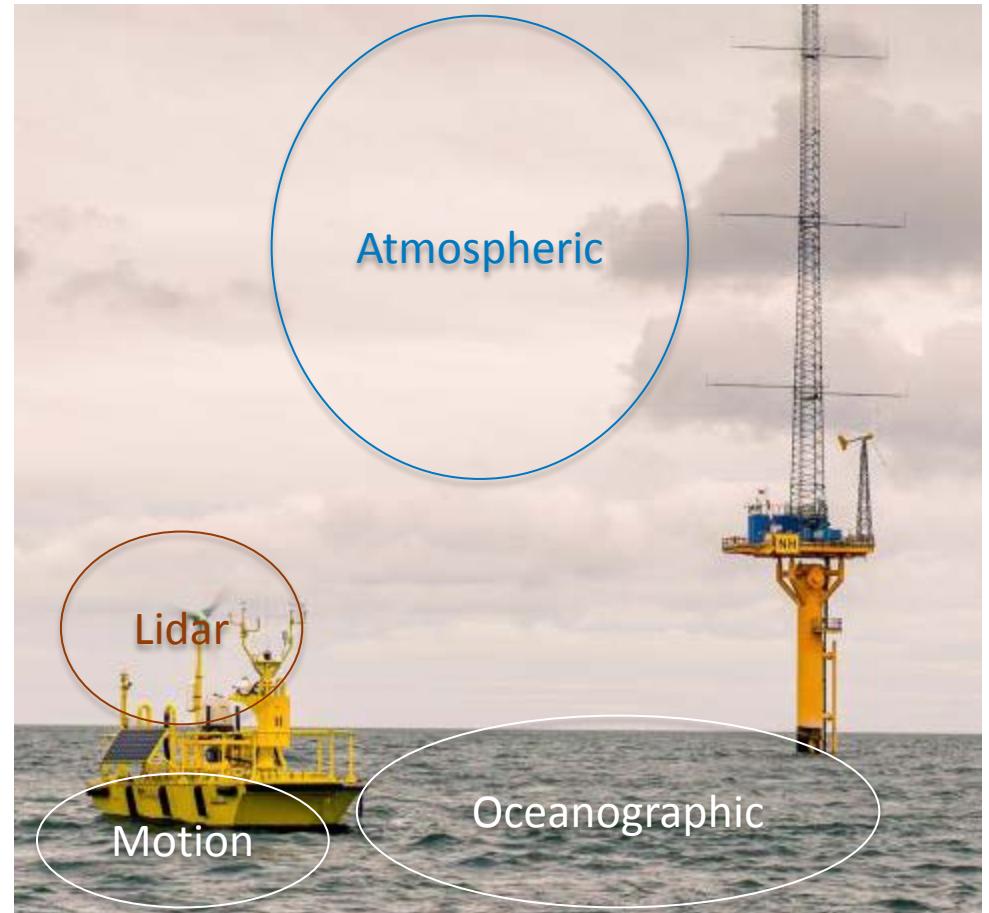
SB = Spectral Backscattering
CD = Centroid detection

High level Category	Physical Biases	How interest fits in the Uncertainty Framework		Available in ad-hoc Observation	Available in ad-hoc Proxys
		Observation	Proxy		
LOS = FOF centroid detection	<ul style="list-style-type: none"> Probe length (SB, CD) Aerosol distribution (SB) Lidar noise (SB) Backscatter & Signal strength (SB) SNR 	<ul style="list-style-type: none"> Lidars Atmosphere Lidar Lidar 	<ul style="list-style-type: none"> FWHM(z) 	<ul style="list-style-type: none"> SNR internal temperature, SNR Range, aerosol, light scattering? 	
Mast distortion Windfield reconstruction (Algorithmic off)	<ul style="list-style-type: none"> Assumed homogeneity Lidar Range/cont. Pointing accuracy Assumed shadowing 	<ul style="list-style-type: none"> Atmospheric $\sqrt{(\partial U/\partial x)^2 + (\partial U/\partial z)^2}$ Motion 	<ul style="list-style-type: none"> Vertical start T 	<ul style="list-style-type: none"> Variability across scanning circle 	<ul style="list-style-type: none"> Snowdrift Pitch, roll, yaw
flow direction			Pointing accuracy		Shifting

The diagram illustrates the 'Windfield reconstruction (Algorithmic off)' process. It shows a mast distortion component at the top, followed by a flow direction component at the bottom. These components are part of a larger system labeled 'Windfield reconstruction (Algorithmic off)'. A dashed red box highlights the 'CAN BE CORRECTED' area, which includes the mast distortion and flow direction components.

What's an Uncertainty Framework?

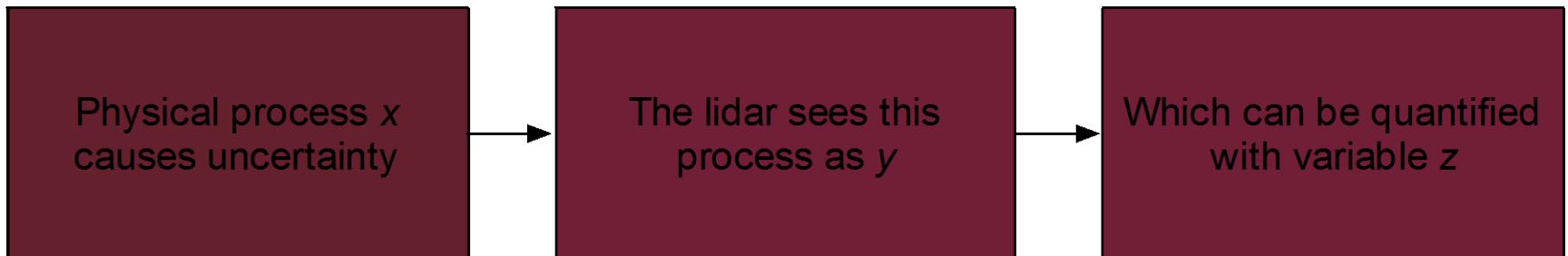
- Assign all sources of uncertainties to clear categories
- Create models for each of them
 - Physics or data-driven
- Apply them to every measurement.



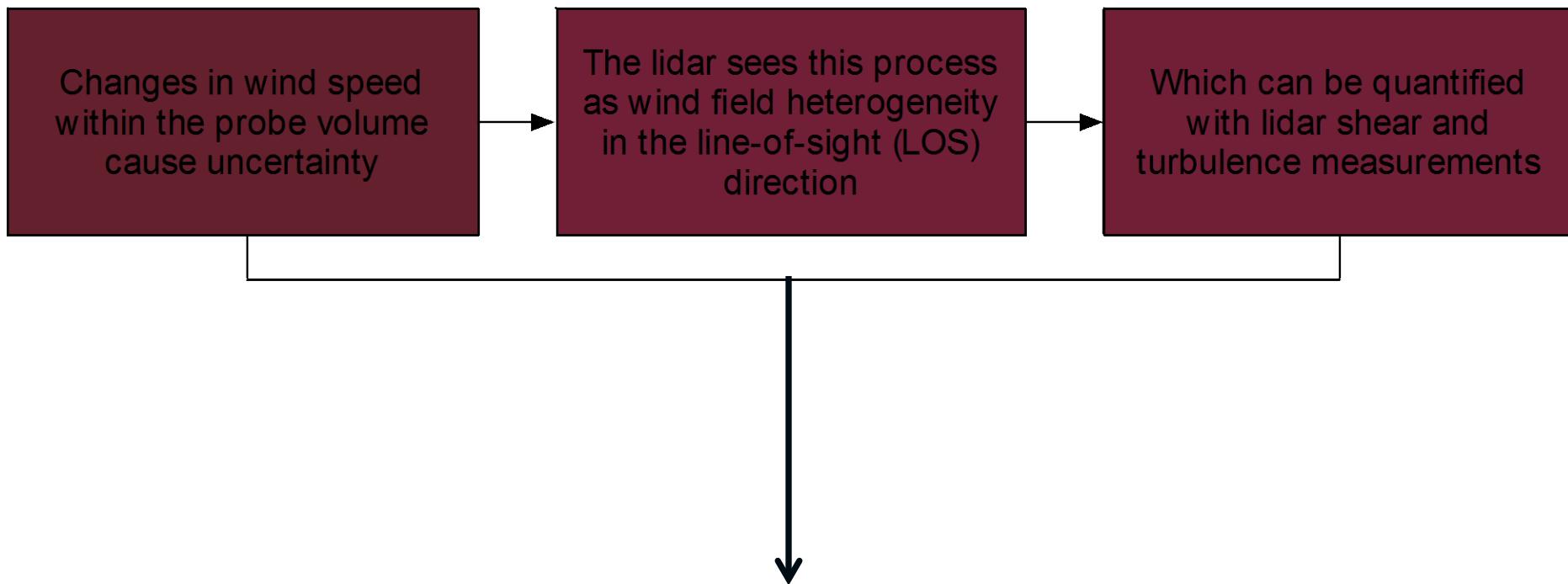
AXYS FLiDAR 6-meter buoy. Photo from AXYS Technologies

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.

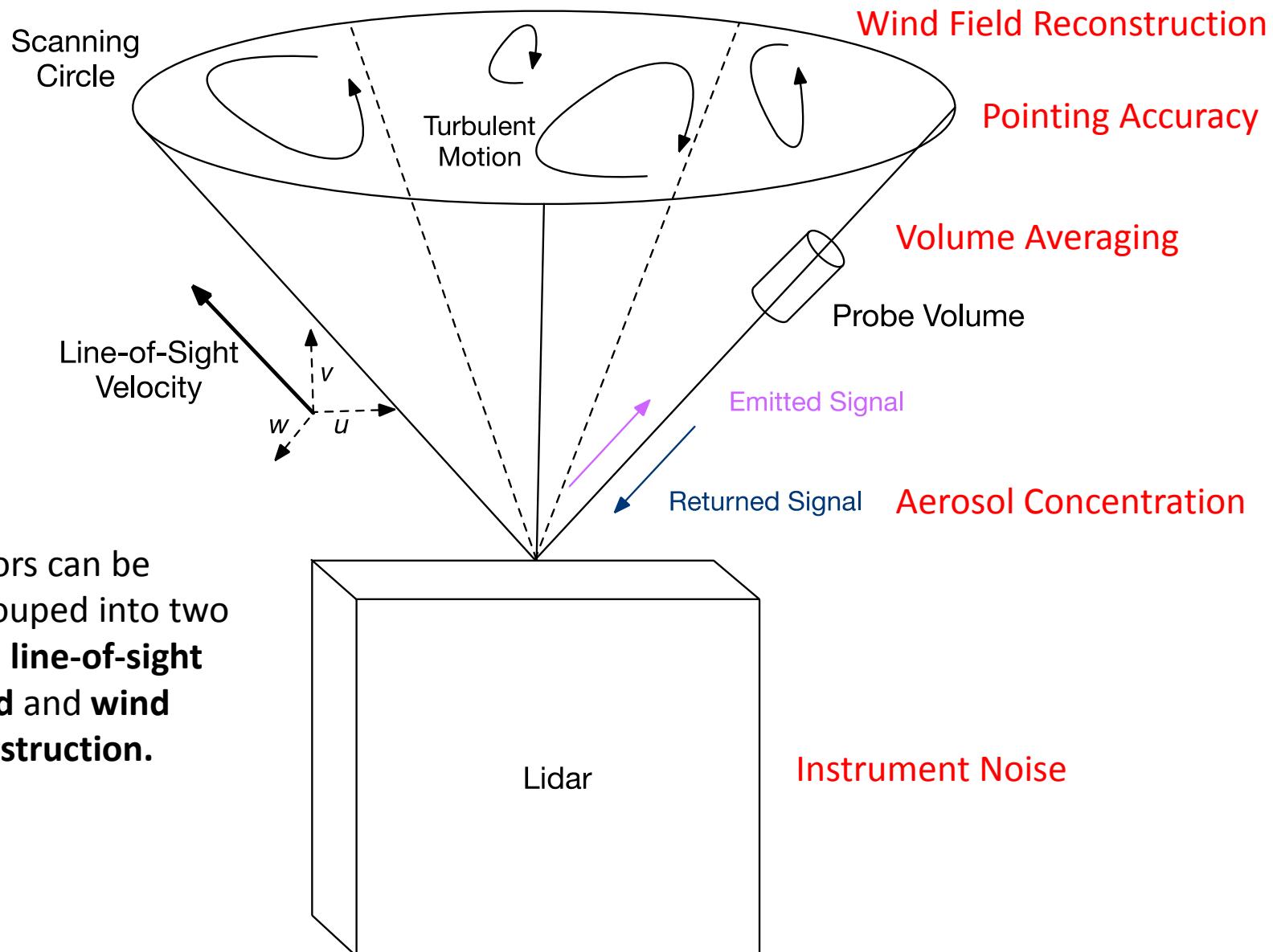


Example: Wind Shear



The key of the framework is figuring out this relationship.

Factors That Affect Uncertainty



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?

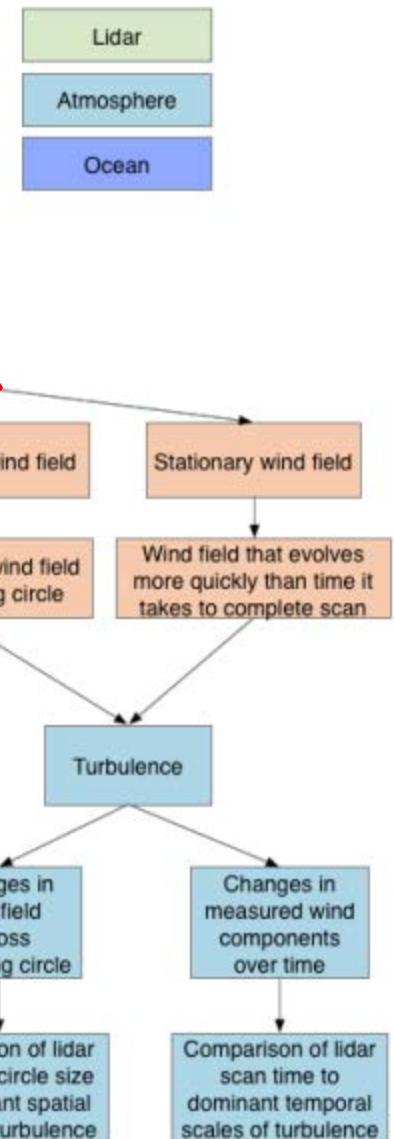
What is the ideal measurement case?

What causes deviations from the ideal case?

What is the physical basis of these effects?

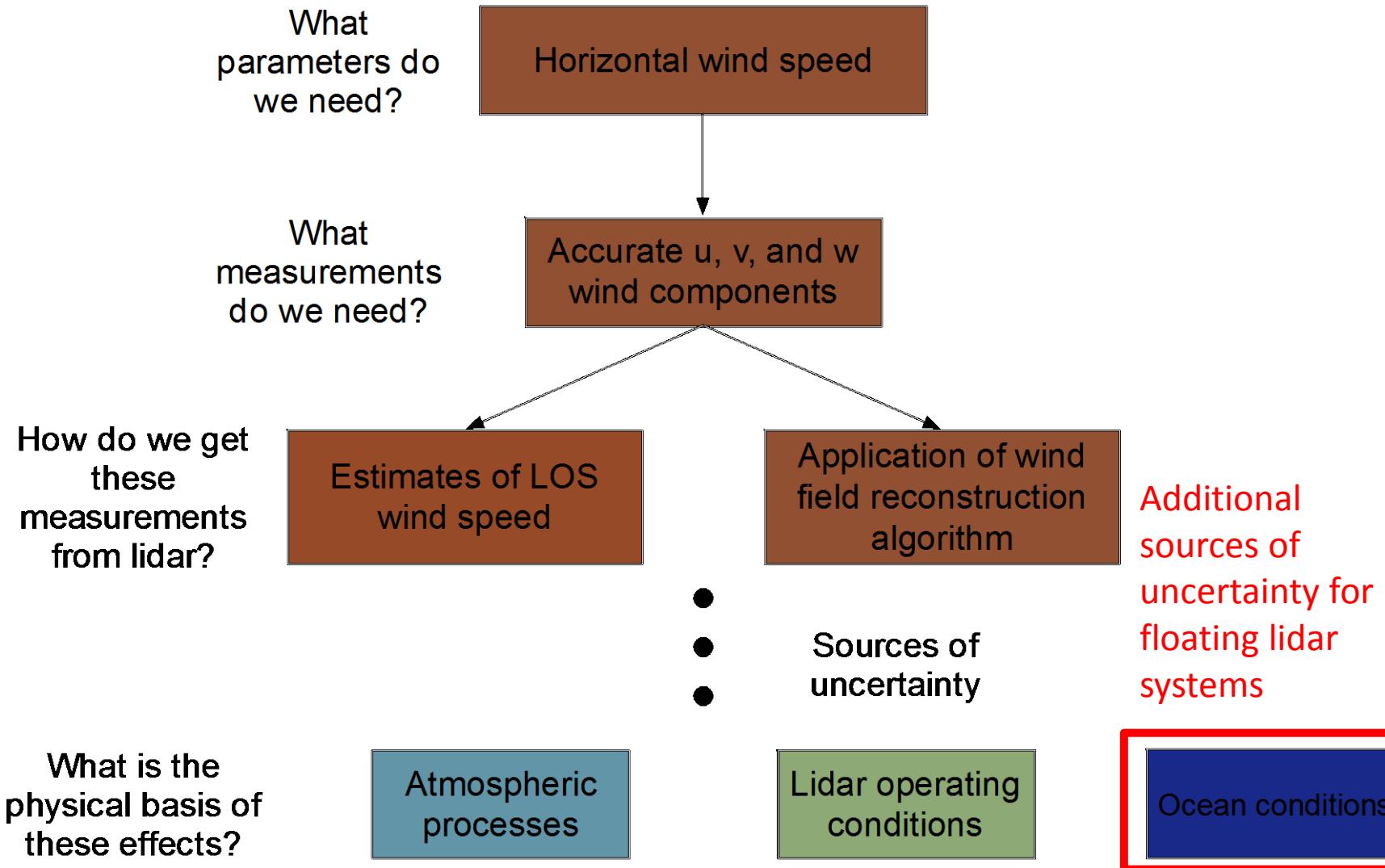
How does the lidar see these effects?

How can we quantify these effects?



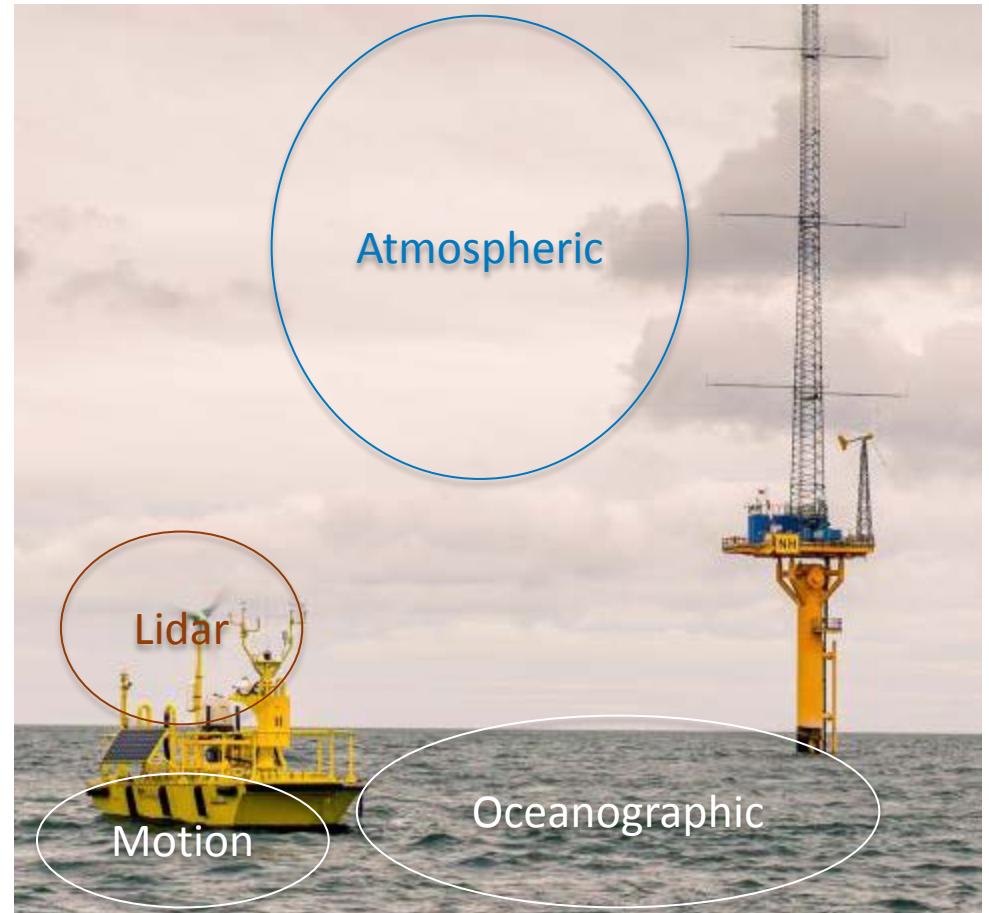
PRELIMINARY EXAMPLE ONLY

Simplified Framework



What's an Uncertainty Framework?

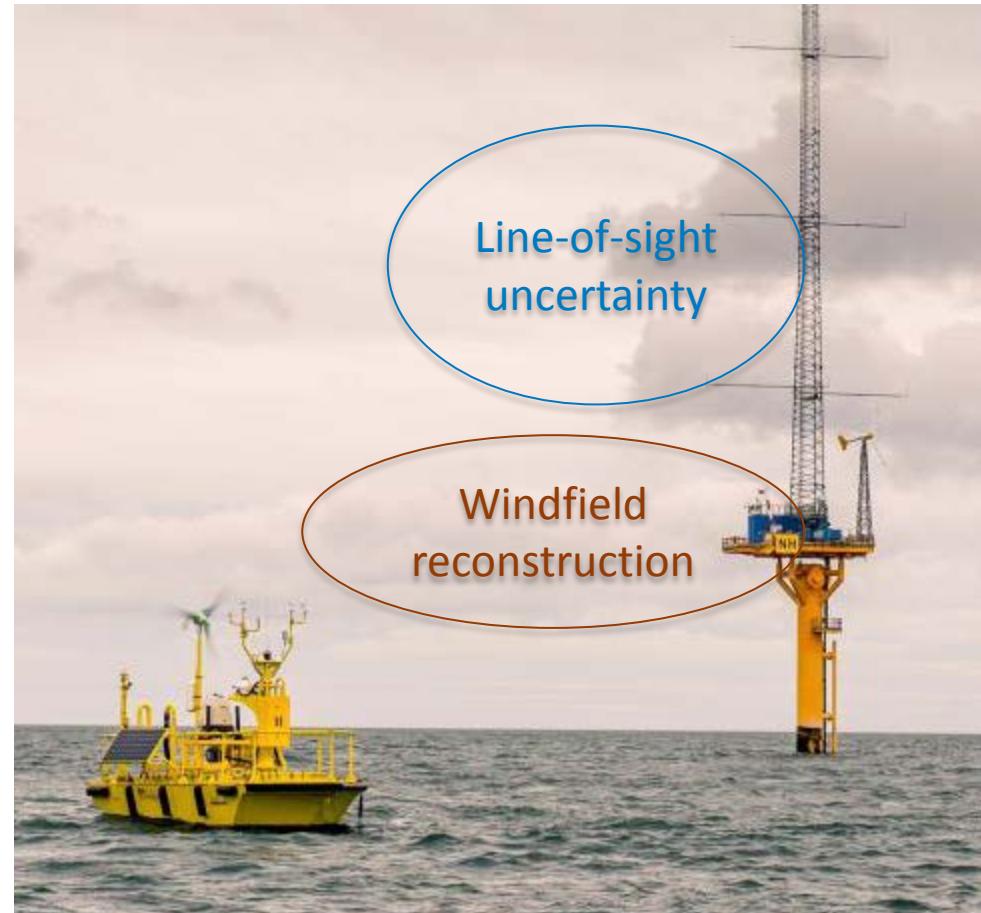
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AXYS FLiDAR 6-m buoy. Photo from AXYS Technologies

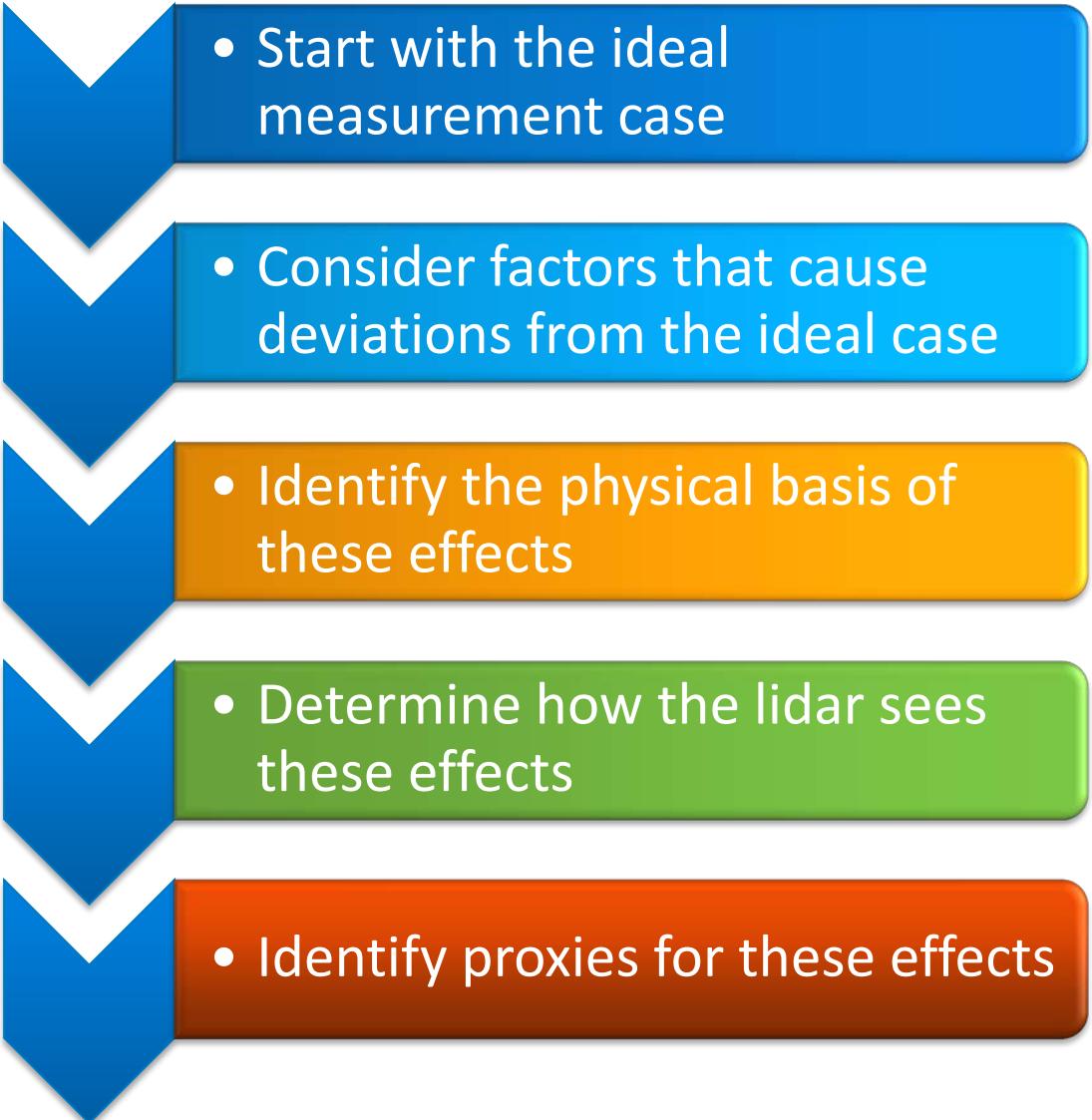
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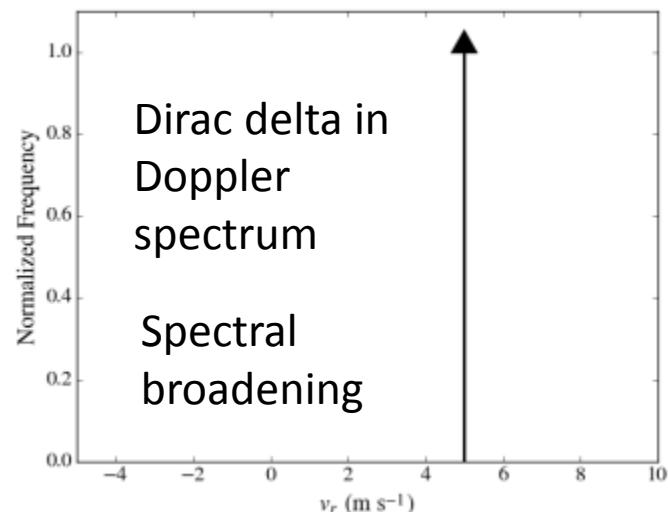
AXYS FLiDAR 6-m buoy. Photo from AXYS Technologies

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

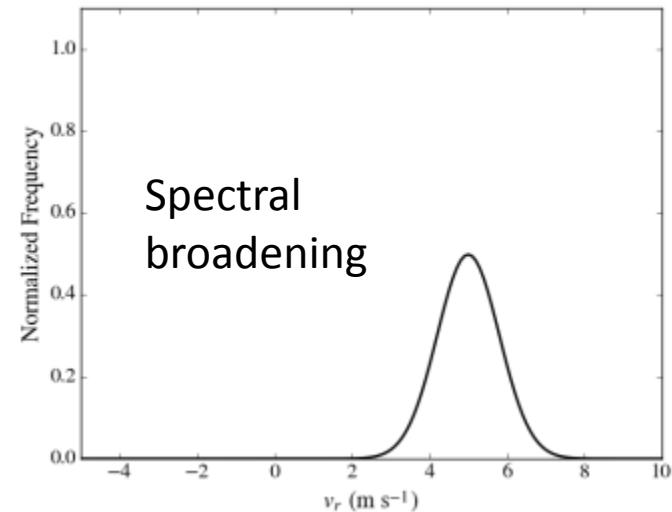
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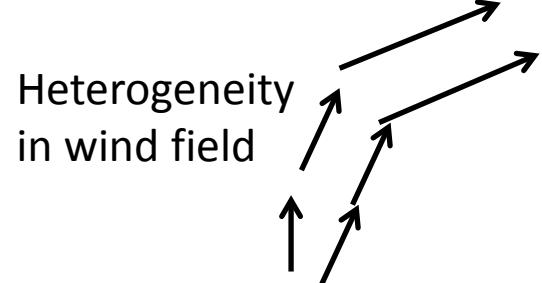
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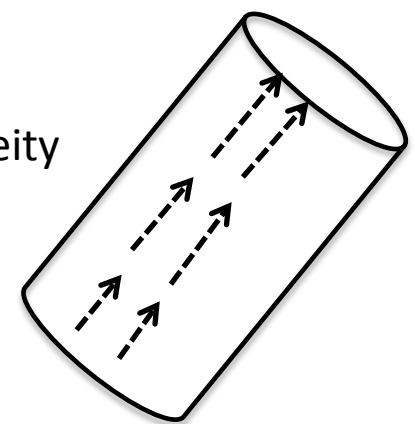
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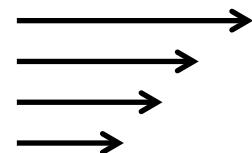
Heterogeneity along LOS direction



Workflow: Framework Development

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Lidar measurements
of vertical wind
shear



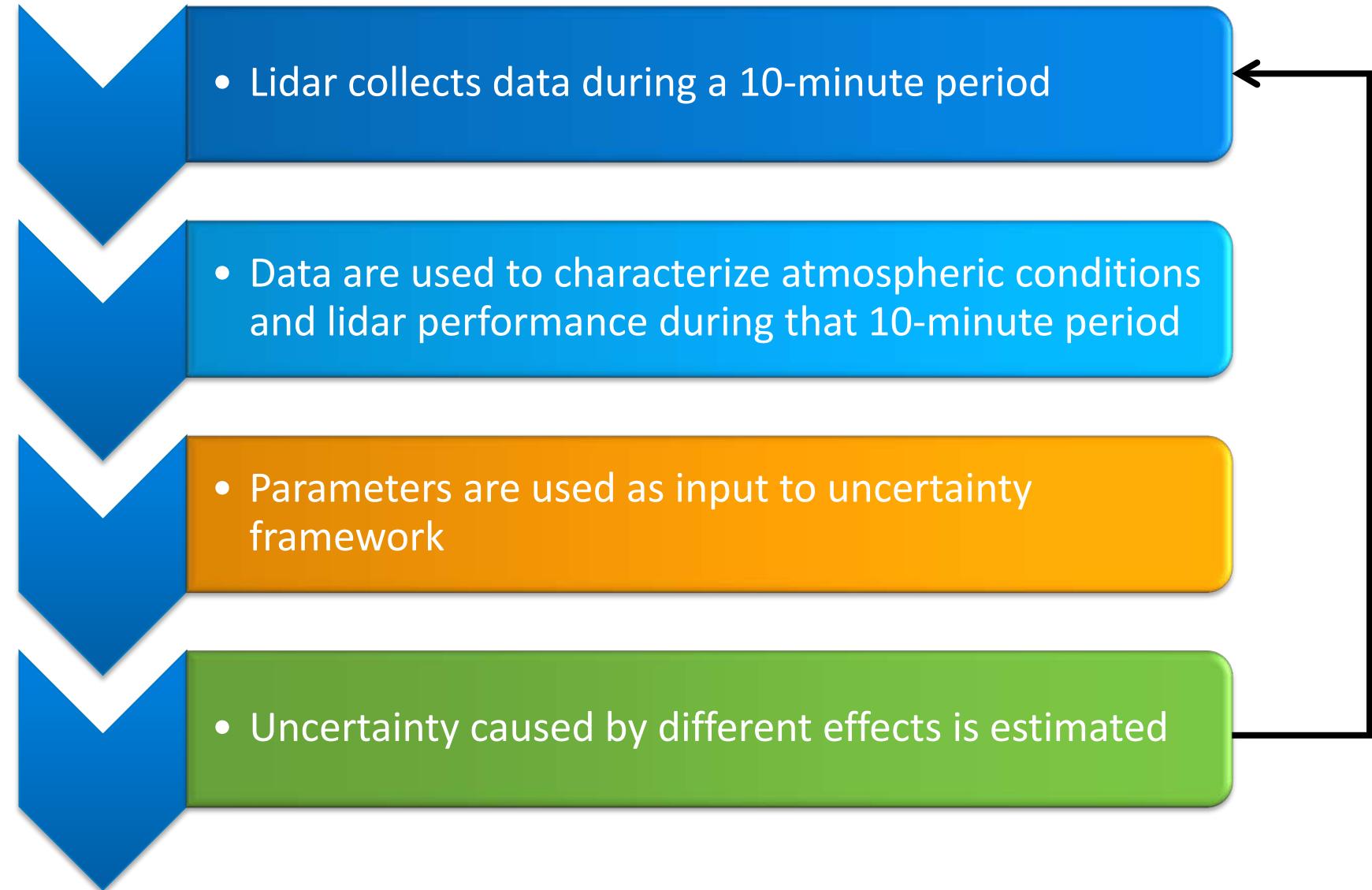
Workflow: Framework Application

- 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



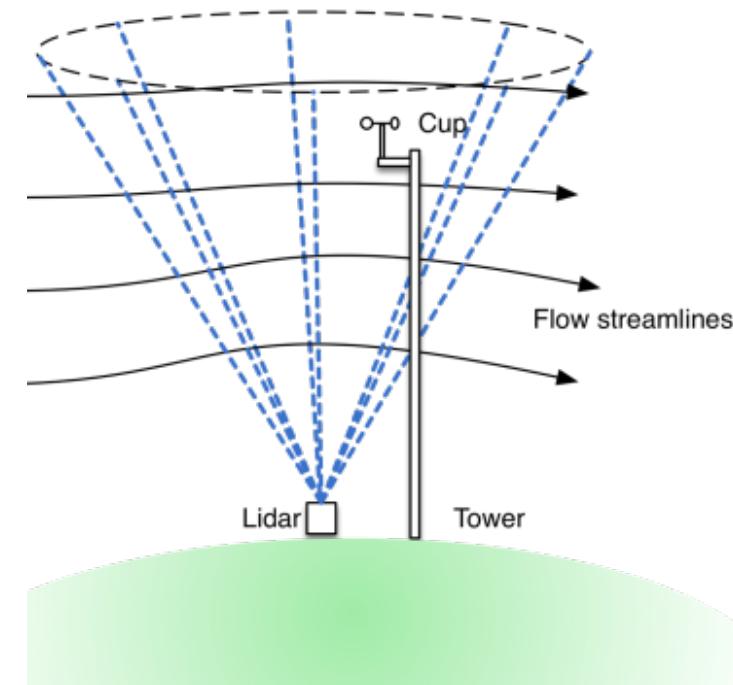
How to Move Beyond Climatic Uncertainty Values

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.**

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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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*