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Development of a Dynamic Lidar Uncertainty Framework

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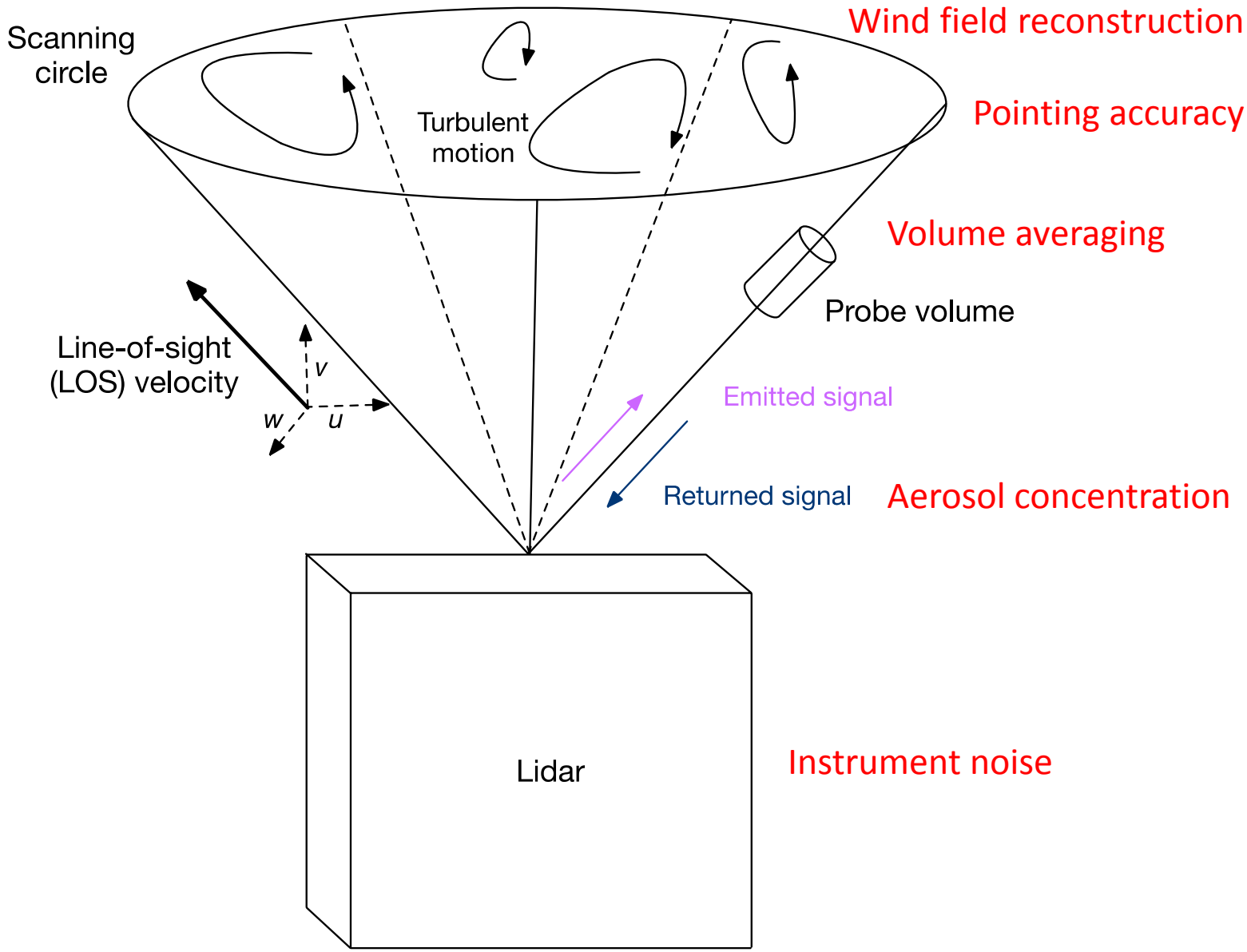
Factors That Affect Uncertainty



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

Estimate uncertainty resulting from:

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

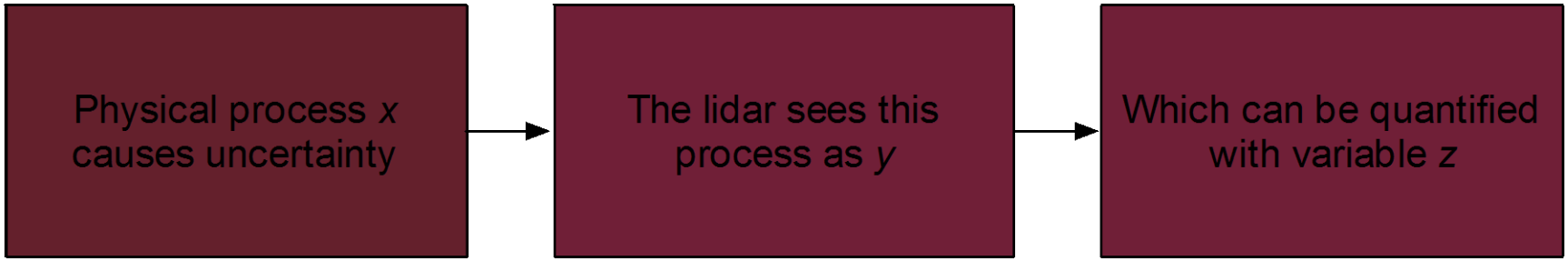
Limitations:

- 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

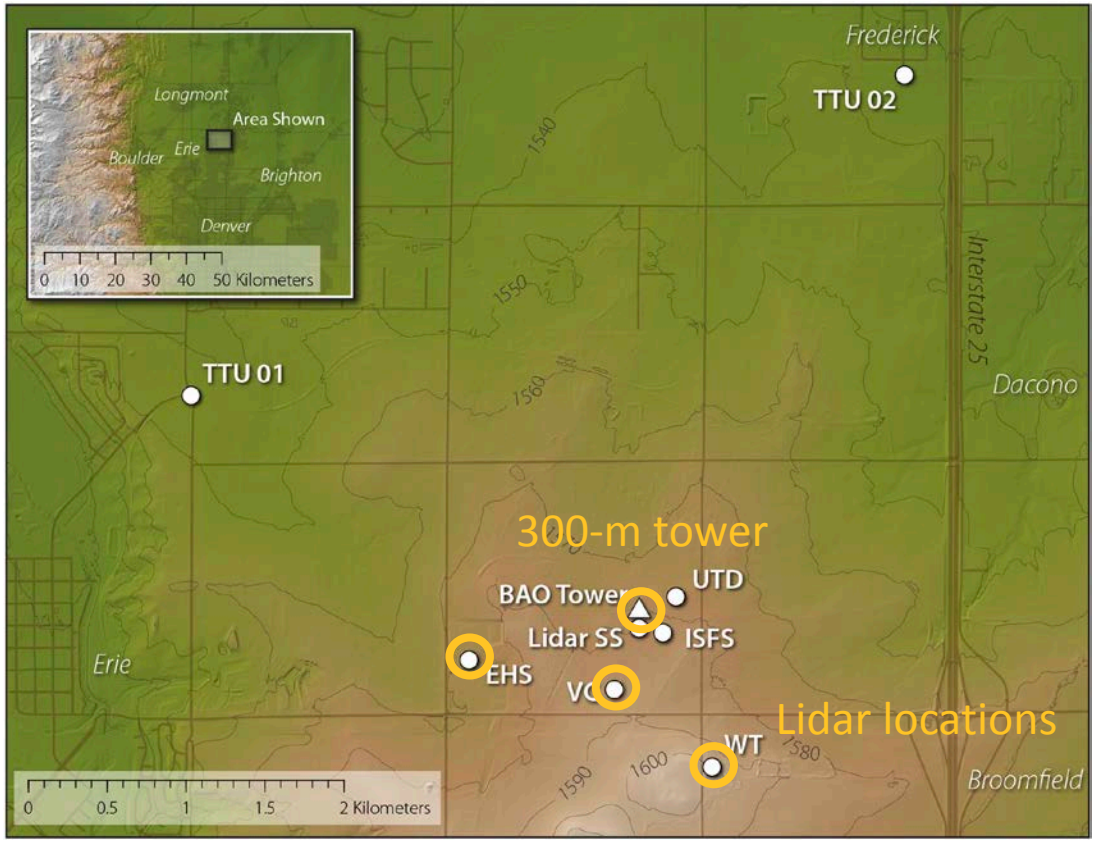
New Uncertainty Framework

- 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)



From Lundquist et al. (2017)

Lundquist, J.K., et al., 2017. Assessing state-of-the-art capabilities for probing the atmospheric boundary layer: the XPIA field campaign. *Bulletin of the American Meteorological Society*, doi: 10.1175/BAMS-D-15-00151.1.

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).

Photo by Aditya Choukulkar

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).

Frehlich, R., 2001: Estimation of velocity error for Doppler lidar measurements. *Journal of Atmospheric and Oceanic Technology*, 18, 1628–1639.

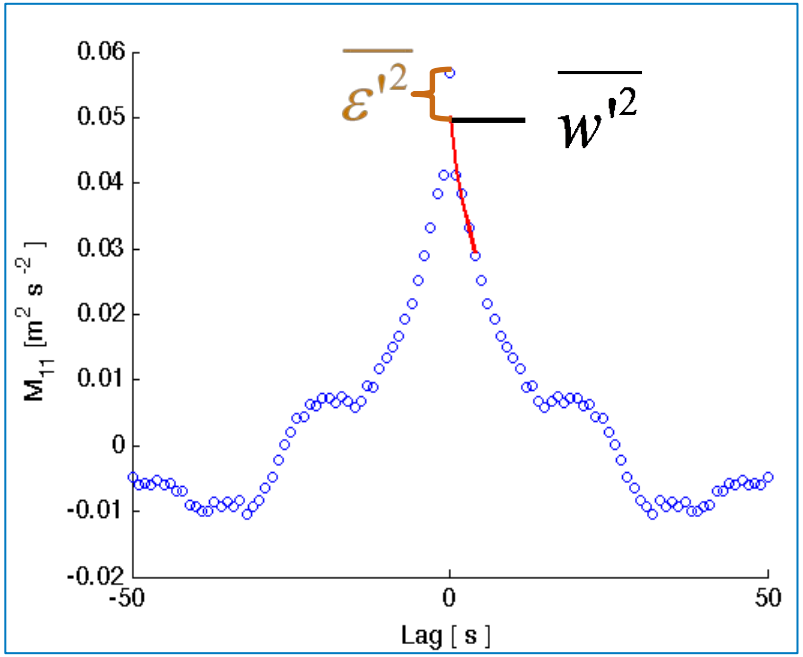
Physical Model: Estimation of Noise Uncertainty from Vertical Stares

- 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):

$$M_{11}(0) = \overline{q^2} + \overline{\epsilon^2}$$

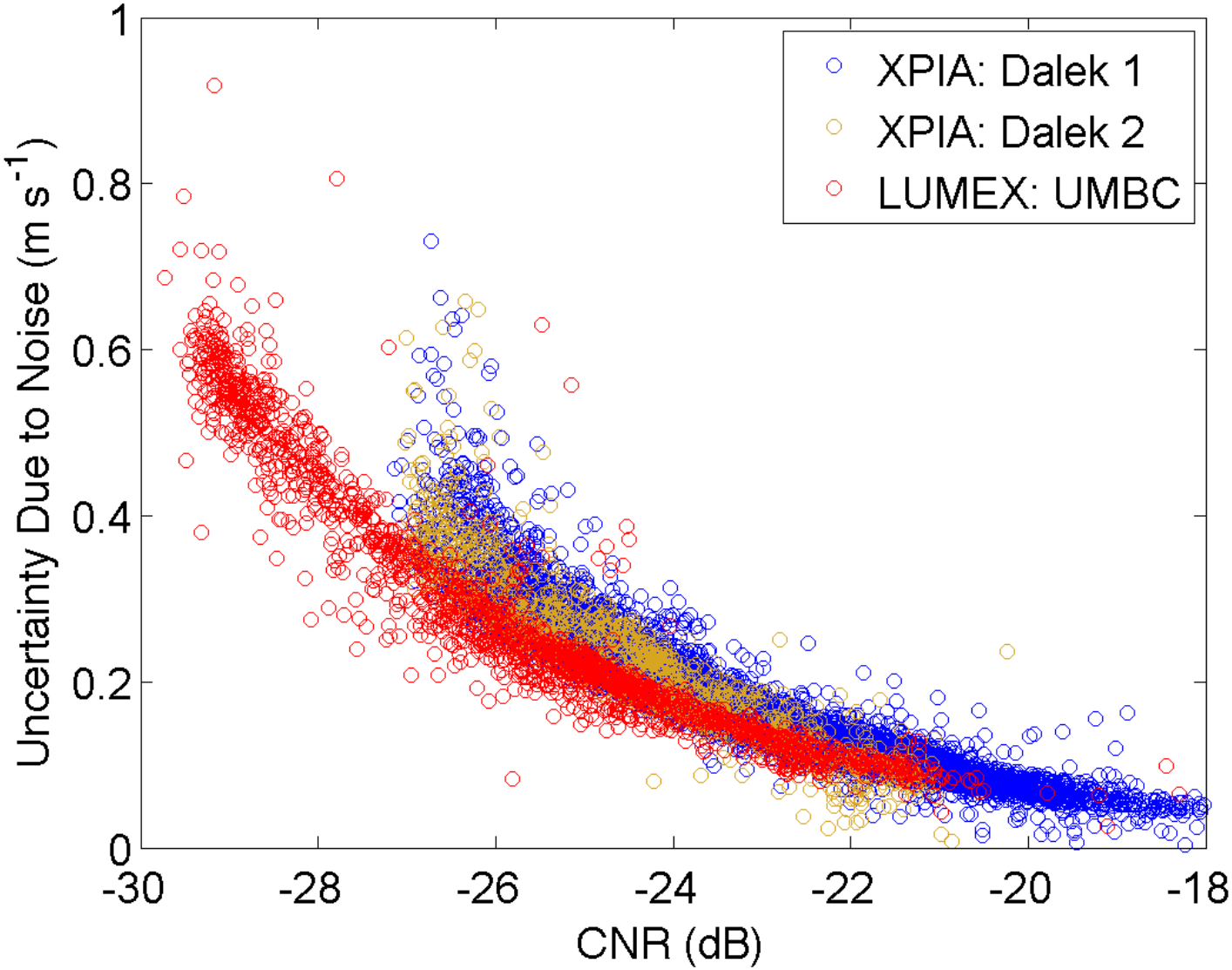
Variance of atmospheric signal — Variance due to noise

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

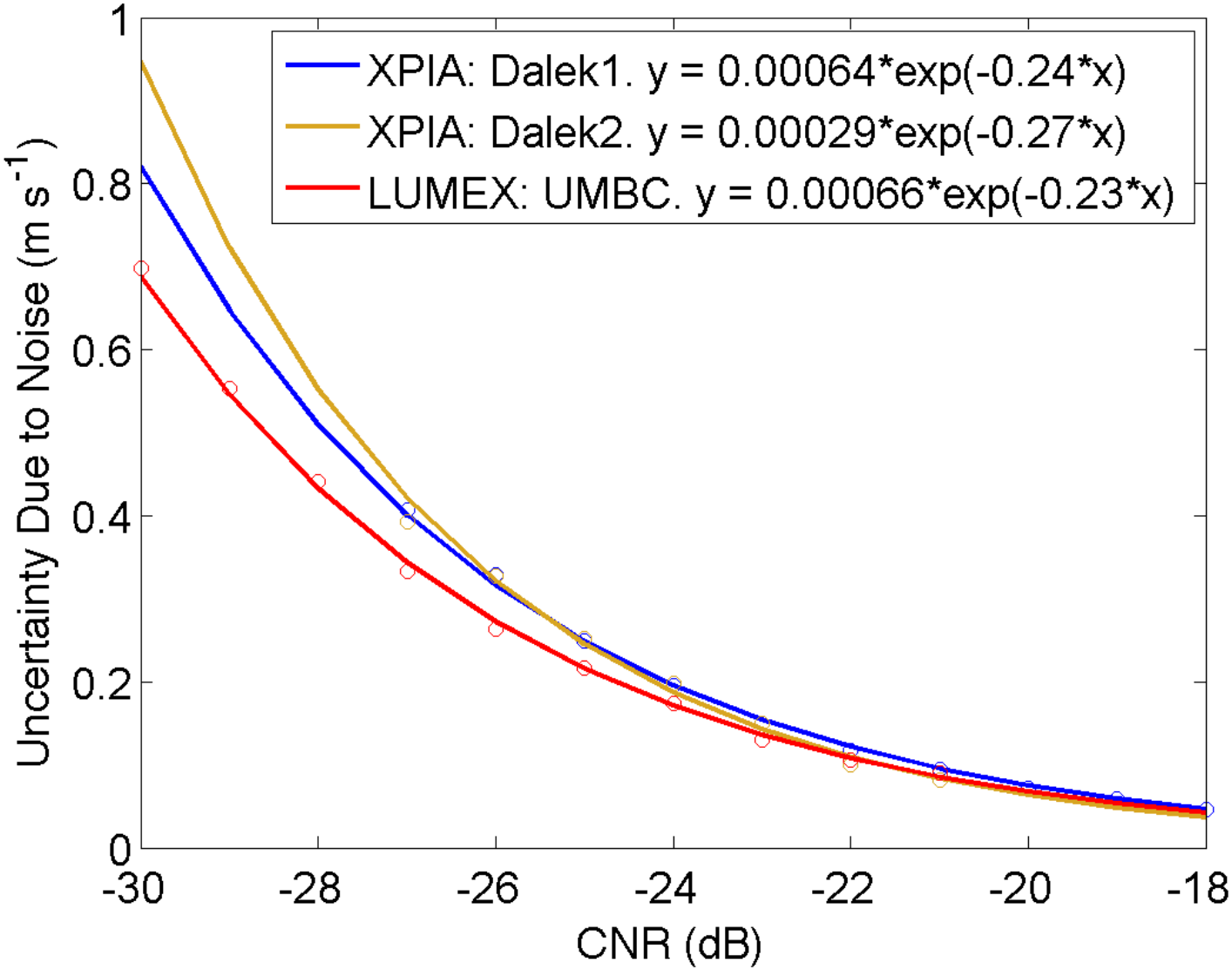


Lenschow, D.H., V. Wulfmeyer, and C. Senff, 2000: Measuring second-through fourth-order moments in noisy data. *Journal of Atmospheric and Oceanic Technology*, **17**, 1330–1347.

Noise Uncertainty as a Function of CNR



Noise Uncertainty as a Function of CNR

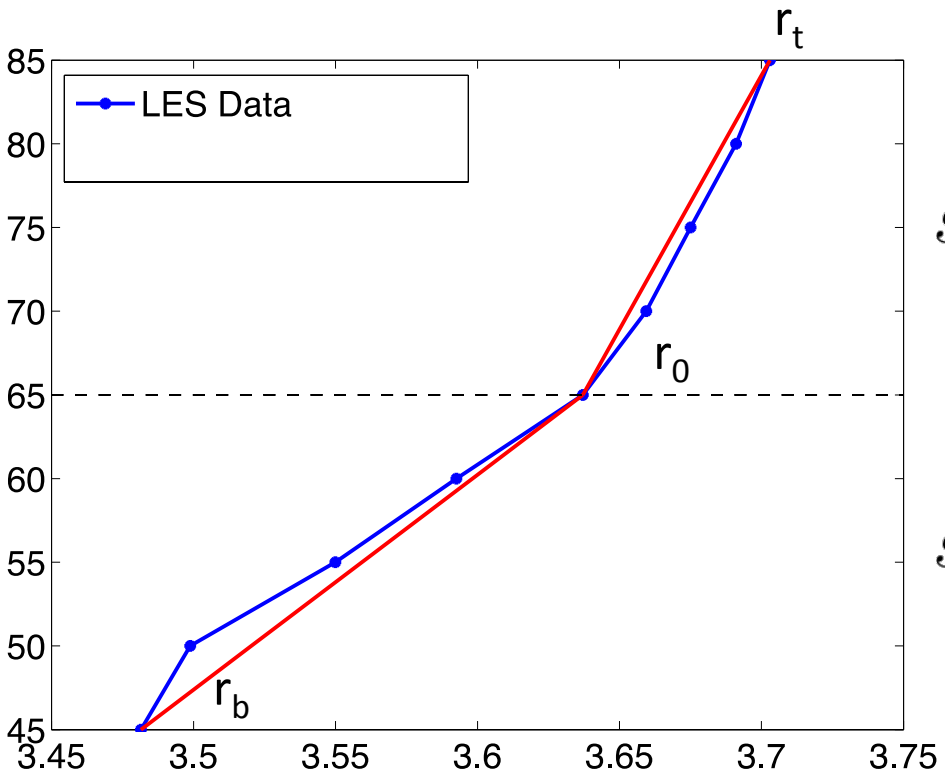


Data-Driven Model: Uncertainty Due to Volume Averaging

- 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



$$shear_t = \frac{V(r_t) - V_0}{r_t - r_0}$$

$$shear_b = \frac{V_0 - V(r_b)}{r_0 - r_b}$$

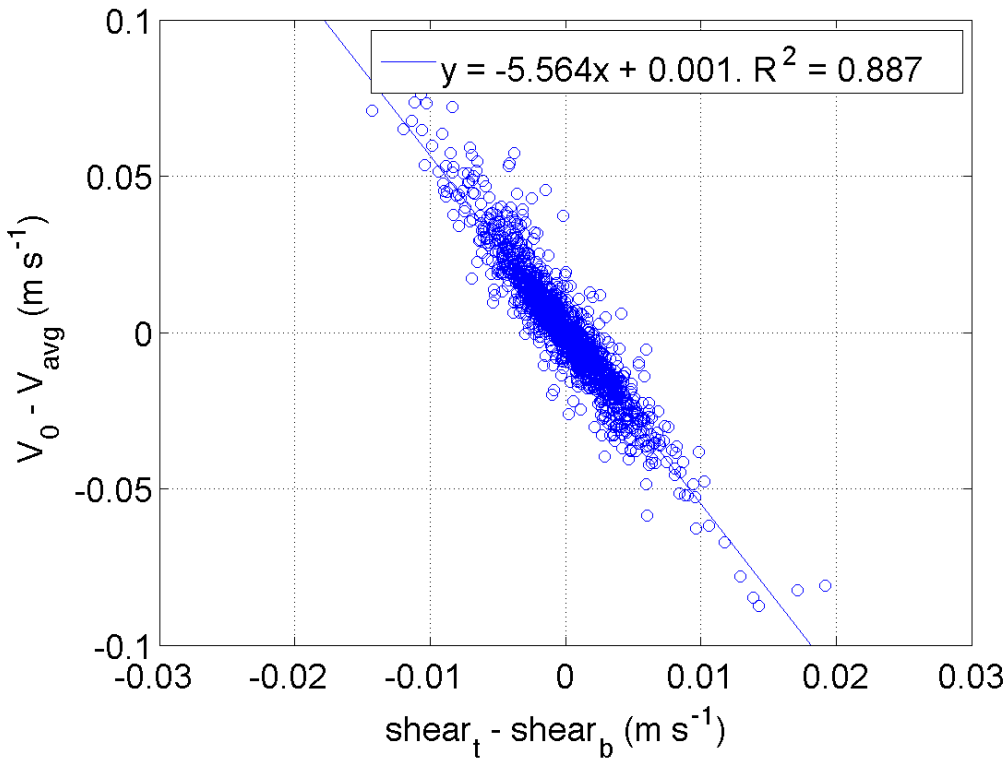
How Do Changes in Shear Relate to Volume Averaging Error?

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

Analytical expression (assuming uniform range-weighting)

$$V_0 - V_{avg} = -5.556(shear_t - shear_b)$$

Actual data from neutral and unstable LES runs



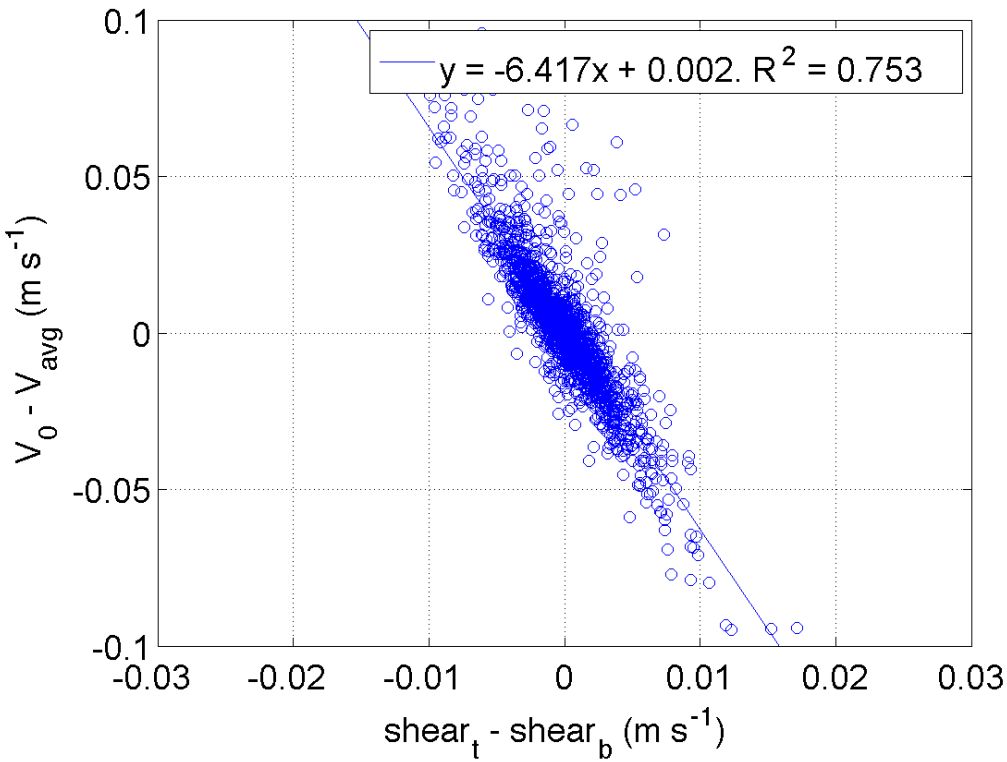
How Do Changes in Shear Relate to Volume Averaging Error?

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

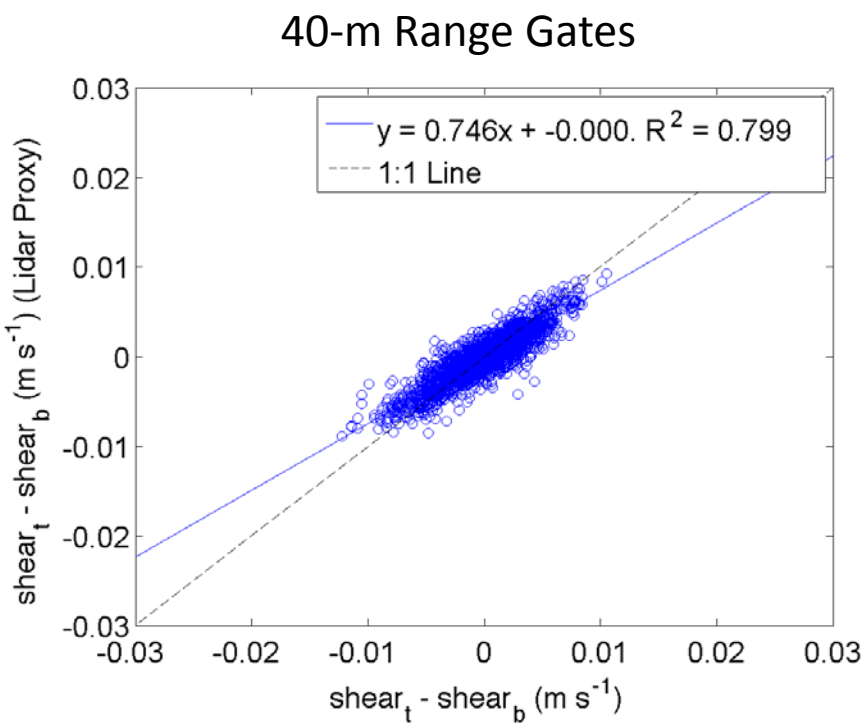
Analytical expression (assuming uniform range-weighting)

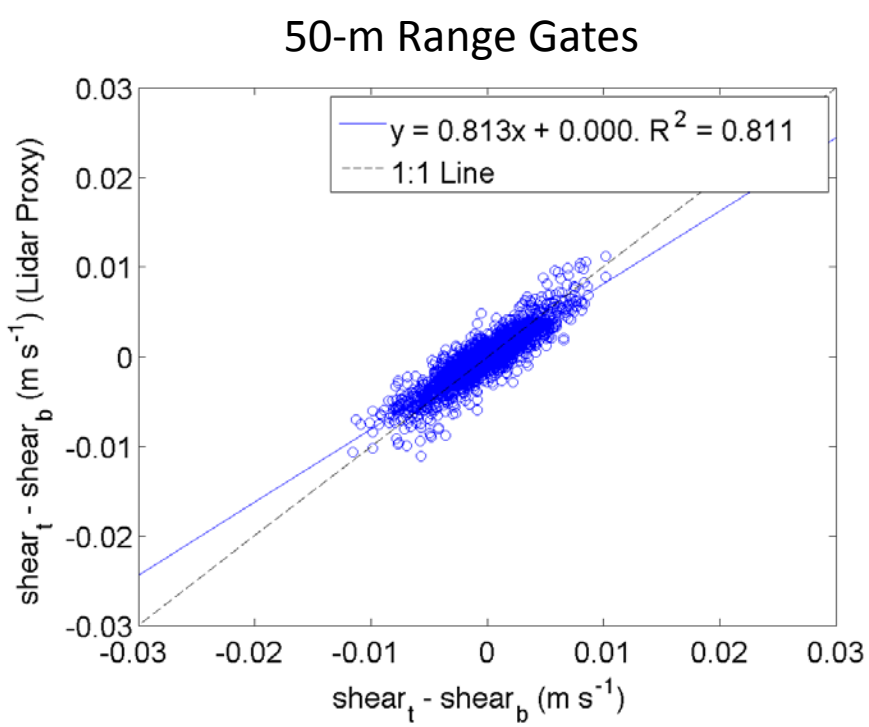
$$V_0 - V_{avg} = -6.818(shear_t - shear_b)$$

Actual data from neutral and unstable LES runs



Can Lidar Approximate Shear Within a Range Gate?

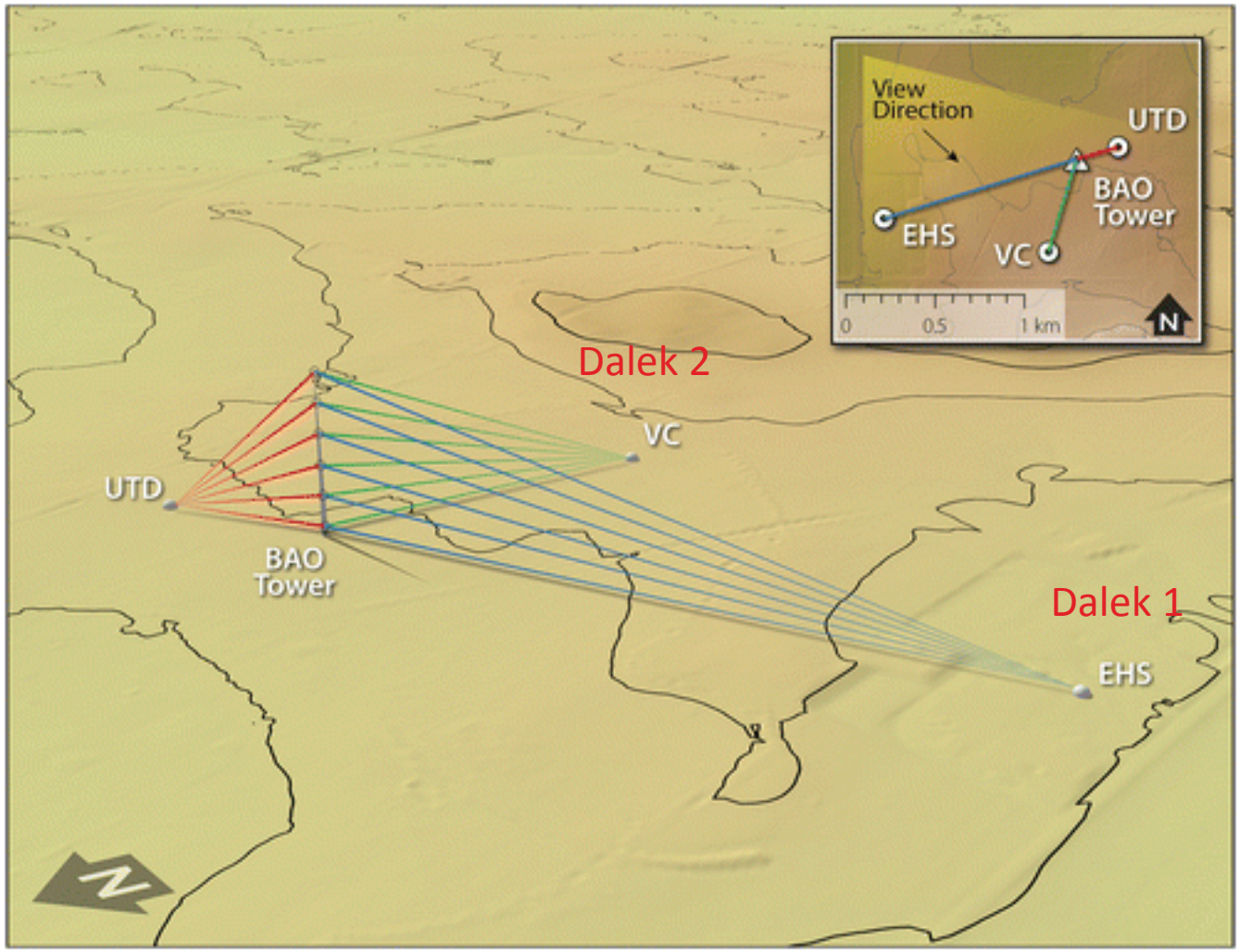




Shear between range gates is a decent approximation for neutral and unstable conditions, but this relation still needs to be tested on stable conditions.

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:

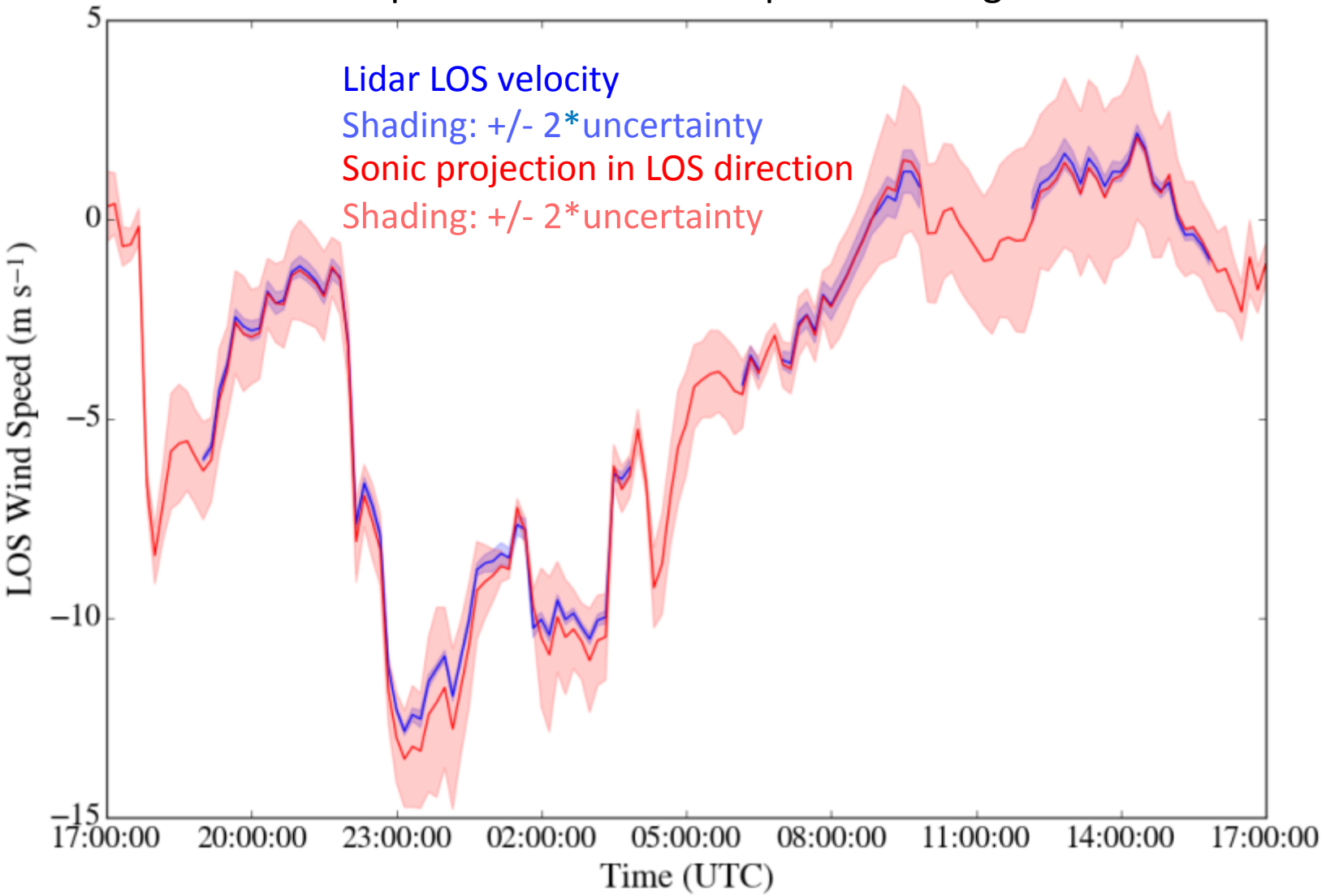
Uncertainty in azimuth and elevation angle from lidar

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

Uncertainty in sonic anemometer measurements

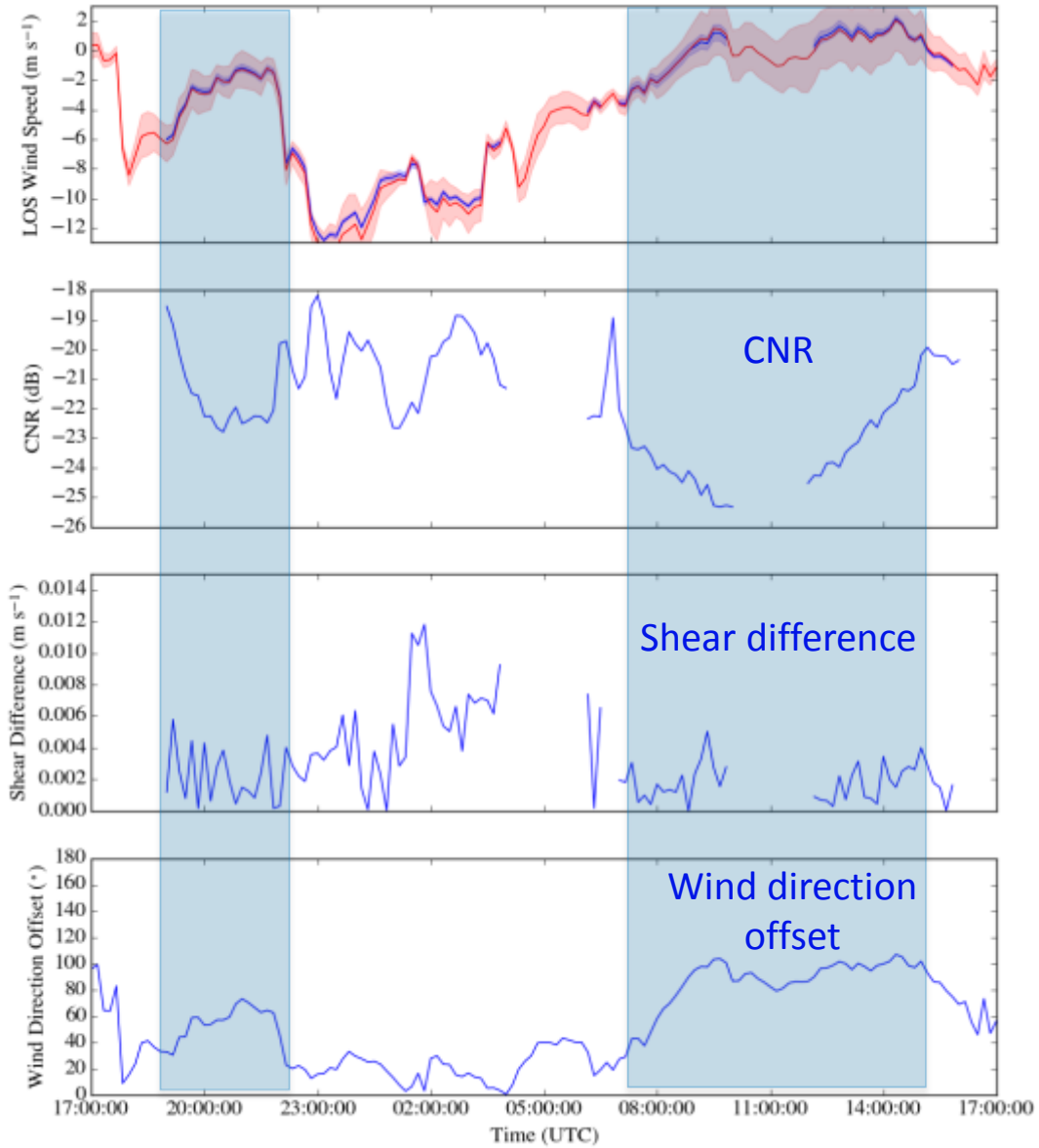
Dynamic Framework in Action

LOS wind speed from a 24-hour period during XPIA



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

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.

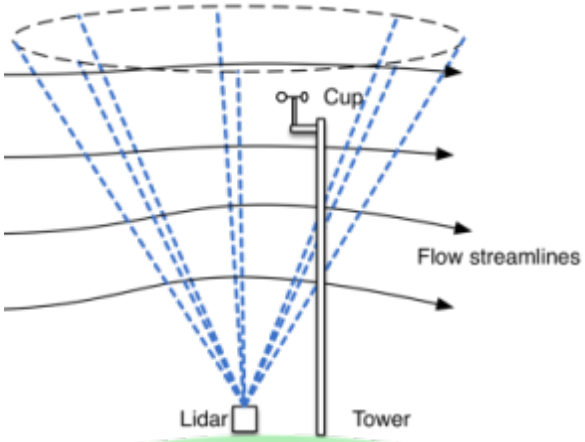


Illustration by Andy Clifton

Thank You!

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