Measurements of Turbulence Profiles with Scanning Doppler Lidar for Wind Energy Applications

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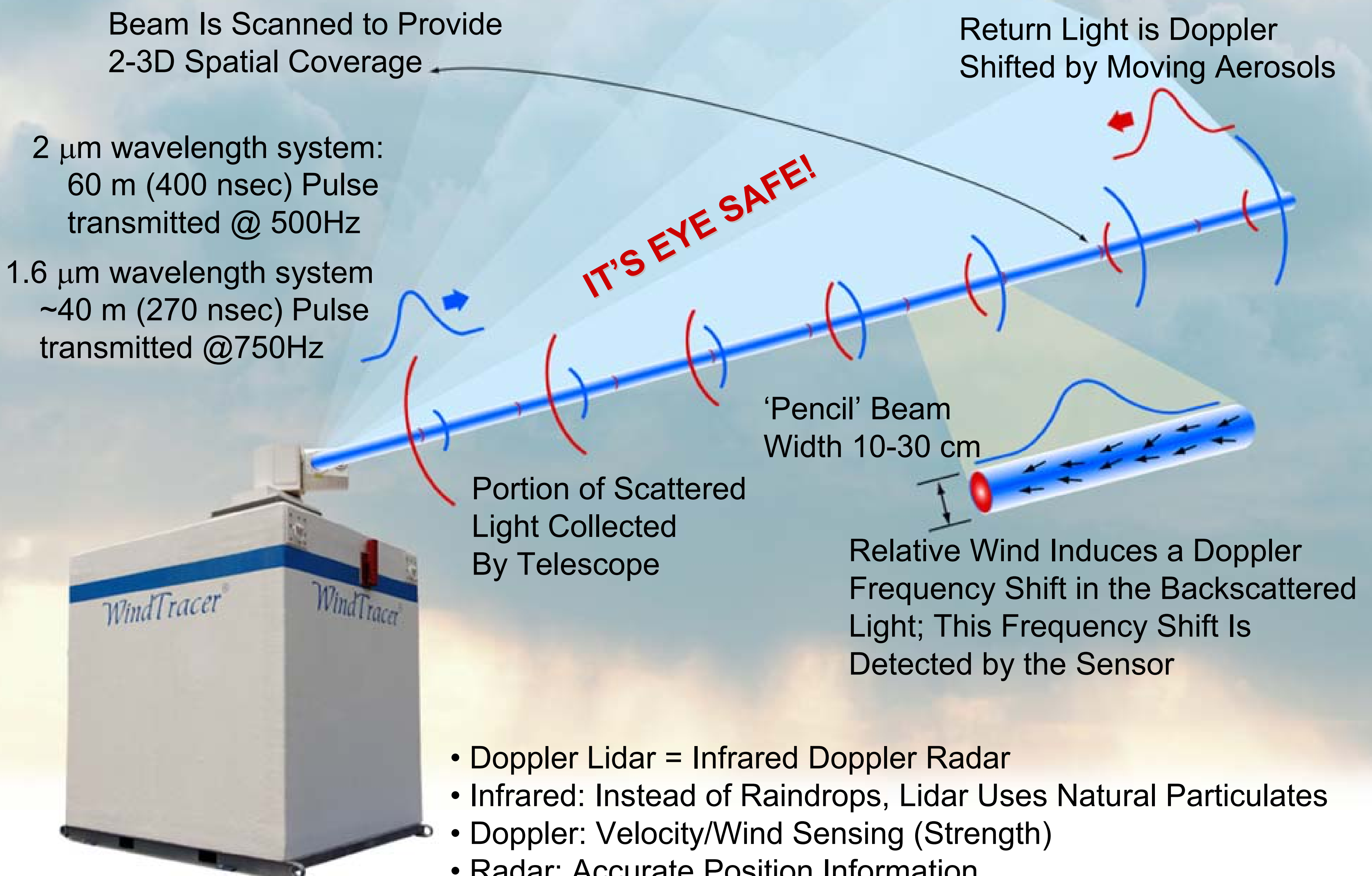
Acknowledgments

- CTI (Steve Hannon, Sammy Henderson, Jerry Pelk, Mark Vercauteren, Keith Barr)
- Larry Cornman, Kent Goodrich (Juneau)
- DARPA – Pentagon Shield (Paul Benda)
  - R. Sharman, T. Warner, J. Weil, S. Swerdlin (NCAR)
  - Y. Meillier, M. Jensen, B. Balsley (CU)
- Army Research Office (Walter Bach)
- NSF (Steve Nelson)
- NREL (Neil Kelley, Bonnie Jonkman)
- CU renewable energy seed grant
- NOAA (Bob Banta, Yelena Pichugina)

Complements of Steve Hannon



- Doppler Lidar = Infrared Doppler Radar
- Infrared: Instead of Raindrops, Lidar Uses Natural Particulates
- Doppler: Velocity/Wind Sensing (Strength)
- Radar: Accurate Position Information

Graphics Courtesy Lockheed Martin

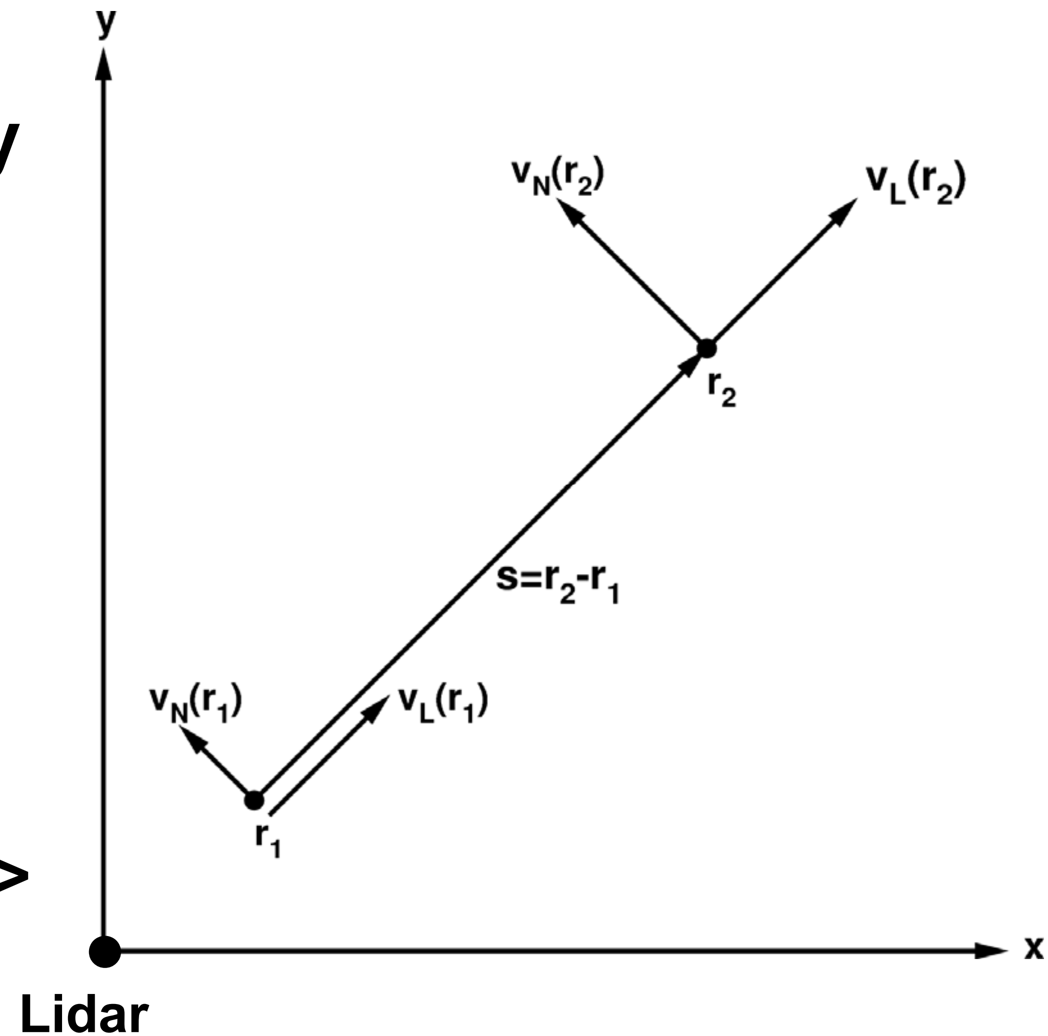
Point Statistics of Turbulence

- Longitudinal velocity (radial)
- Transverse velocity
- Longitudinal structure function

$$D_{LL}(s)=<[v_L(r_2)-v_L(r_1)]^2>$$

- Transverse structure function

$$D_{NN}(s)=<[v_N(r_2)-v_N(r_1)]^2>$$



Horizontal Isotropic Turbulence

- **Universal description - longitudinal**

$$D_{LL}(s) = 2\,\sigma_u^2 \Lambda(s/L_{0u})$$

- σ_u – **longitudinal standard deviation**
- L_{0u} – **longitudinal outer scale**
- $\Lambda(x)$ – **universal function (von Kármán)**
- $s \ll L_{0u}$

$$D_{LL}(s) = C_K\, \varepsilon_u^{2/3}\, s^{2/3} \qquad C_K \sim 2.0$$

- ε_u = **energy dissipation rate**

Horizontal Isotropic Turbulence

- Universal description - transverse

$$D_{NN}(s) = 2\,\sigma_v^2 \Lambda(s/L_{0v})$$

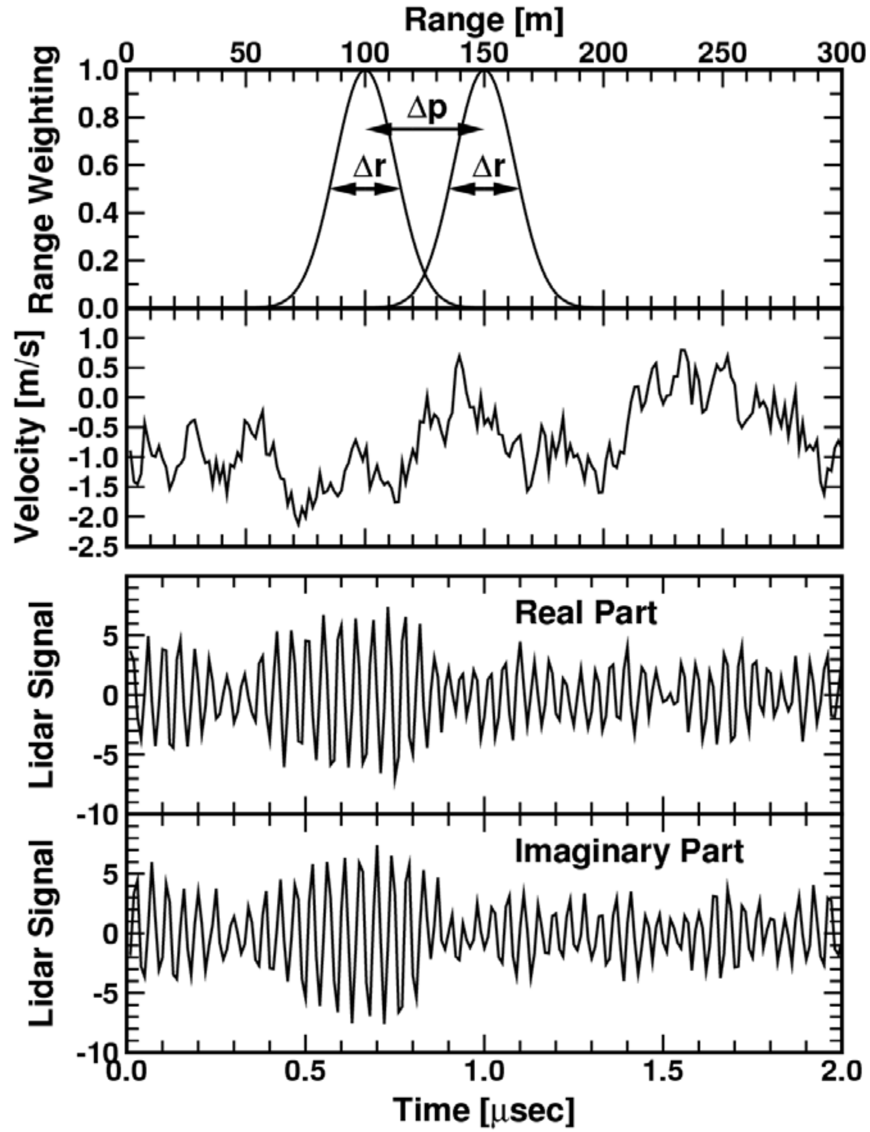
- σ_v – transverse standard deviation
- L_{0v} – transverse outer scale
- $\Lambda(x)$ – universal function (von Karman)
- $s \ll L_{0v}$

$$D_{NN}(s) = C_J\, \varepsilon_v^{2/3}\, s^{2/3} \qquad C_J \sim 2.67$$

- ε_v = energy dissipation rate

Doppler LIDAR Range Weighting

- Time of data maps to range (1 μs = 150 m)
- Pulsed lidar velocity measurements filter the random radial velocity $v_r(z)$
- Pulse width Δr
- Range gate length defined by processing interval Δp
- Range weighting W(r)

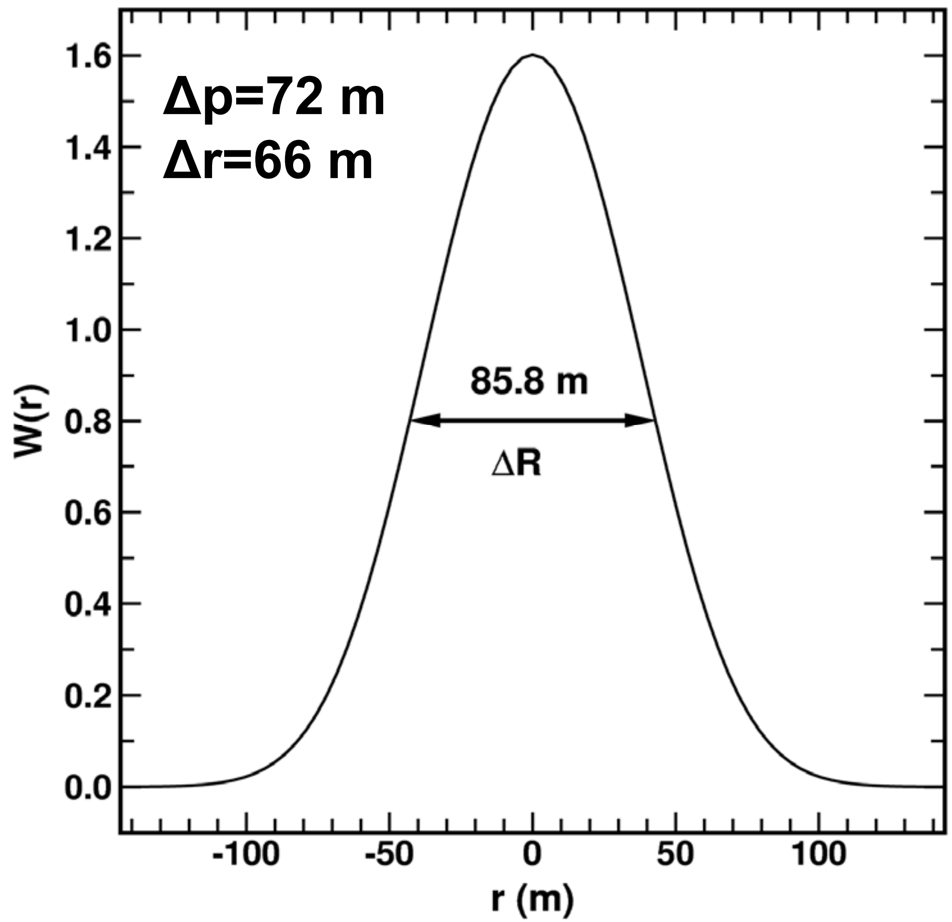


LIDAR Data and Range Weighting

- LIDAR radial velocity estimates at range R
  $v(R) = v_{wgt}(R) + e(R)$
- $v_{wgt}(R)$ - pulse weighted velocity
- e(R) estimation error

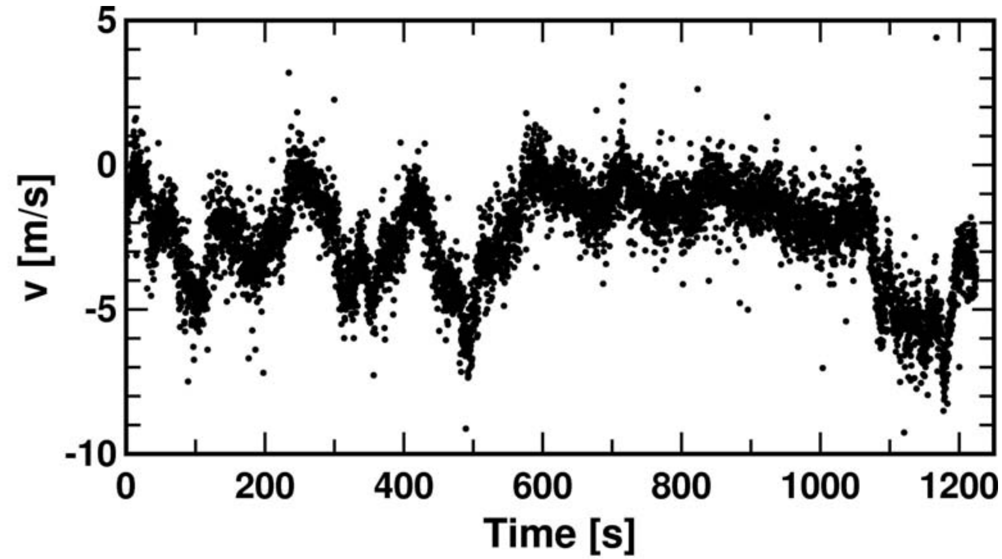
$$v_{wgt}(R) = \int v_r(z) W(R-z)\, dz$$

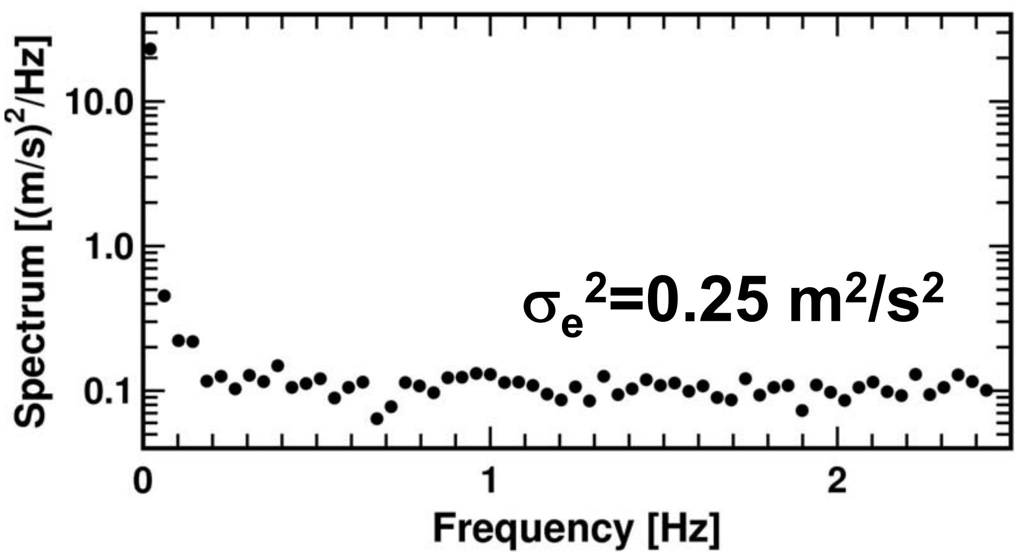
- $v_r(z)$ - random radial velocity
- W(r) - range weighting



Estimates of Random Error

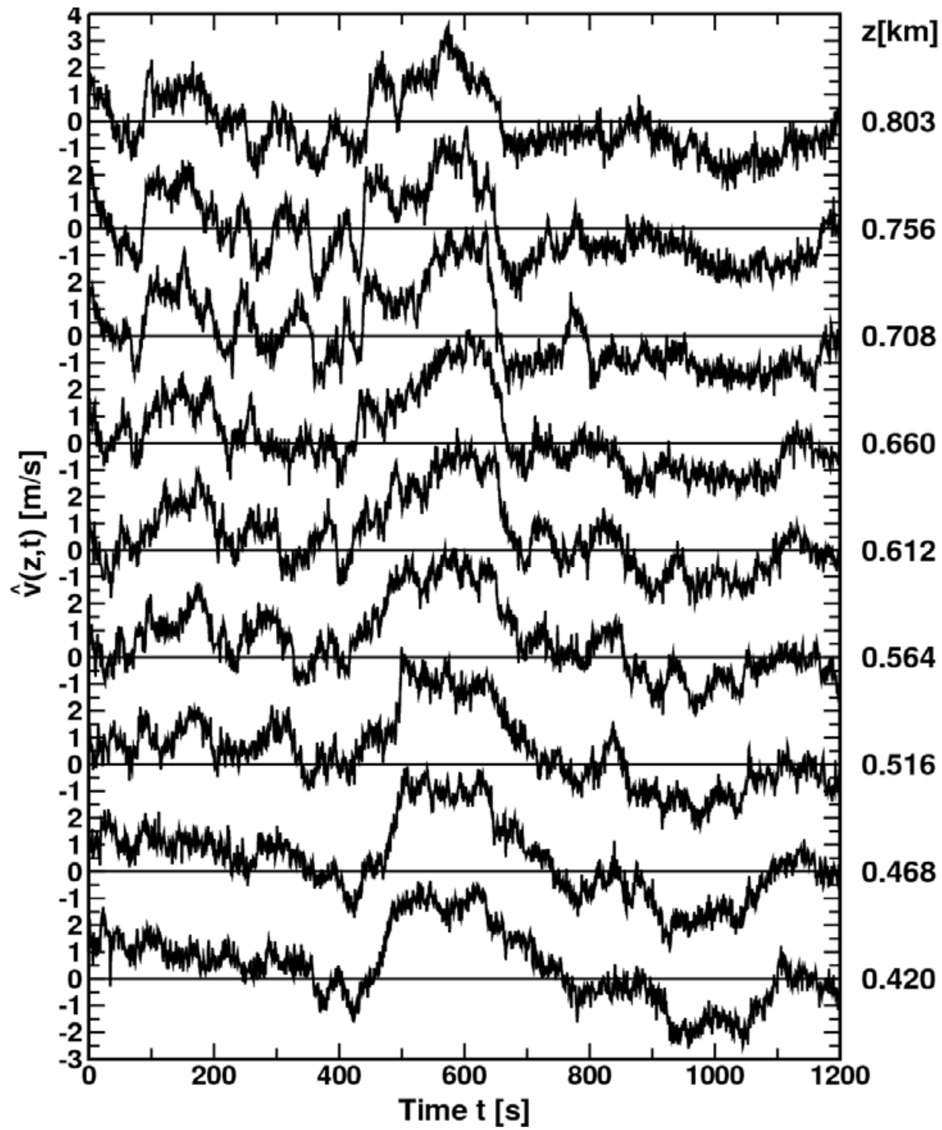
- **Radial velocity error variance σ_e^2 can be determined from data**
- **Spectral noise floor is proportional to σ_e^2**





Non-Scanning Lidar Data

- **Vertically pointed beam**
- **Time series of velocity for various altitudes z**
- **High spatial and temporal resolution**
- **Resolves turbulence**



Lidar Structure Function (Radial)

- Corrected longitudinal structure function

$$D_{wgt}(s) = D_{raw}(s) - 2\,\sigma_e^2(s)$$

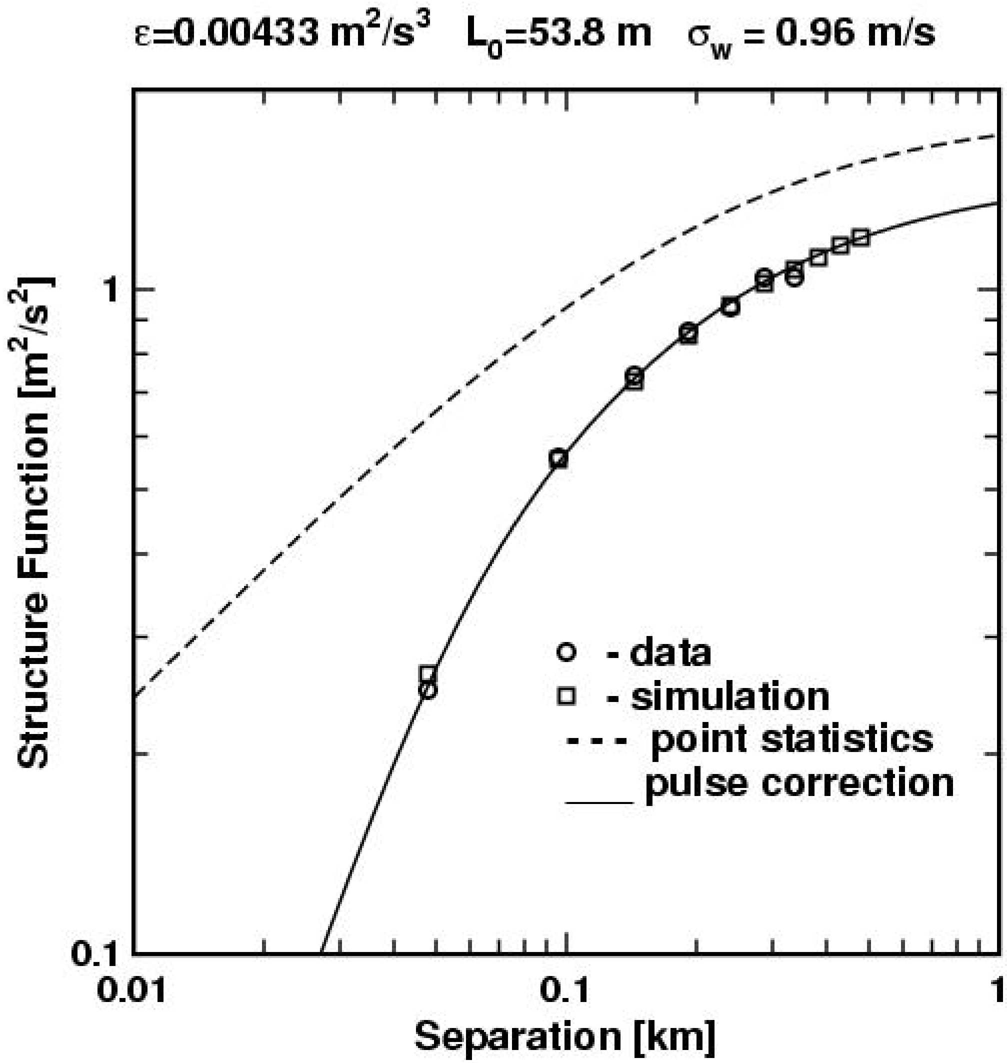
- $D_{raw}(s)$ – raw structure function
- $\sigma_e^2(s)$ – correction for estimation error
- Theoretical relation ($\Delta h \ll \Delta p$)

$$D_{wgt}(s) = 2\,\sigma_u^2\,G(s, L_{0u}, \Delta p, \Delta r)$$

- Best-fit to data produces estimates of σ_u, L_{0u}, ε_u

Turbulence Statistics

- **Calculate corrected structure function**
- **Determine best-fit to theoretical model**
- **Best-fit parameters are estimates of turbulence statistics**

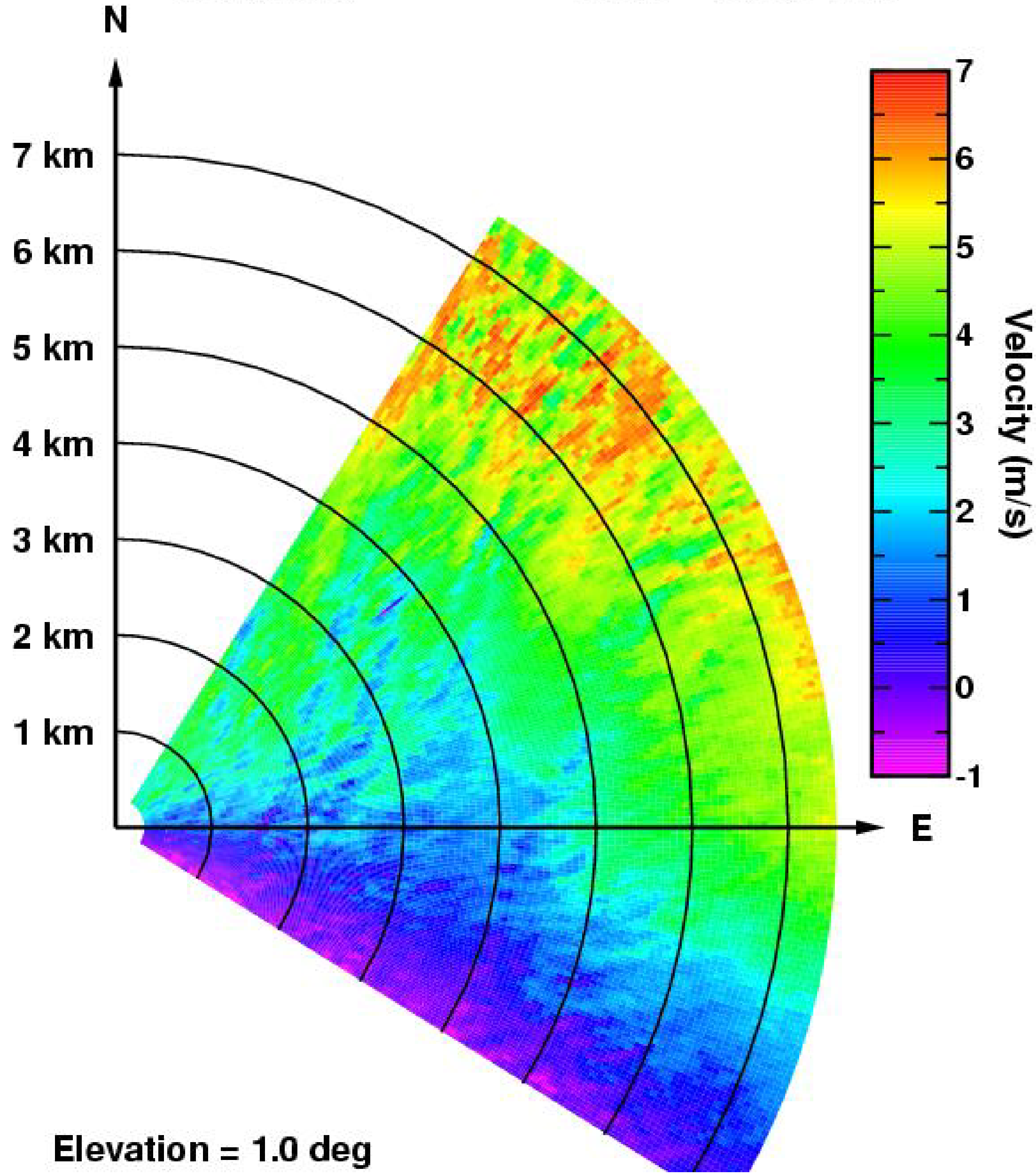


Scanning Lidar Data

- High-resolution profiles of wind speed and turbulence statistics
- Highest statistical accuracy
- Rapid update rates compared with tower derived statistics
- Can provide profiles at multiple locations
- Ideal for some wind energy applications

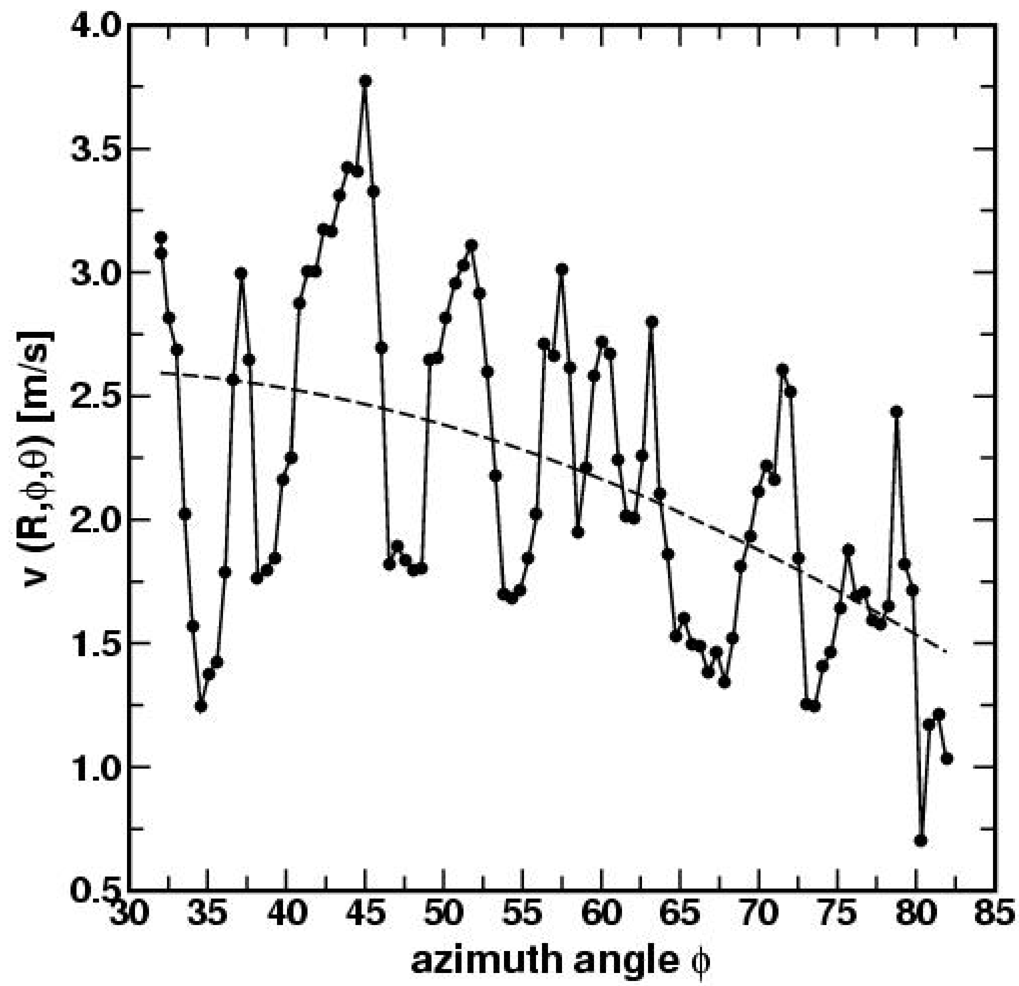
LIDAR Velocity Map for 1°

- Radial velocity
- 100 range-gates along beam
- 180 beams ($\Delta\varphi$=0.5 degree)
- 18 seconds per scan
- $\Delta h = R\,\Delta\varphi \ll \Delta p$ for R<2km



Wind Speed and Direction

- Best-fit lidar radial velocity for best-fit wind speed and direction
- Fluctuations are turbulence
- Longitudinal fluctuations along the lidar beam
- Transverse fluctuation in azimuth direction



Lidar Structure Function (Azimuth)

- Corrected azimuth structure function

$$D_{wgt}(s) = D_{raw}(s) - 2\,\sigma_e^2(s)$$

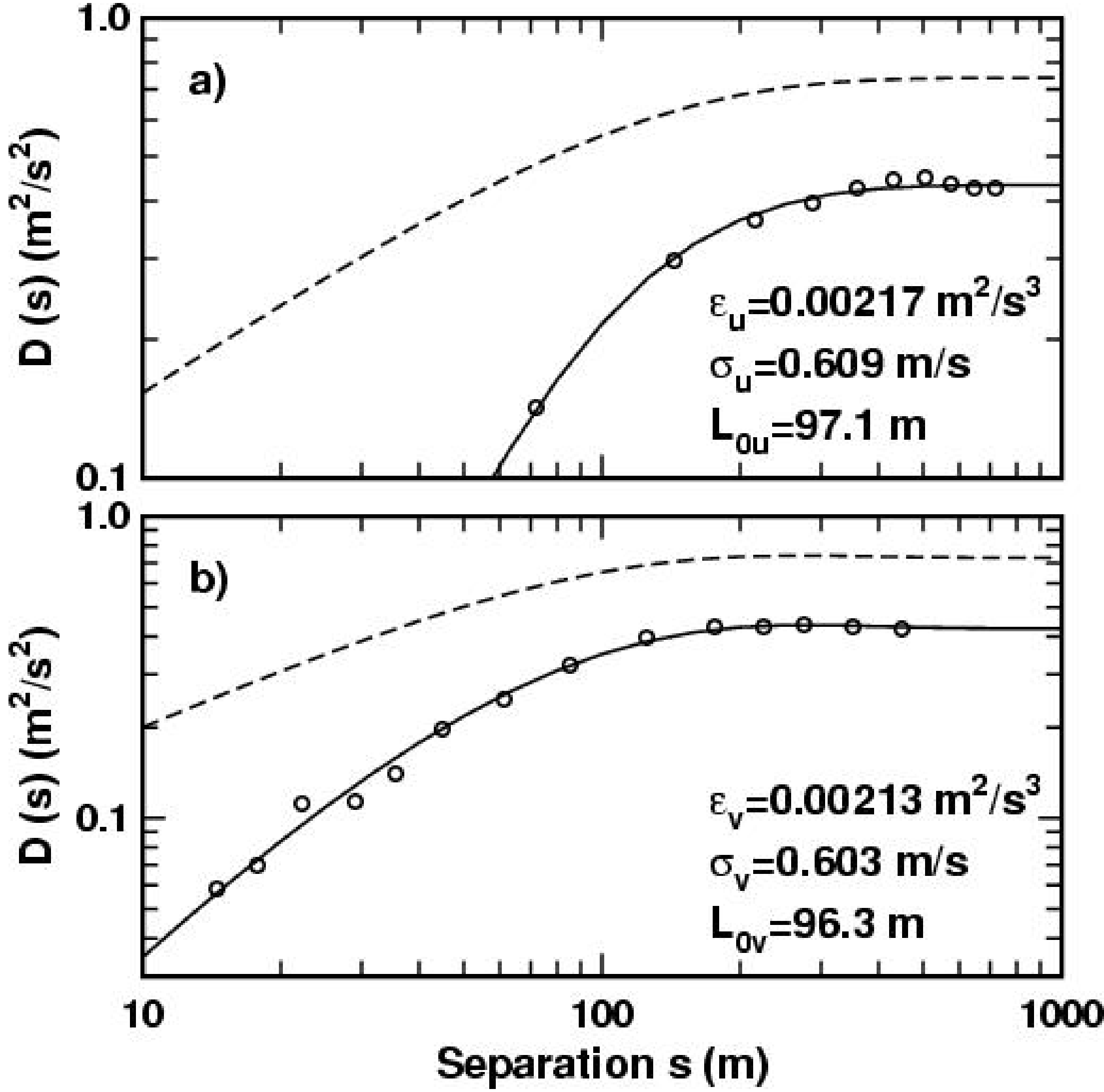
- $D_{raw}(s)$ – raw structure function
- $\sigma_e^2(s)$ – correction for estimation error
- Theoretical relation ($\Delta h \ll \Delta p$)

$$D_{wgt}(s) = 2\,\sigma_v^2\, G_\varphi(s, L_{0v}, \Delta p, \Delta r)$$

- Best-fit to data produces estimates of $\sigma_v, L_{0v}, \varepsilon_v$

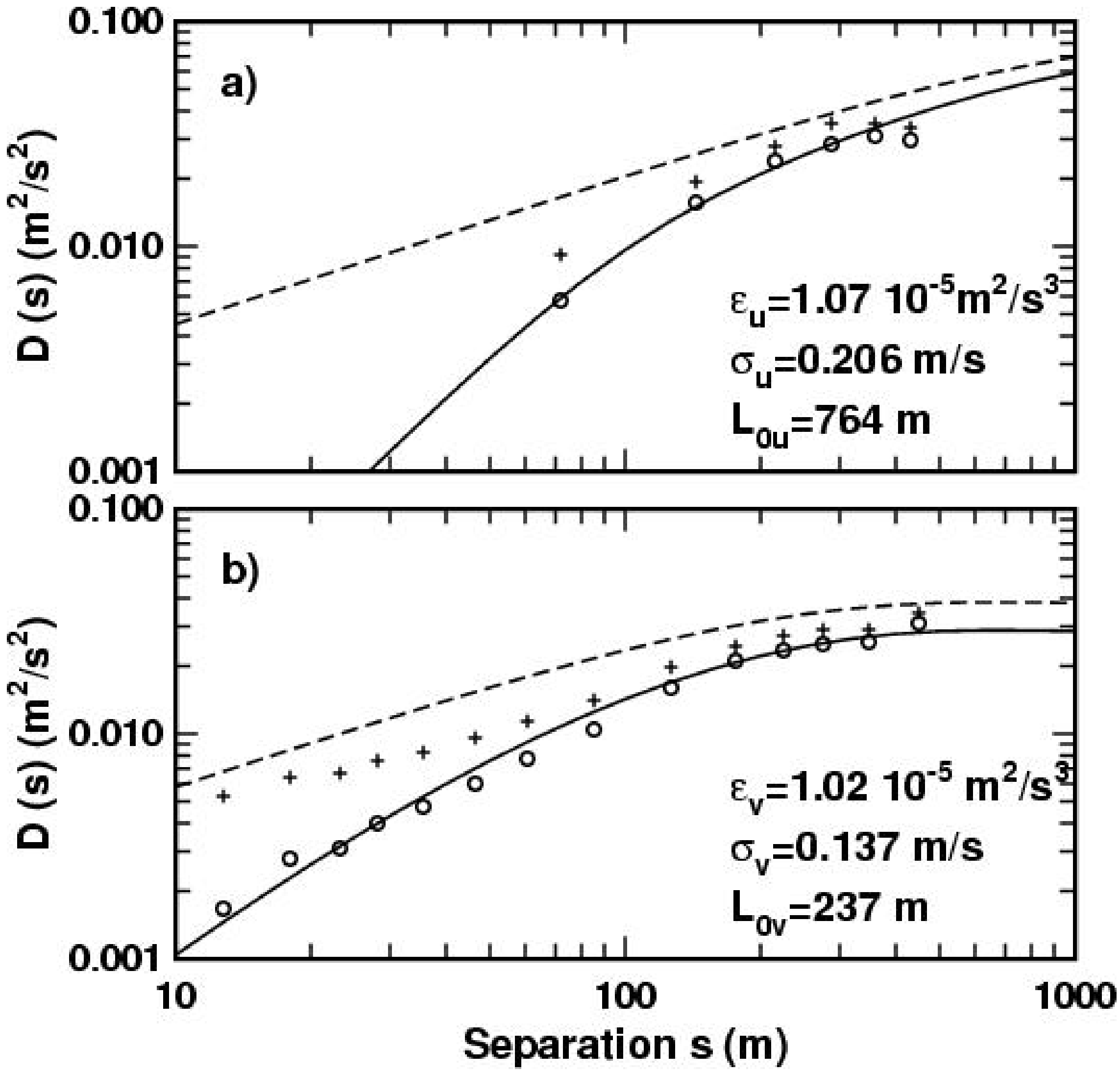
Turbulence Estimates Zero Elevation

- Structure function of radial velocity in range a)
- Best fit produces estimates of σ_u, ε_u, L_{0u}
- Structure function in azimuth b)
- Best fit produces estimates of σ_v, ε_v, L_{0v}

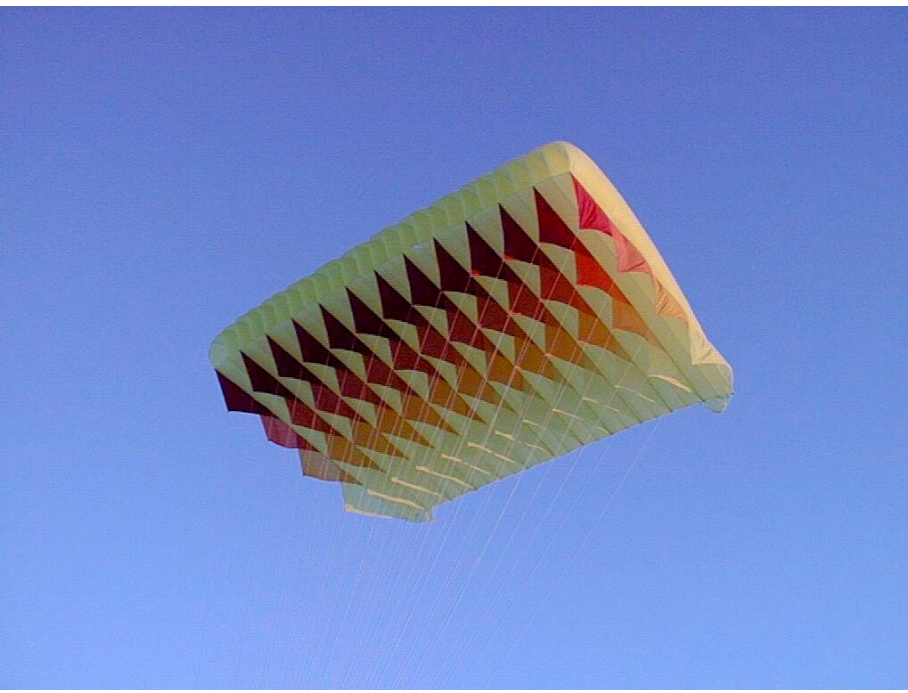


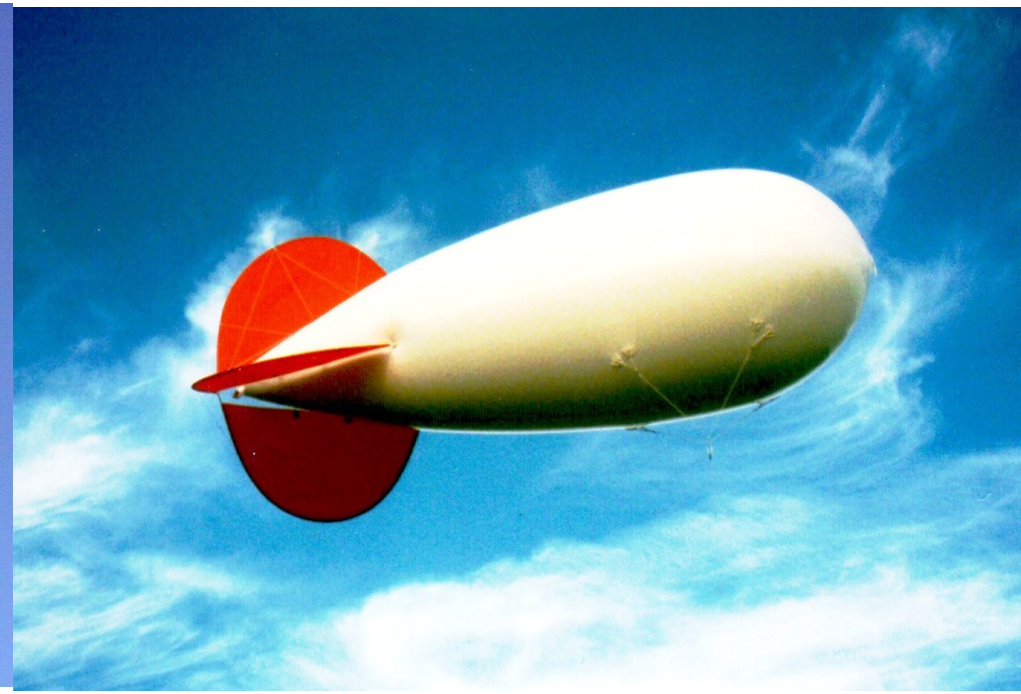
Turbulence Estimates H=80 m

- **Best fit for noise corrected structure function (o)**
- **Raw structure functions (+)**
- **Radial velocity a) has small elevation angles (<= 4°)**
- **Structure function in azimuth b)**
- **Good agreement in ε_u and ε_v (isotropy)**



CIRES Tethered Lifting System (TLS): Hi-Tech Kites or Aerodynamic Blimps



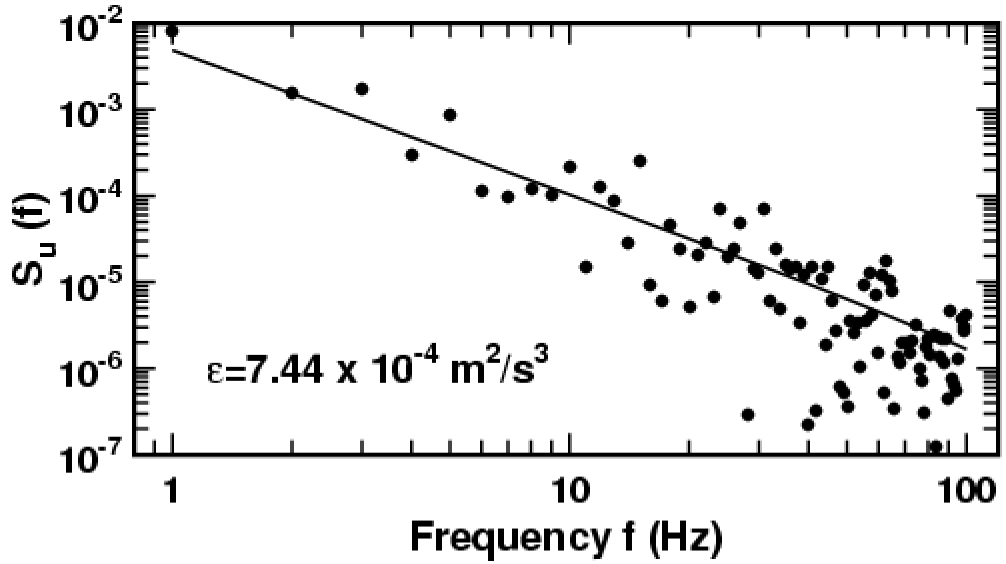


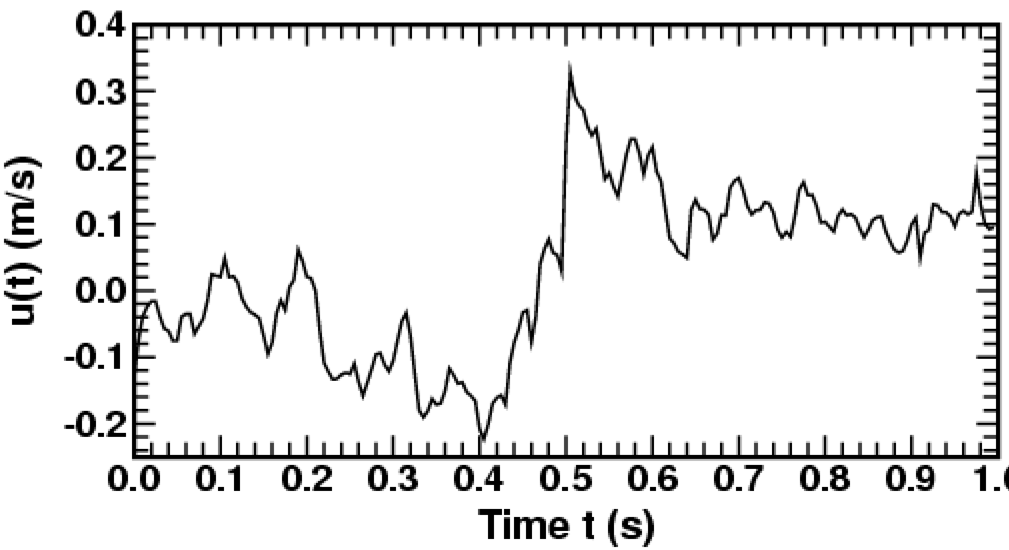
High Resolution Profiles from TLS Data

- **TLS instrumentation used as “truth” for turbulence profiles**
- **Hot-wire sensor for small scale velocity**
- **Cold-wire sensor for small scale temperature**

Velocity Turbulence

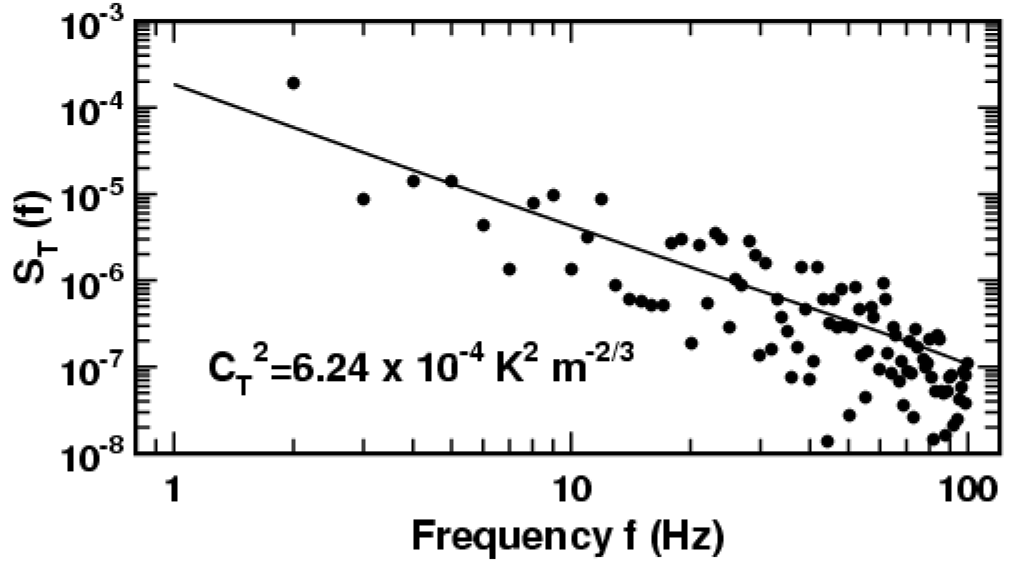
- **Along-stream velocity u(t)**
- **Spectrum $S_u(f)$**
- **Taylors frozen hypothesis**
- **Energy dissipation rate ε**

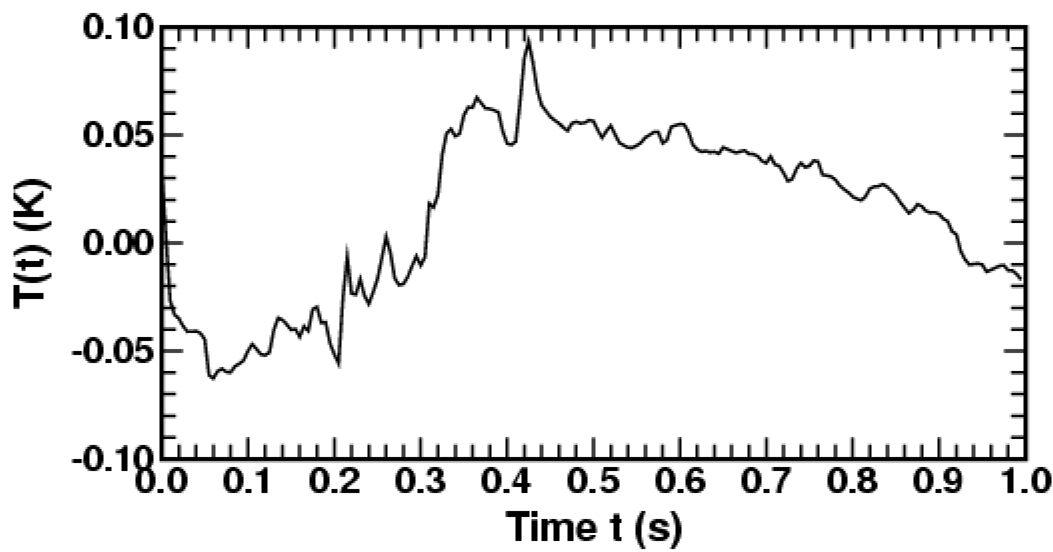




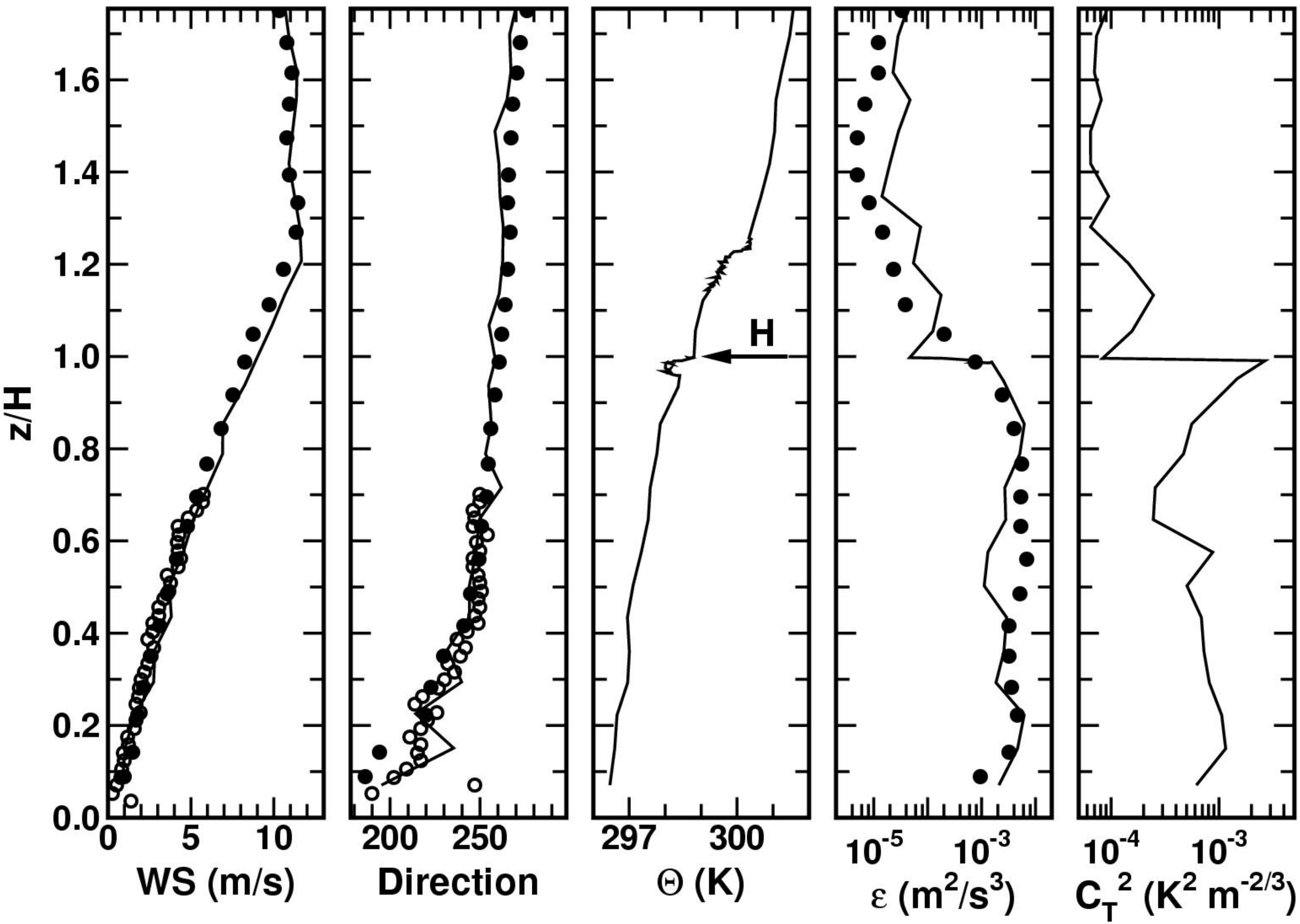
Temperature Turbulence

- Along-stream temperature T(t)
- Spectrum $S_T(f)$
- Taylors frozen hypothesis
- Temperature structure constant C_T^2

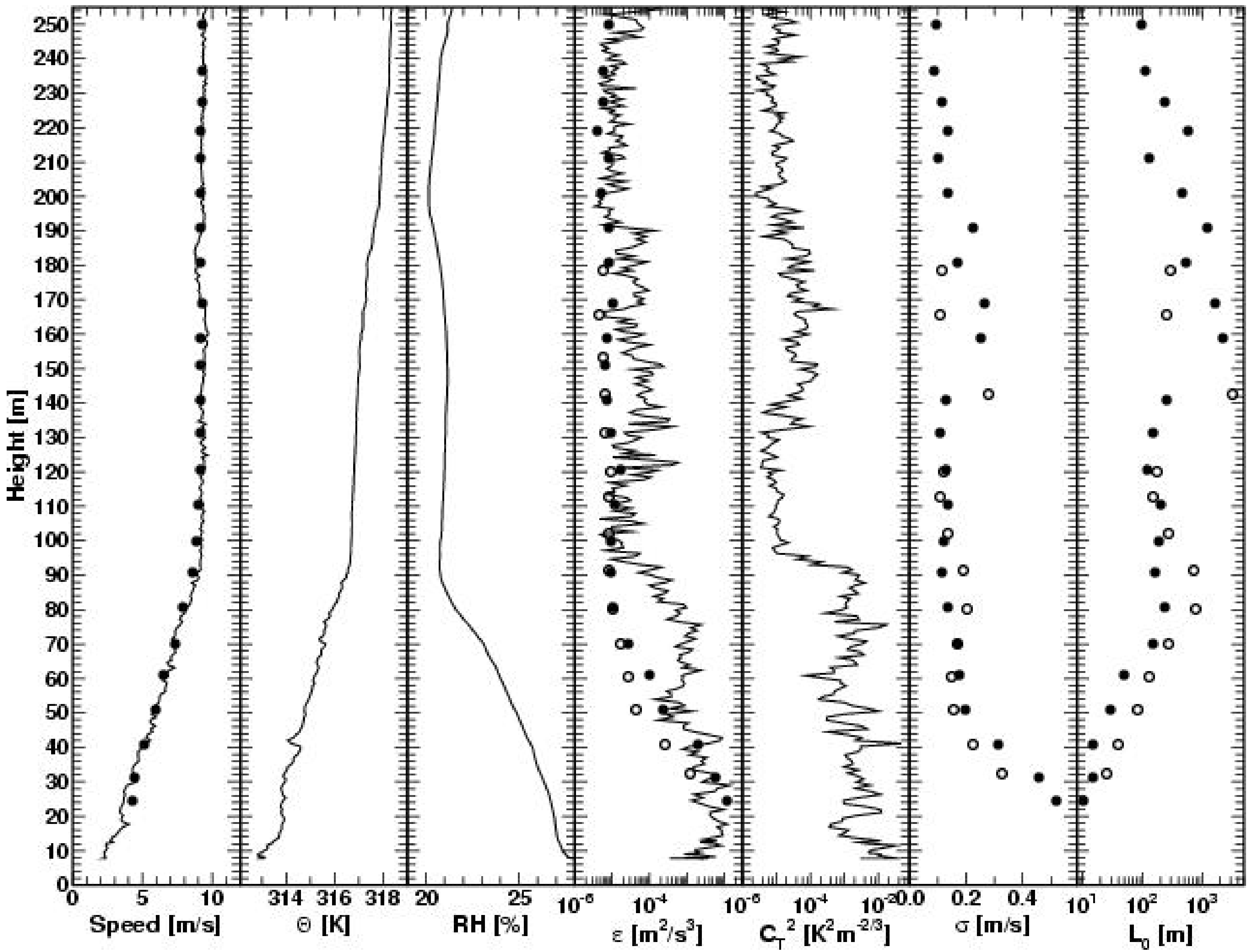




LIDAR, SODAR and TLS (Blimp)



Lidar and TLS Profiles

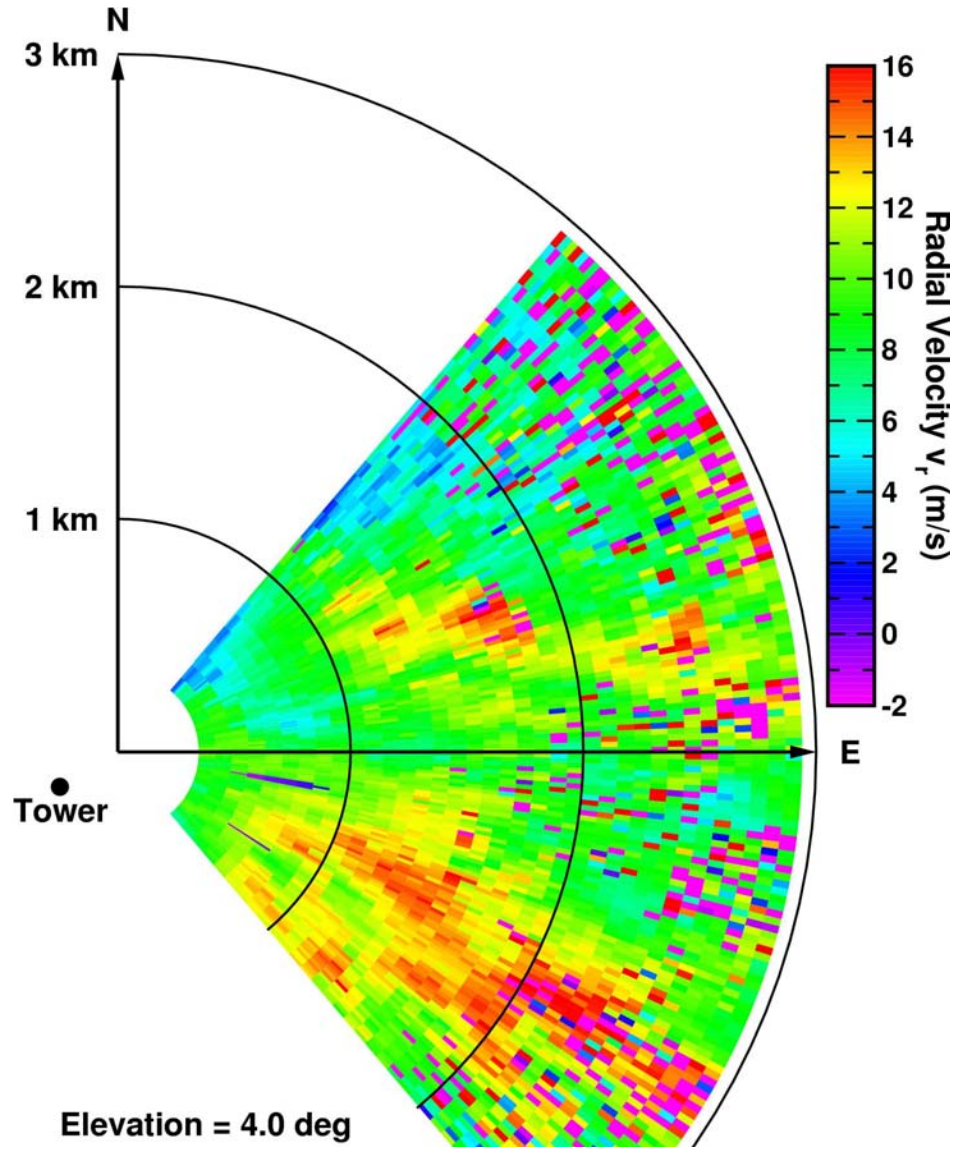


Wind Energy Applications

- **Towers are expensive and limited in height coverage**
- **CW Doppler lidar can measure winds near an individual turbine**
- **Scanning Doppler lidar can monitor large area upstream of a wind farm**
- **Autonomous lidar (CTI)**
  - **Airports**
  - **Homeland security DC**

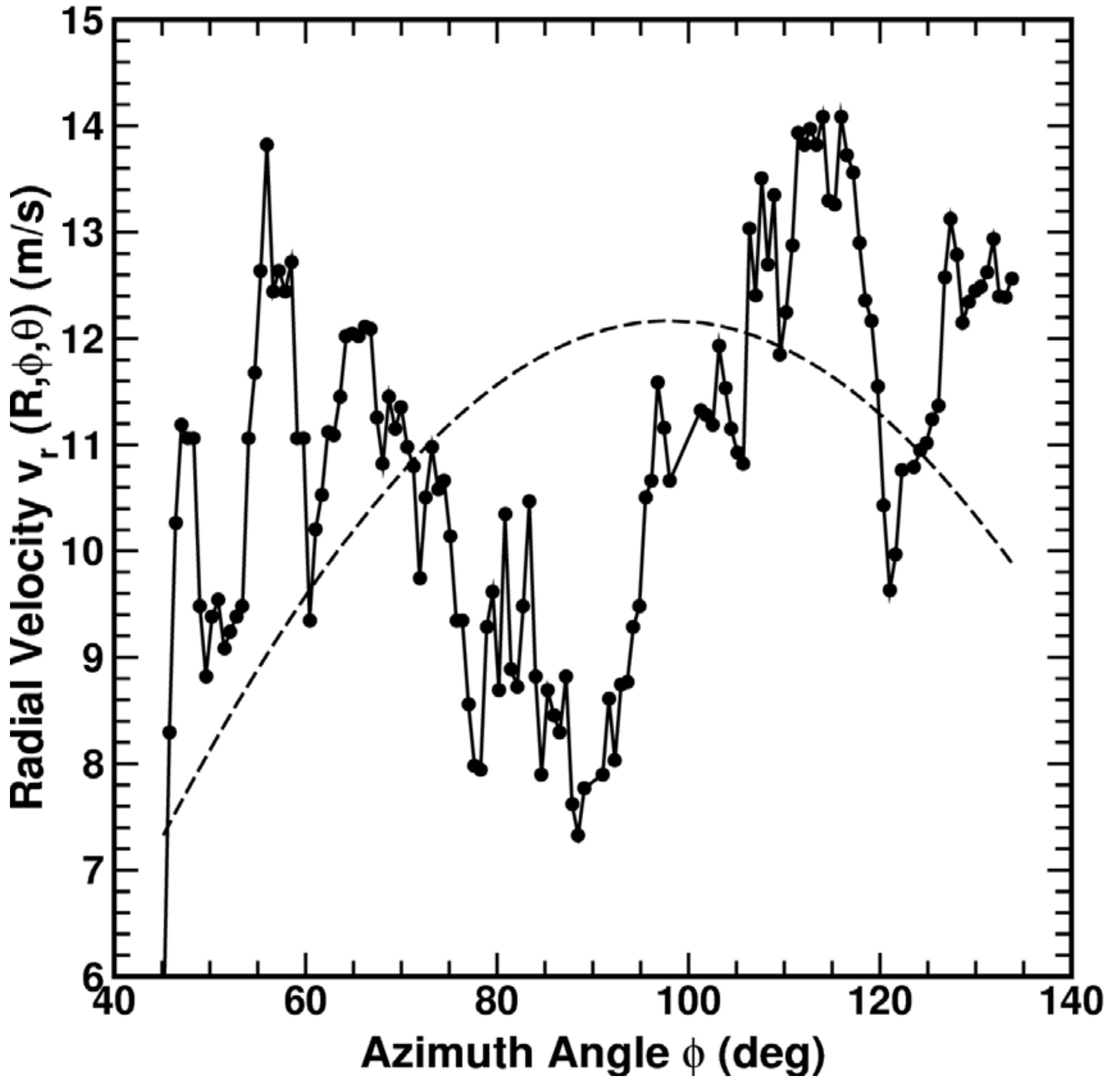
Doppler Lidar at NREL

- Radial velocity map
- Large eddies
- Large velocity variations
- Multiple elevation angles provide 3D sampling



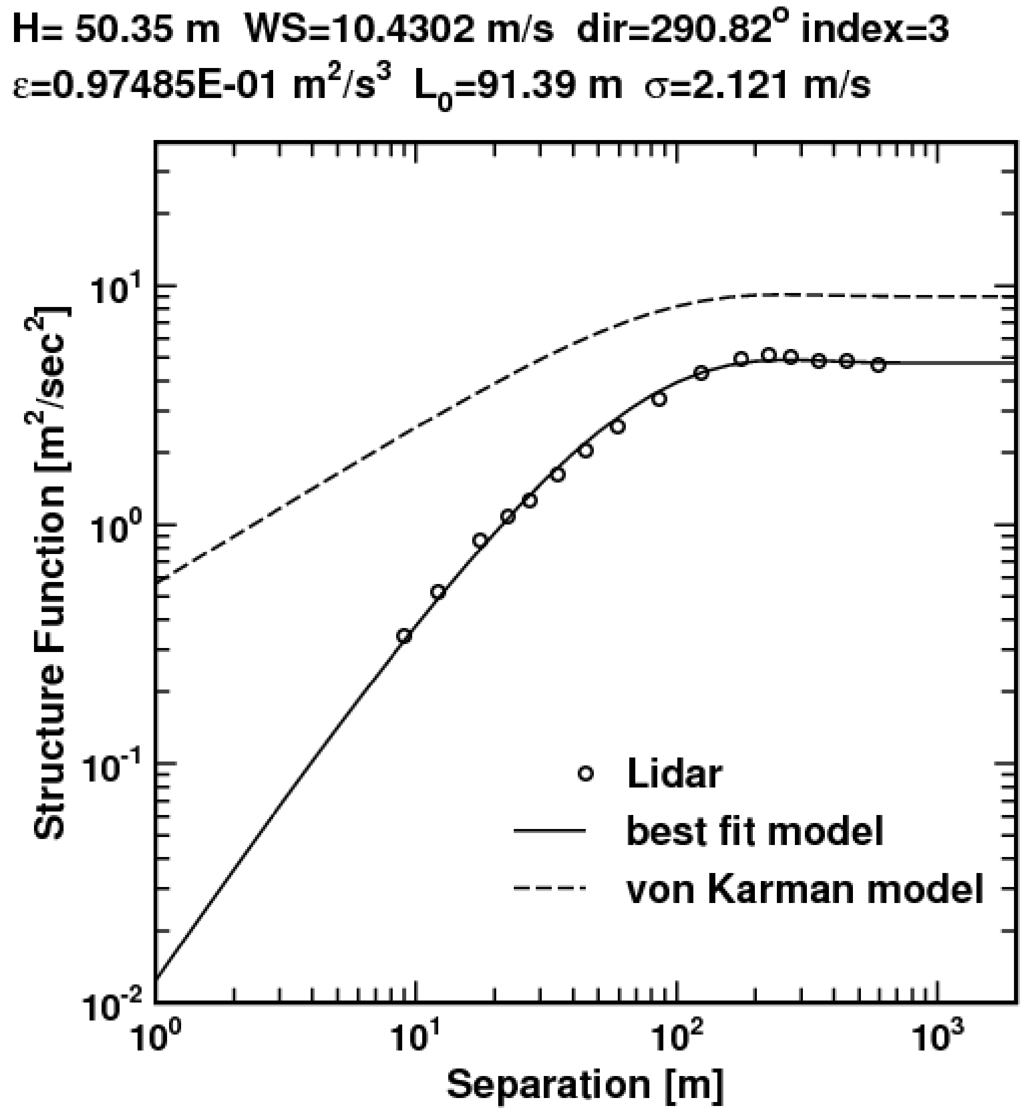
High Turbulence

- Large fluctuations about the best fit wind speed
- 3D average required for accurate statistics



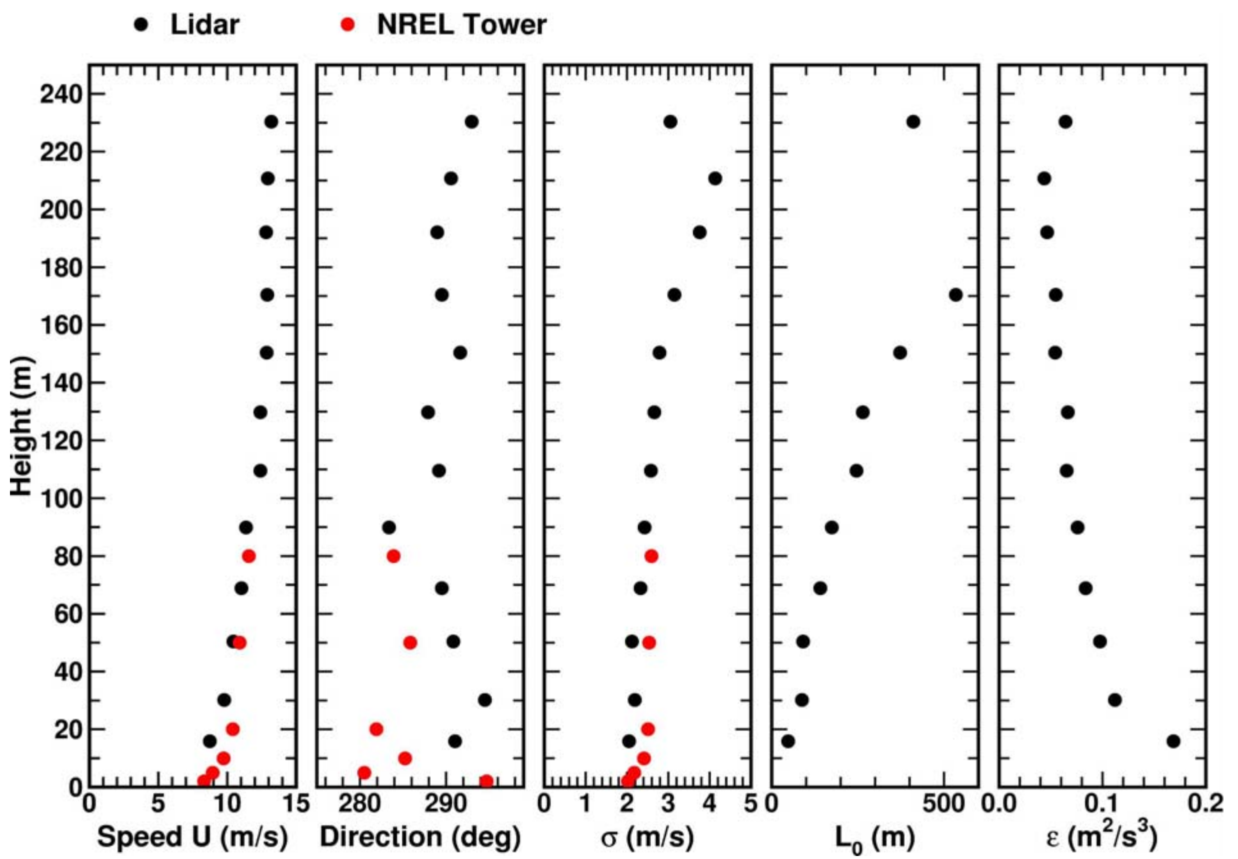
Azimuth Structure Functions

- **Best-fit model provides robust turbulence statistics**
- **Profiles produced from 3D volume scan by processing data in altitude bins**



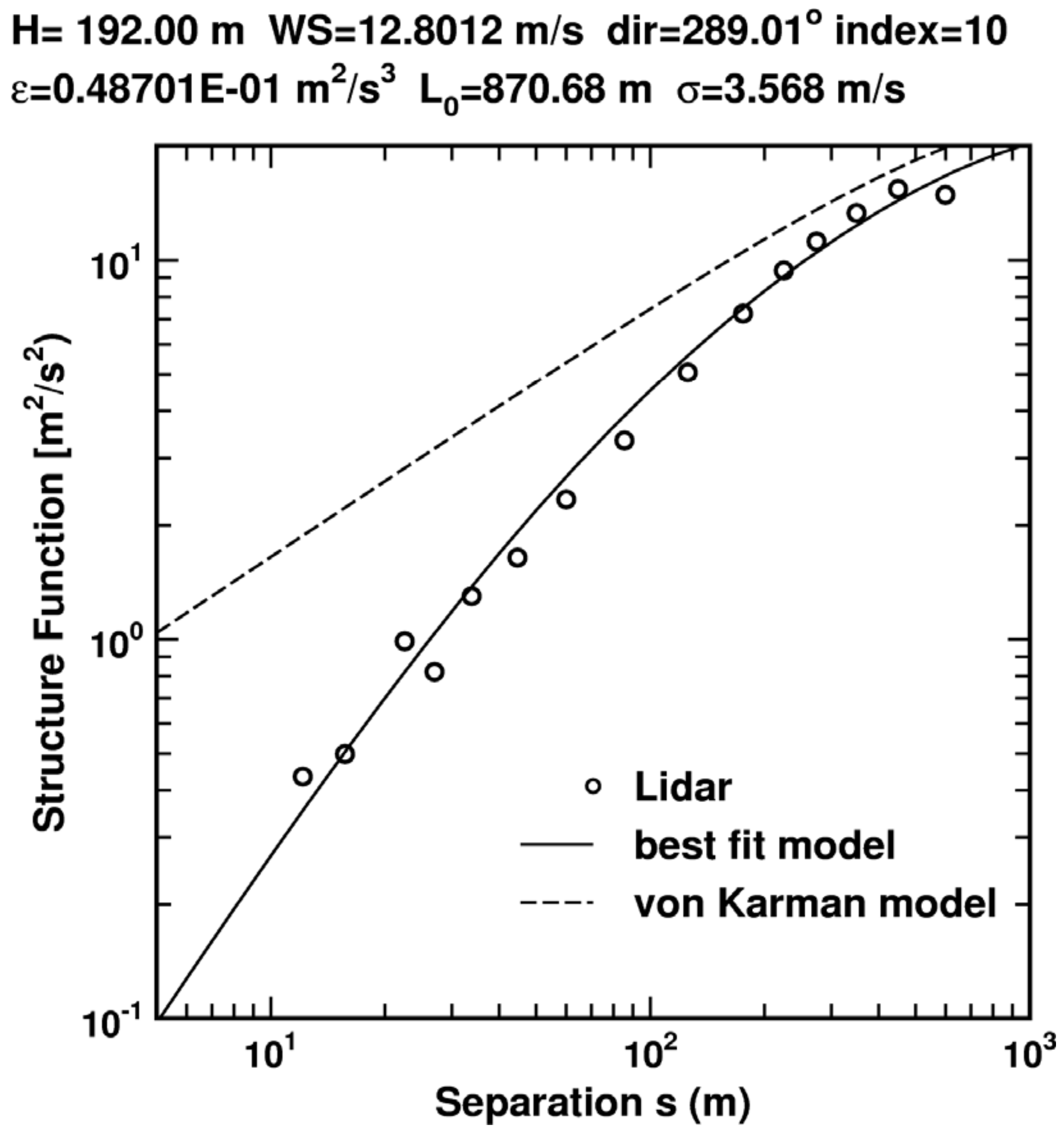
Atmospheric Profiles

- **Accurate profiles produced**
- **Most complete description of wind and turbulence available**
- **Ideal for site resource assessment**



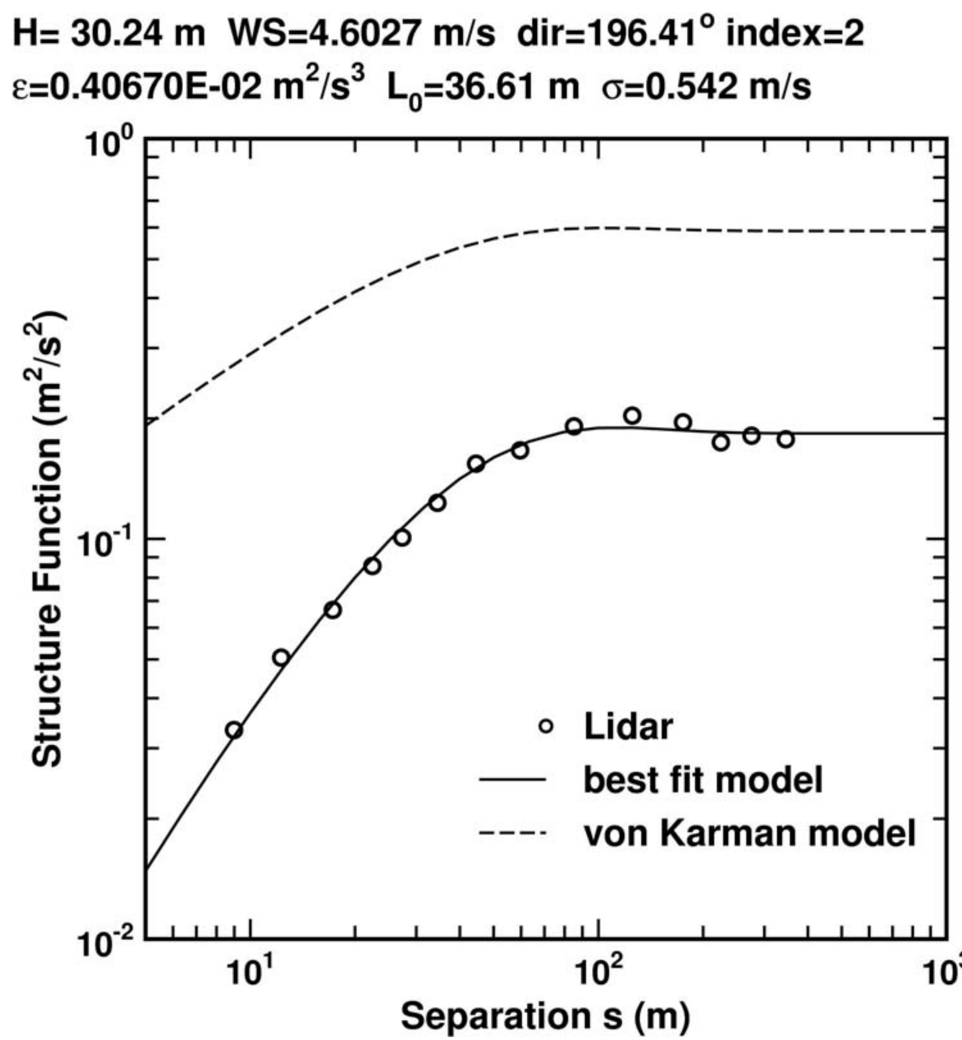
Large Turbulent Length Scale

- Difficult to separate turbulence and larger scale processes
- Similar to troposphere and Boreas Data
- Violates Cartesian approximation of analysis
- What is optimal methodology?



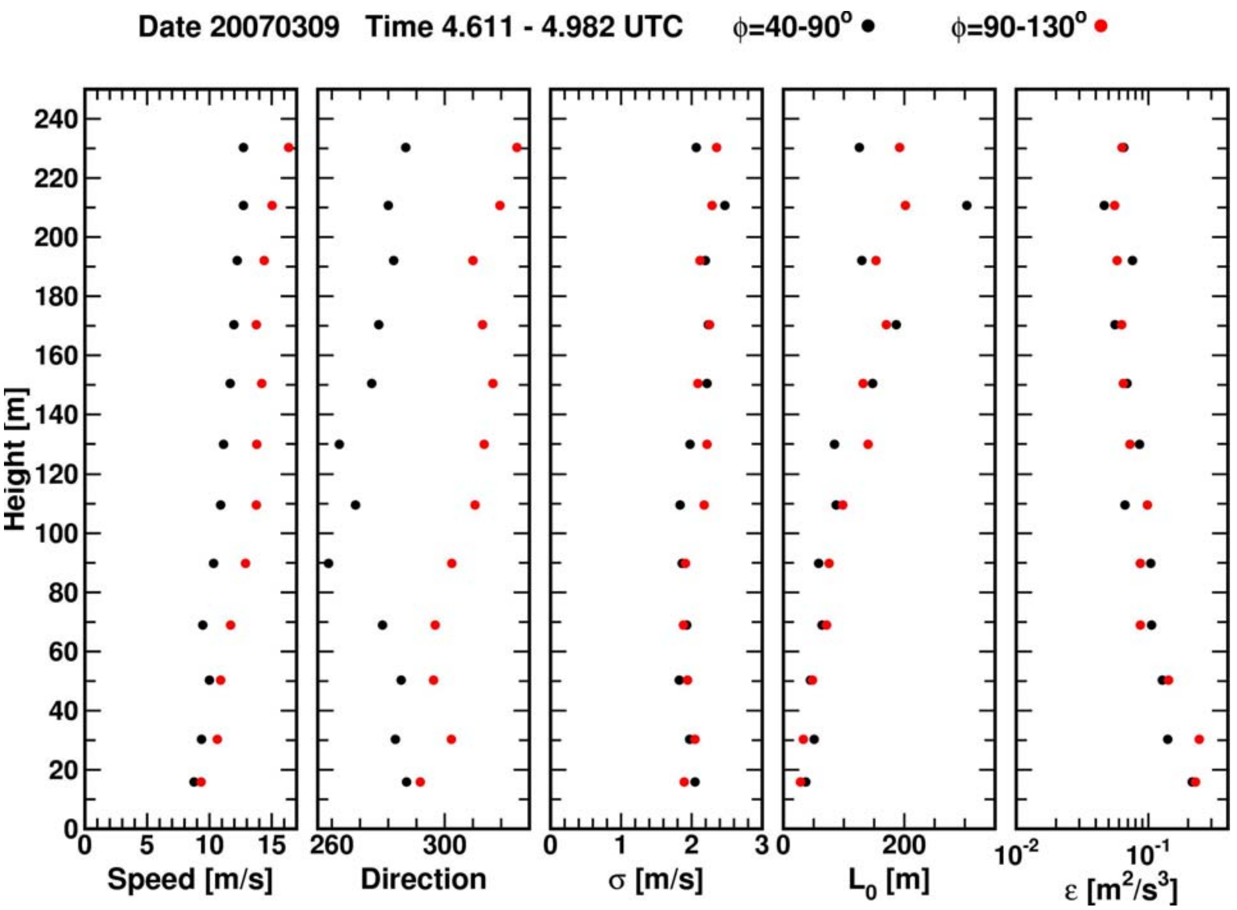
Small Turbulent Length Scale

- **Large corrections for spatial filtering**
- **Requires shorter lidar pulse and more accurate corrections**
- **Critical for lower altitudes**



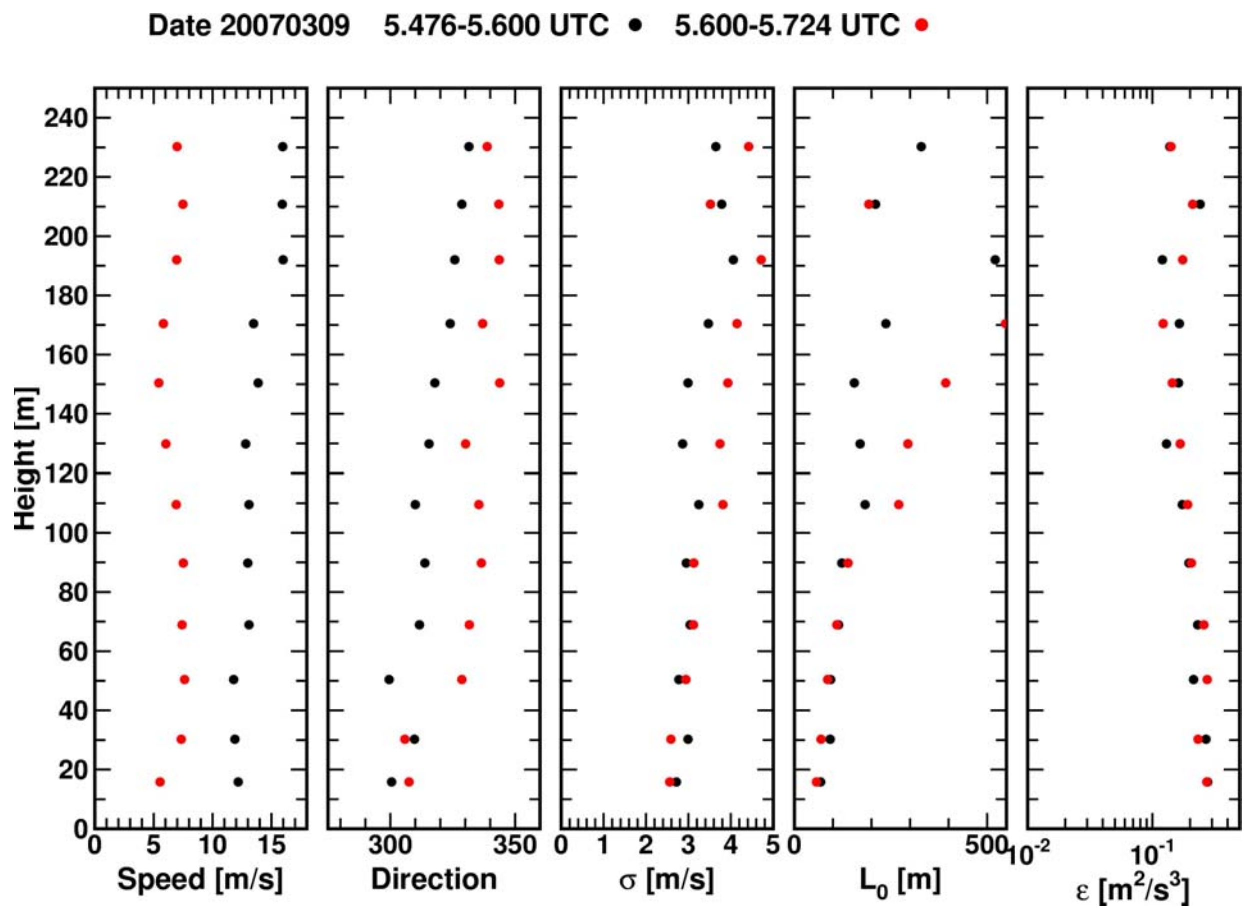
Profiles from Two Angular Sectors

- **Differences in wind speed and direction**
- **Turbulence profiles similar**
- **Implications for site resource assessment**



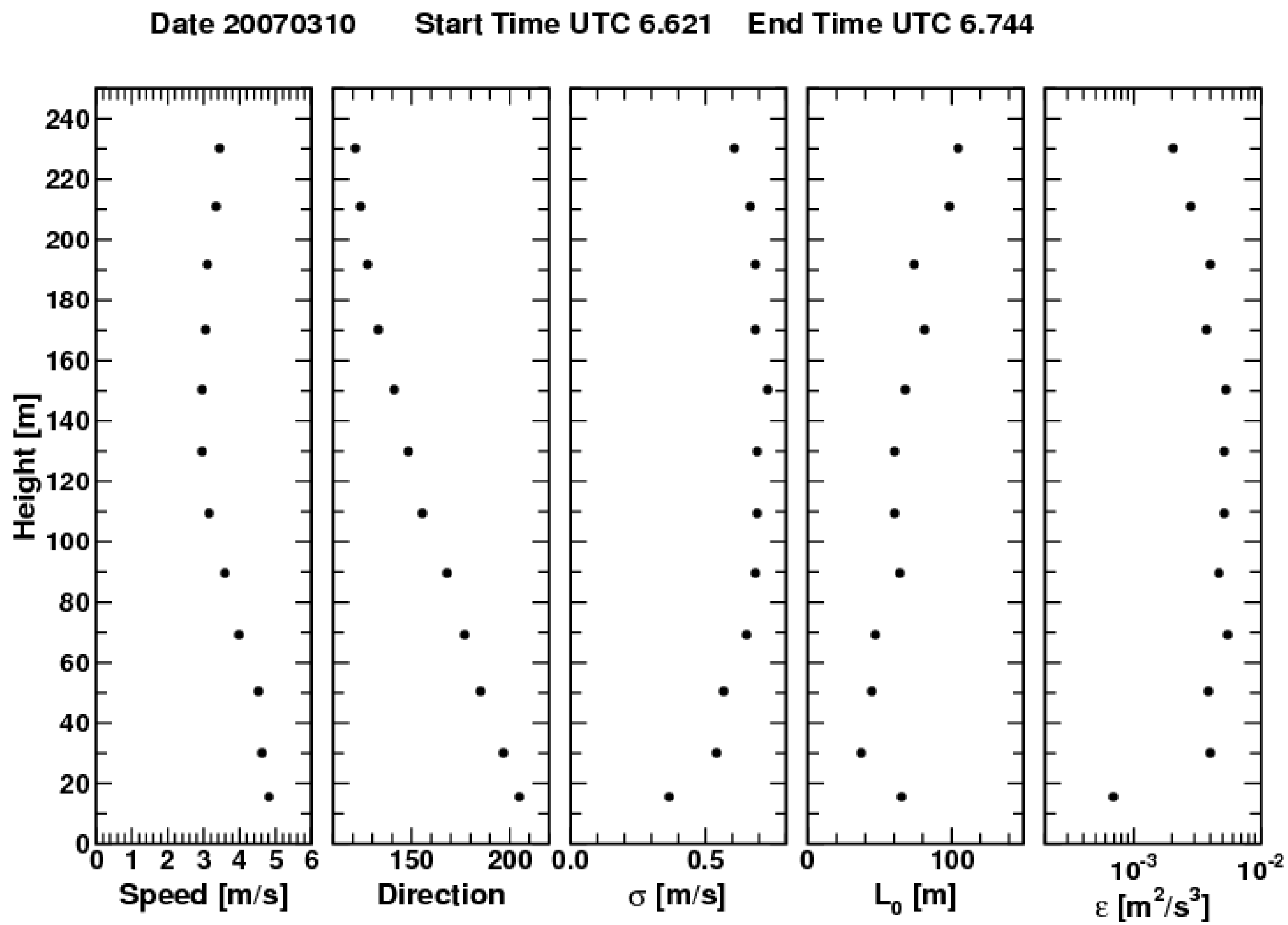
Rapid Evolution in 7 Minutes

- Rapid change in wind speed
- Turbulence levels are not reduced with lower winds
- 3D scanning required for short time averages



Directional Shear

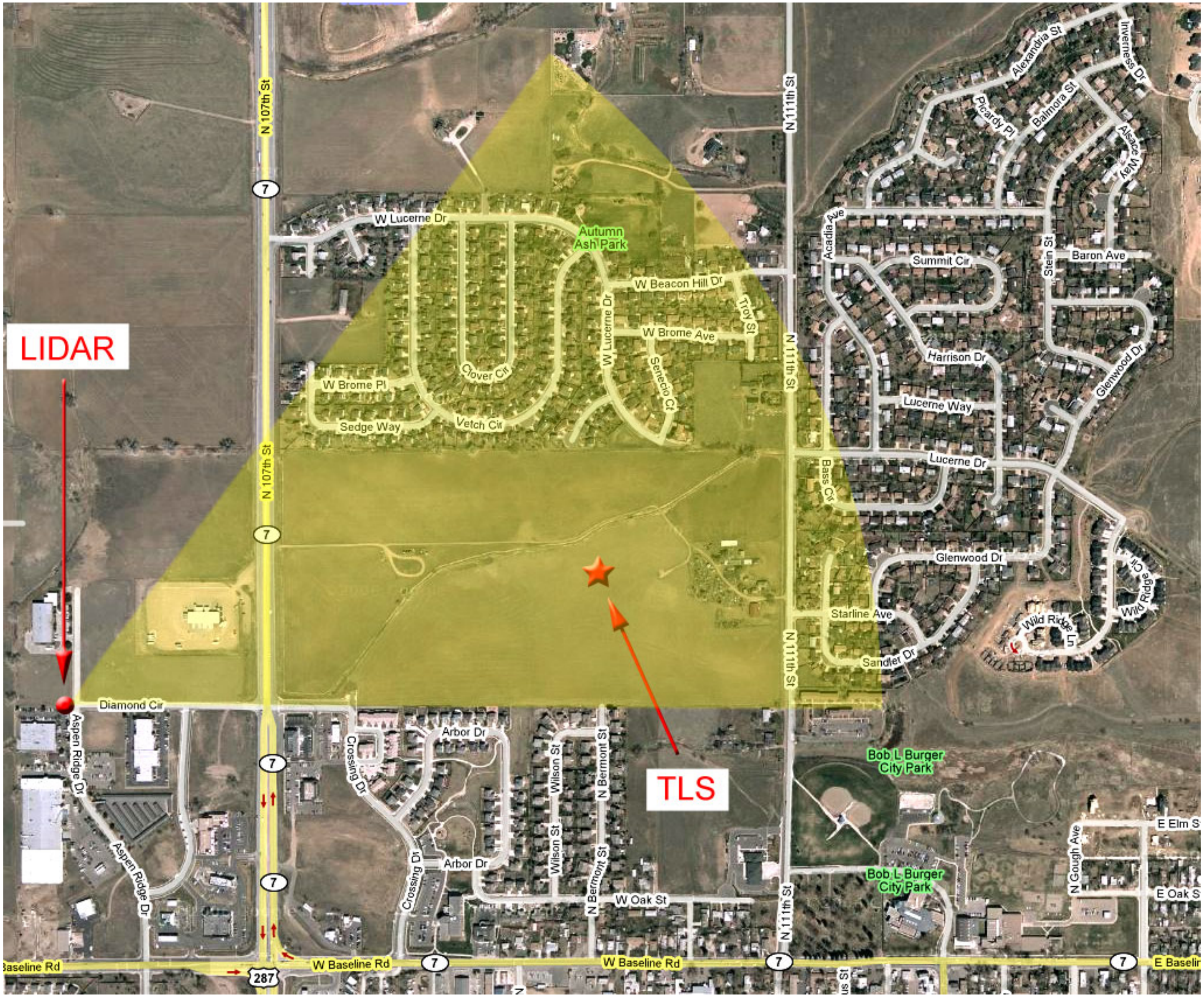
- Large shear in wind direction
- Typically at night with light winds
- More data required for wind energy applications



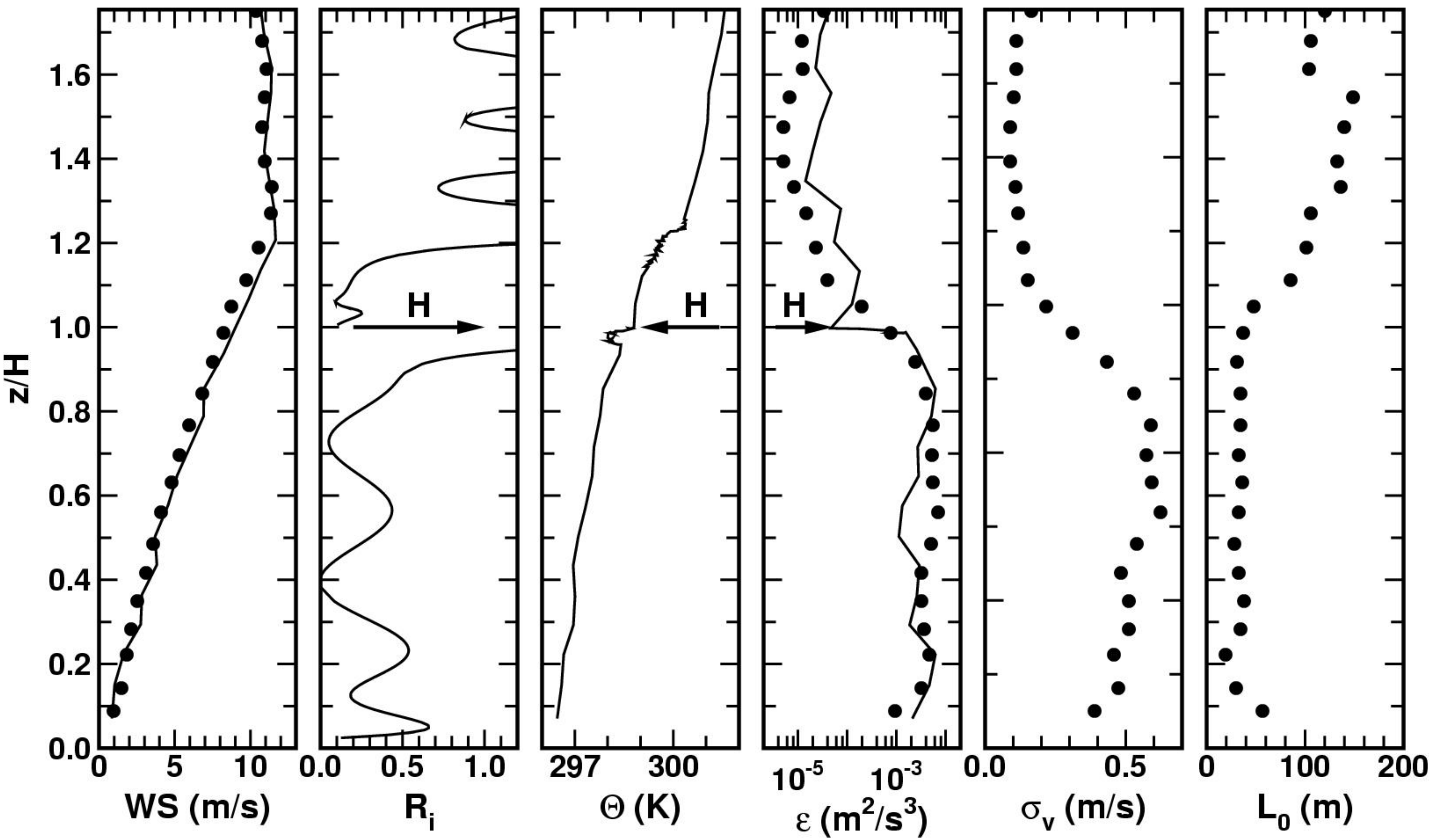
Future Work

- **Optimize Lidar design, signal processing, and scanning patterns**
- **Determine universal description of turbulence for better turbulence estimates (anisotropy?)**
- **Extend spatial filter correction to two dimensions for faster scanning and larger maximum range**
- **Improve algorithms for large length scale L_0 (relax Cartesian approximation)**
- **More data required, especially for wind energy research**

Lafayette Campaign

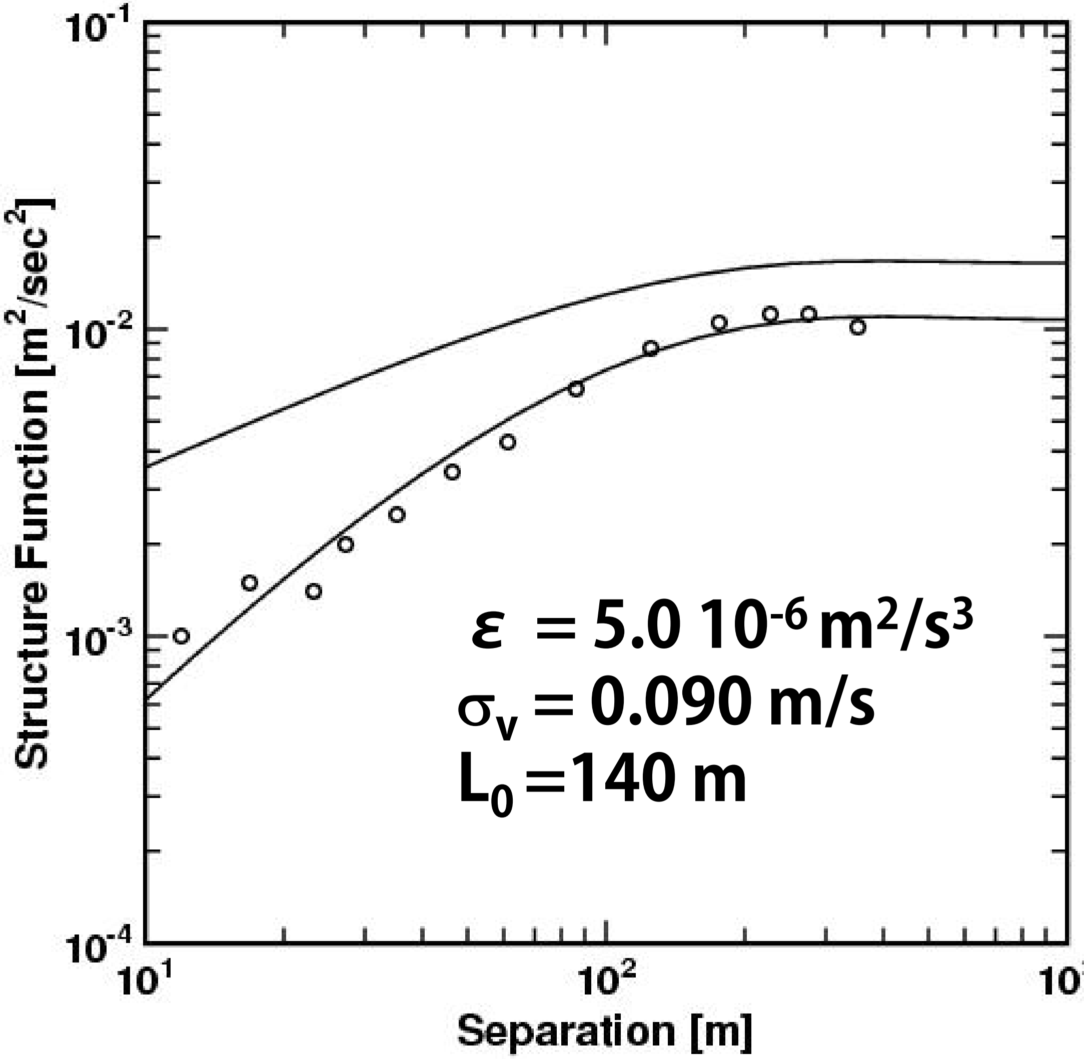


LIDAR and TLS (Blimp)

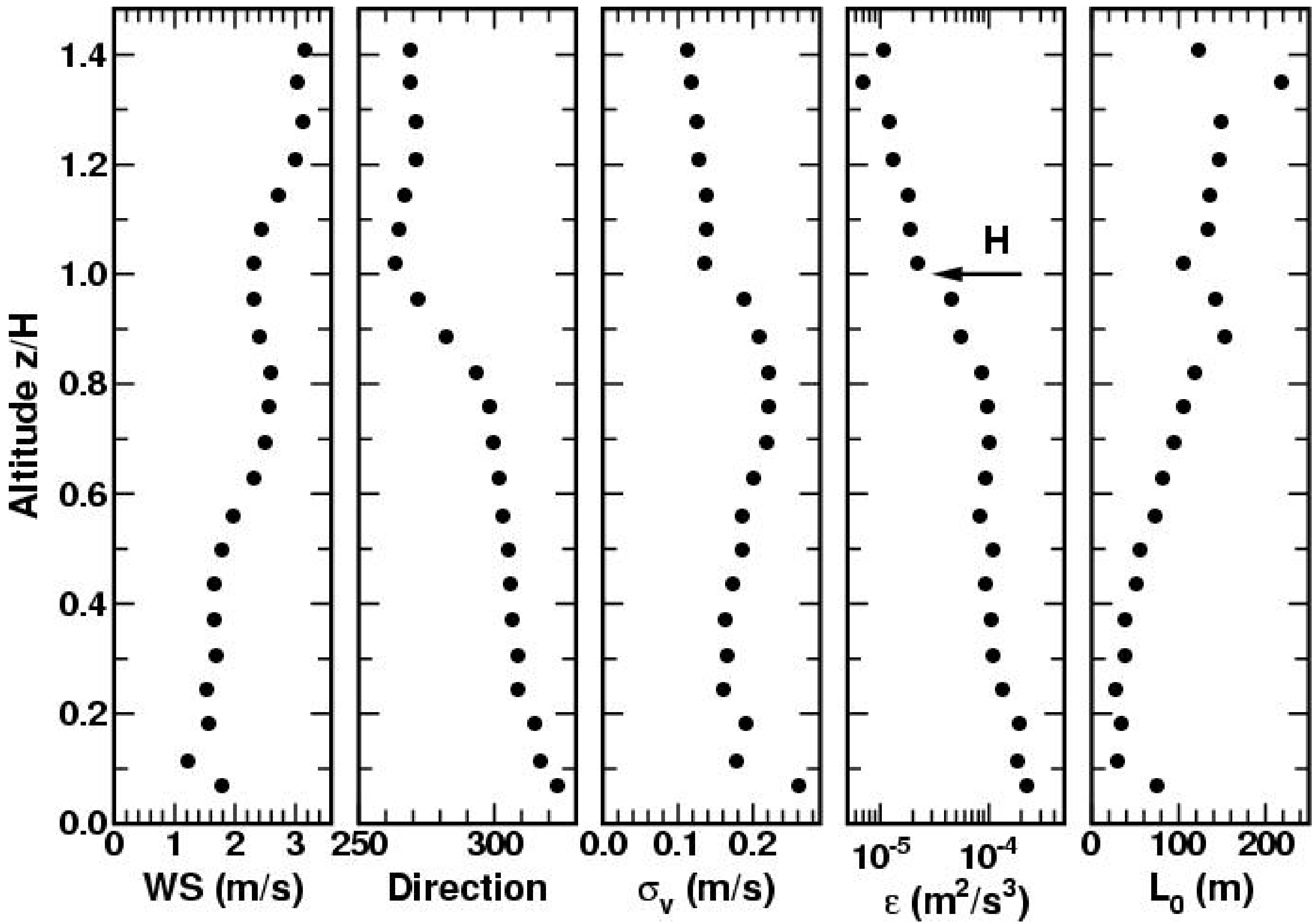


Low Turbulence Data

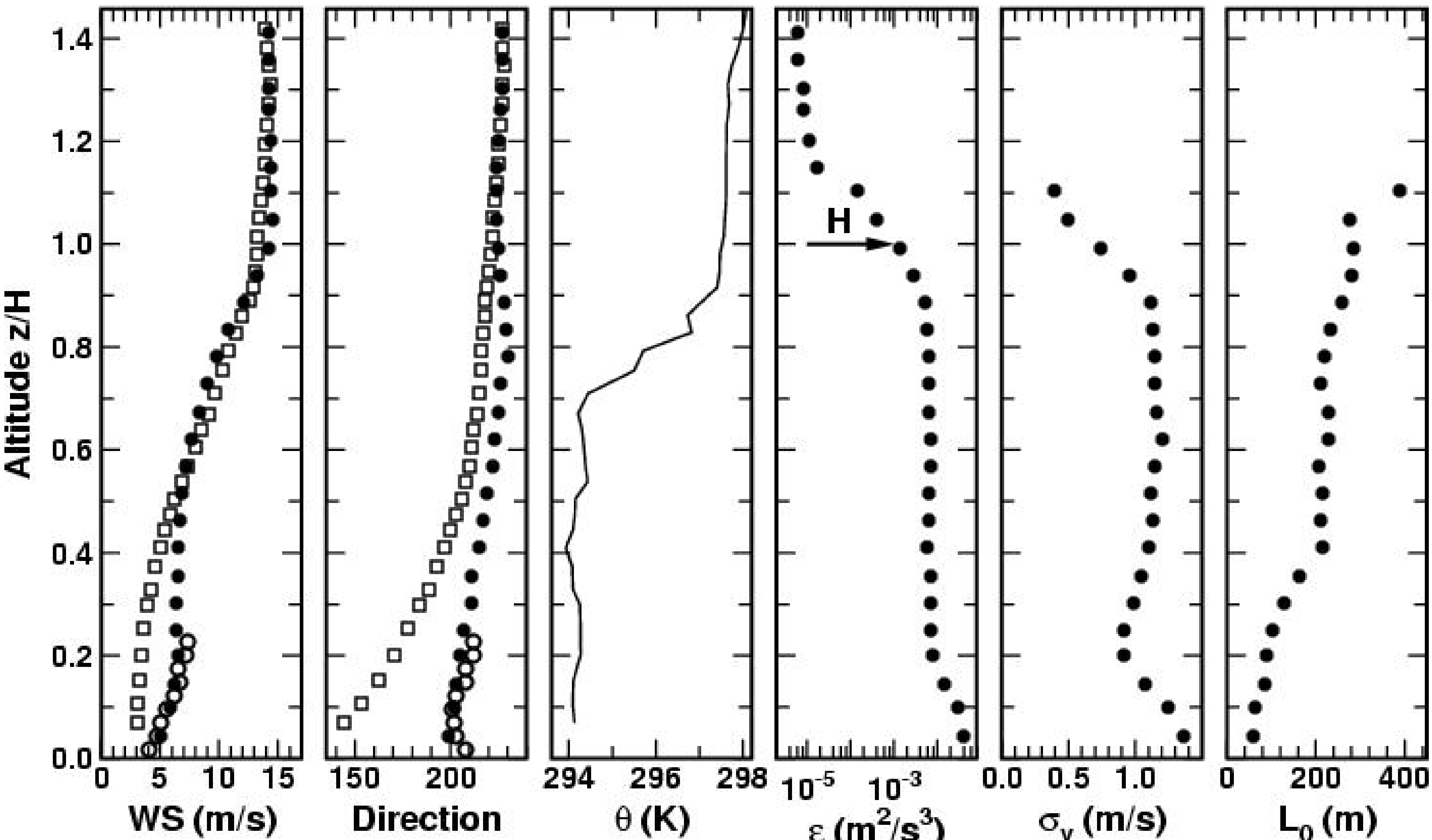
- **Accurate corrections for pulse filtering required**
- **Correct turbulence model for spatial statistics**



Low Turbulence Conditions



Convection



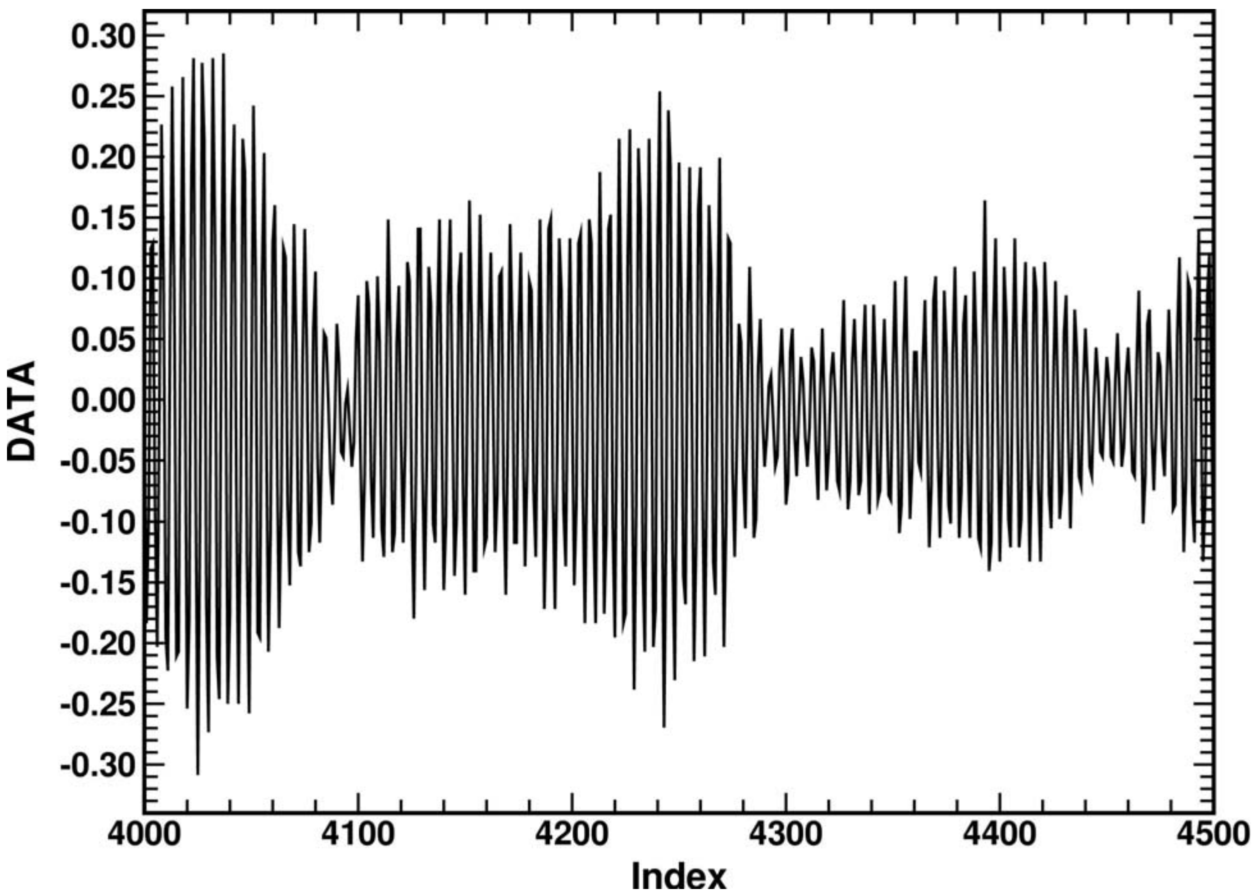
Altitude z/H
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
WS (m/s)
150
200
Direction
294
296
298
θ (K)
H
10^-5
10^-3
ε (m^2/s^3)
0.0
0.5
1.0
σ_v (m/s)
0
200
400
L_0 (m)

Coherent Doppler Lidar Properties

- **Direct measurement of Doppler shift from aerosol particles**
- **Doppler shift 1 MHz for 1 m/s (2 µm)**
- **Accurate radial velocity estimates with little bias**
- **Most sensitive detection method**
- **Immune to background light**
- **Eye safe operation**

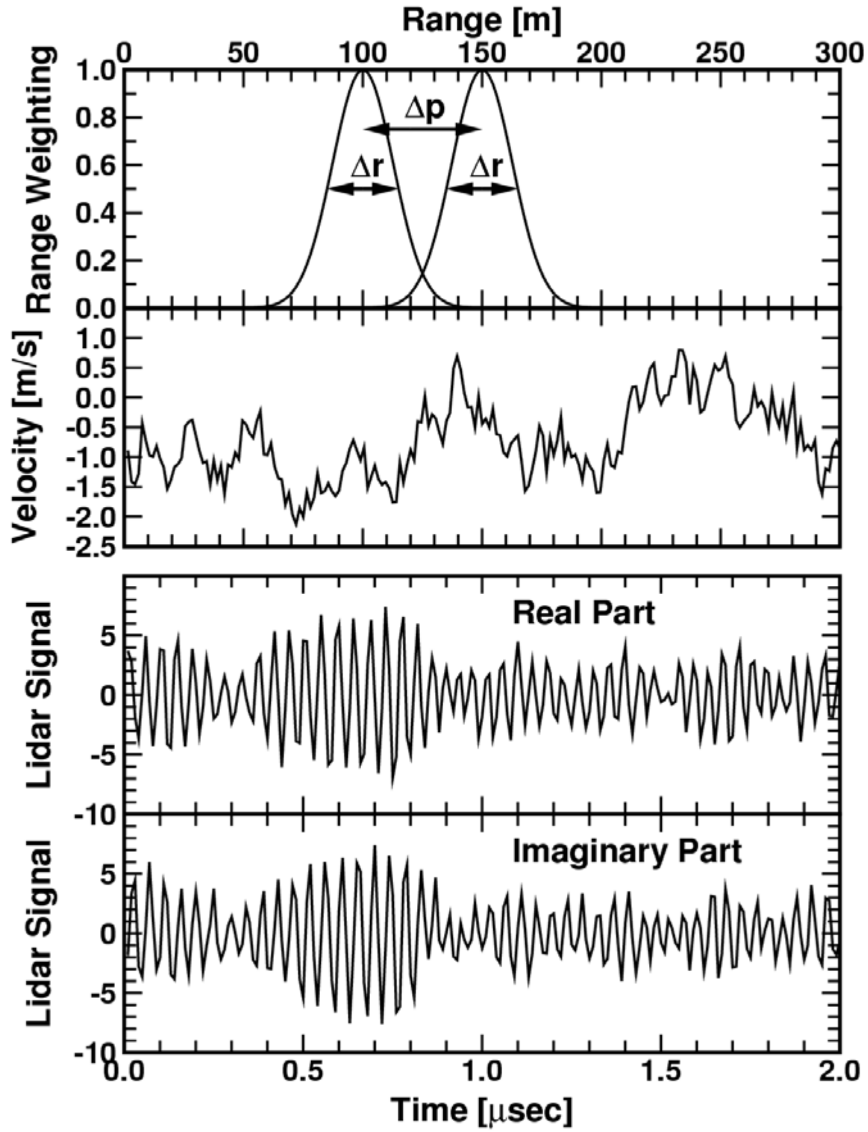
Atmospheric LIDAR Data

- Lidar signal is a narrow band Gaussian random process
- Simple statistical description for constant velocity and aerosol backscatter



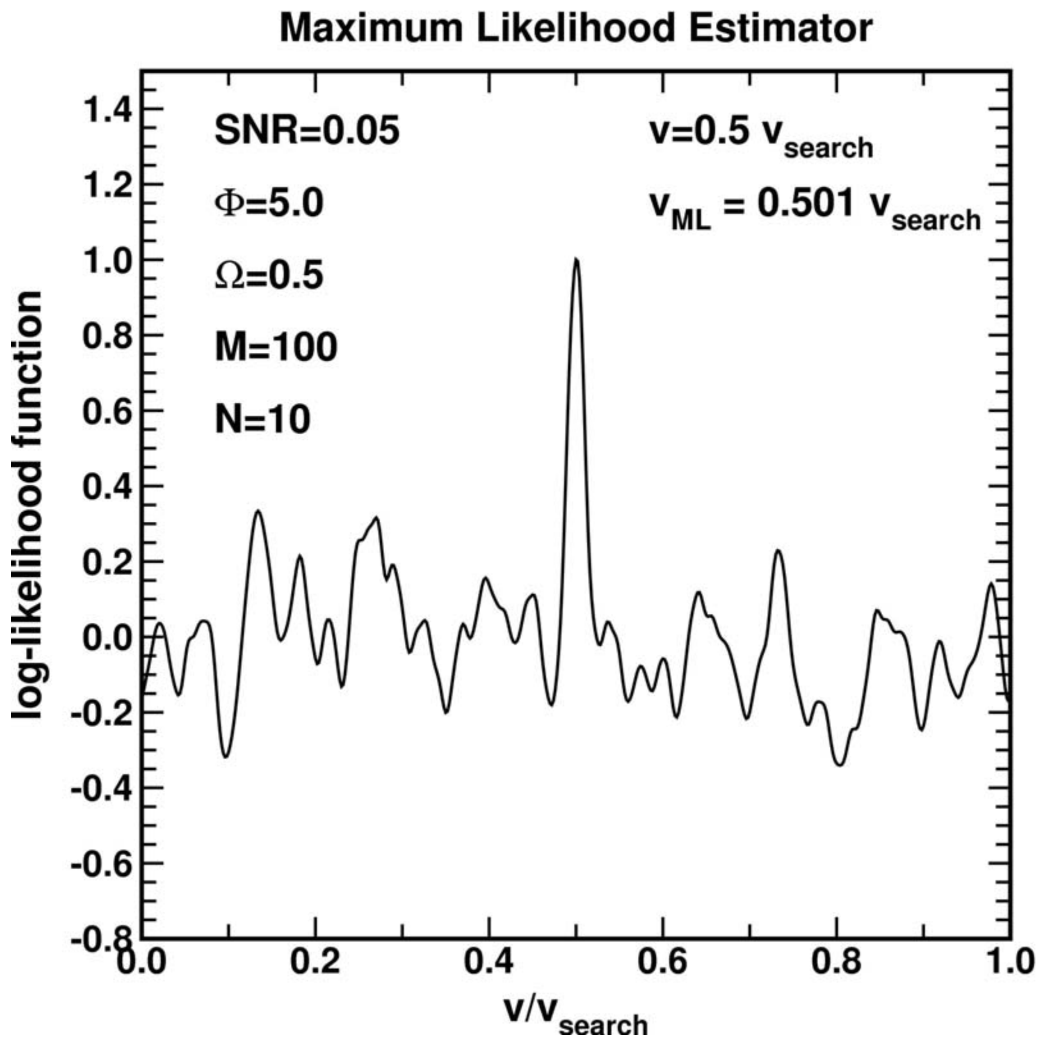
Atmospheric LIDAR Data

- **Lidar signal**
- **Random velocity**
- **Pulse weighting**
- **Range gate defined by processing interval**



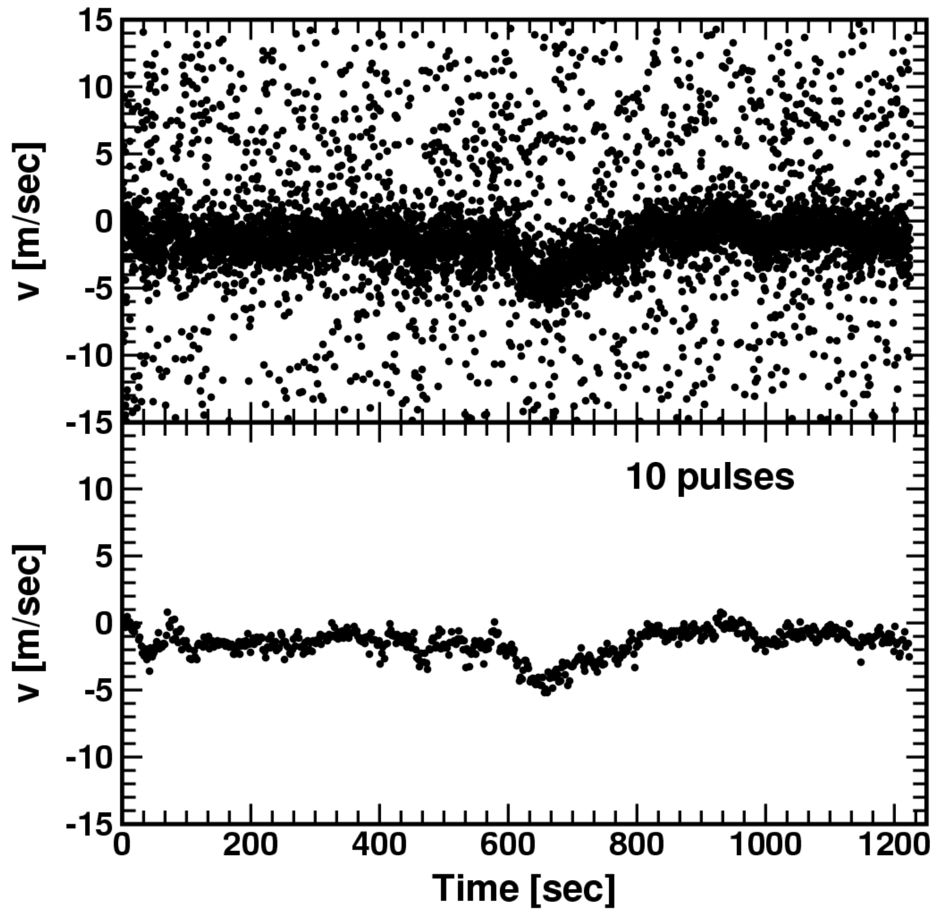
Estimation of Velocity

- Data from multiple pulses N improves performance
- Spectral based estimators
- Maximum Likelihood has best performance



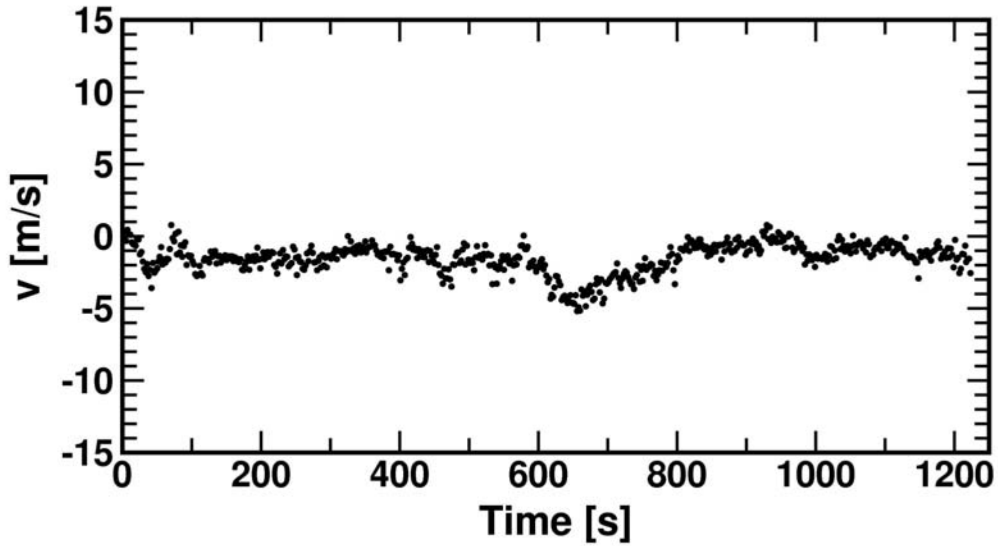
Multiple Pulse Estimates

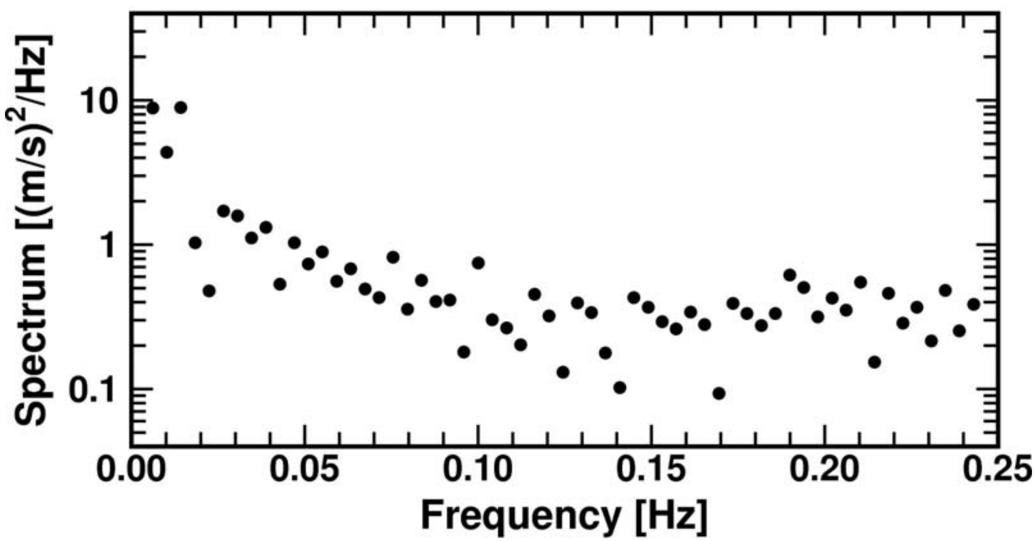
- **Single pulse data has random outliers**
- **Pulse accumulation removes outliers**
- **Temporal resolution reduced**



Estimates of Random Error-cont.

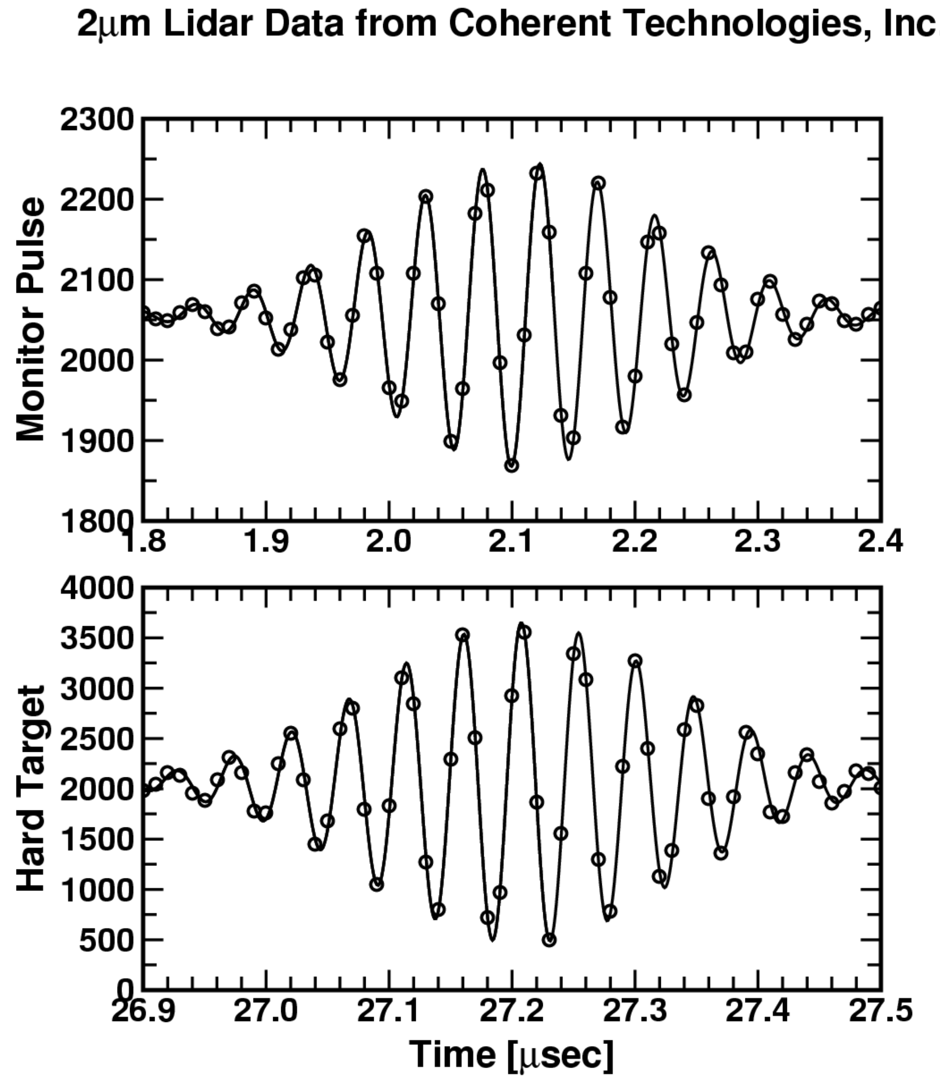
- **Multiple pulse data has a smaller region for the noise floor**
- **The atmospheric signal must have low frequency content**





Hard Target Data

- **Velocity bias determined from hard target data**
- **Bias is typically less than 2 cm/s**



Verification of Accuracy

- **Velocity random error depends on signal energy**
- **Accuracy is very good**
- **Agrees with theoretical predictions if turbulence is included**