Wind Power Needs

• Upstream wind profiles for short term forecasts

• Nearby wind and turbulence profiles for operations
Short Term (30 minute) Advection Forecast

- Power initiation requires a wind speed observation increasing above 5 m/s at a range of 9 km
- Full power production requires a wind speed observation increasing above 10 m/s at a range of 18 km
- Hub-height wind speeds are most desirable for short term forecasts
Beam is scanned to provide 2-3D spatial coverage.

2 \( \mu m \) wavelength system:
- 60 m (400 nsec) pulse transmitted at 500 Hz
- Portion of scattered light collected by telescope

1.6 \( \mu m \) wavelength system:
- ~40 m (270 nsec) pulse transmitted at 750 Hz
- ‘Pencil’ beam width 10-30 cm

Relative wind induces a Doppler frequency shift in the backscattered light; this frequency shift is detected by the sensor.

- 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
LIDAR Data and Turbulence
Frehlich 1997, 2008; Banakh and Smalikho 1997; Frehlich 2008

- LIDAR radial velocity estimates at range $R$
  $v(R) = v_{\text{wgt}}(R) + e(R)$
- $v_{\text{wgt}}(R)$ pulse weighted velocity
- $e(R)$ estimation error
- $v_r(z)$ random radial velocity
- $W(r)$ range weighting

$$v_{\text{wgt}}(R) = \int v_r(z) W(R-z) \, dz$$
LIDAR Radial Velocity Map for 1°
Frehlich et al. 2006

- Range gate 72 m
- 100 range gates along beam
- 180 beams ($\Delta \varphi = 0.5$ degree)
- 10 radial beams per second
- 18 seconds per azimuth scan
- $\Delta h = R \cdot \Delta \varphi << \Delta p$ for $R < 2$ km
Wind Speed and Direction
Frehlich et al. 2006

- Best-fit wind speed and direction at $R=2064$ m
- Fluctuations are turbulence
- Spatial extent of fluctuations is outer scale of turbulence $L_0$
Turbulence Estimates from Lidar

Frehlich et al. 2006

- Structure function of radial velocity in range a)
- Best fit produces estimates of $\sigma_u$, $\varepsilon_u$, $L_{0u}$
- Structure function in azimuth b)
- Best fit produces estimates of $\sigma_v$, $\varepsilon_v$, $L_{0v}$
Night Time Profiles

- Accurate profiles produced because of low instrument error and spatial average
- Most complete description of wind and turbulence
- Hub-height wind speed indicates full power but surface wind speed < 5 m/s
Moderate Turbulence

- Altitude 100 m
- Wind speed 10.6 m/s
- Best fit estimates ($\sigma = 0.79$ m/s, $\varepsilon = 0.011$ m$^2$/s$^3$, $L_0 = 43$ m)
- Test case for simulations of performance
LIDAR DATA at NREL  Frehlich and Kelley 2008

- Large turbulent eddies
- Large velocity variations
- Most challenging conditions for wind energy applications
High Turbulence  Frehlich and Kelley 2008

- Large fluctuations about the best fit wind speed
- 3D average required to increase the number of independent samples for accurate statistics
Atmospheric Profiles
Frehlich and Kelley 2008

- Profiles agree with nearby tower estimates
- Wind storm from foothills of the Rockies
- Challenging conditions for wind turbines
High Turbulence

- Altitude 109 m
- Wind speed 12.4 m/s
- Best fit estimates ($\sigma = 2.54$ m/s, $\varepsilon = 0.064$ m$^2$/s$^3$, $L_0 = 239$ m)
- Test case for simulations of performance
Doppler Lidar Simulation

moderate turbulence

- Hub-height 8° azimuth angle scan
- WindTracer lidar parameters
  - Range 20 km
  - Range-gate 1.5 km
  - 3000 laser pulses

![Signal Spectrum](chart.png)

- $A = 0.055$
- $v = -0.079 \text{ m/s}$
- $w = 0.962 \text{ m/s}$
- $\phi_1 = 1.644$
Estimator Performance

moderate turbulence

- $\Phi_1$-signal energy per shot
- $b$ – random outliers
- $g$-velocity error (instrument error for small $b$)
- $w$ – spectral width
Doppler Lidar Simulation

high turbulence

- Hub-height azimuth angle scan over 8°
- WindTracer lidar parameters
  - Range 20 km
  - Range-gate 1.5 km
  - 3000 laser pulses

![Graph with Signal Spectrum and Velocity in m/s]
Estimator Performance

high turbulence

- $\Phi_1$ - signal per shot
- $b$ – random outliers
- $g$-velocity error
  (instrument error for small $b$)
- $w$ – spectral width
Definition of Error

• For forecast error, truth is defined by the spatial filter of the model numerics

• For the initial field (analysis) truth should have the same definition for consistency

• For observation error, truth must have the same definition

• Data assimilation requires total observation error statistics
Observation Sampling Error

- Truth is the average of the variable $x$ over the $L \times L$ effective model filter.
- Total observation error $\Sigma_x^2 = \sigma_x^2 + \delta_x^2$
- Instrument error $= \sigma_x$
- Sampling error $= \delta_x$
- The observation sampling pattern and the local turbulence determines the sampling error.
# Observation Sampling Error

$L=5 \text{ km}$

<table>
<thead>
<tr>
<th></th>
<th>Moderate</th>
<th>High</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Rawinsonde-u $0.79 \text{ m/s}$</td>
<td>Rawinsonde-u $2.63 \text{ m/s}$</td>
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<tr>
<td></td>
<td>Rawinsonde-v $0.79 \text{ m/s}$</td>
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<td>Linear track $3 \text{ km}$</td>
<td>Linear track $3 \text{ km}$</td>
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<td>Tower-u</td>
<td>$0.11 \text{ m/s}$</td>
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<tr>
<td>Tower-v</td>
<td>$0.08 \text{ m/s}$</td>
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<tr>
<td>Lidar</td>
<td>$&lt; 0.05 \text{ m/s}$</td>
<td>Lidar $&lt; 0.08 \text{ m/s}$</td>
</tr>
</tbody>
</table>
Measurement at 18 km
(Lockheed Martin Coherent Technologies)

- Upstream wind profiles
- Spatial average over turbulence for higher accuracy
- Input for short-term power forecasts

θ=0.8° φ=119.0°-103.0° Δφ=4.962 km
N=6000 R=18.00 km R₁=16.50 km R₂=19.50 ΔR=3.00 km
H=0.251 km H₁=0.230 km H₂=0.272 ΔH=0.042 km
Measurement at 24 km
(Lockheed Martin Coherent Technologies)

- Noise correction has small error
- Light winds and low turbulence
- More data required for ramp events and high wind conditions

\[ \theta = 0.8^\circ \quad \phi = 119.0^\circ - 103.0^\circ \quad \Delta \phi = 6.616 \text{ km} \]
\[ N = 6000 \quad R = 24.00 \text{ km} \quad R_1 = 22.50 \text{ km} \quad R_2 = 25.50 \quad \Delta R = 3.00 \text{ km} \]
\[ H = 0.335 \text{ km} \quad H_1 = 0.314 \text{ km} \quad H_2 = 0.356 \quad \Delta H = 0.042 \text{ km} \]
Future Work

• Optimal signal processing and lidar scanning patterns

• Develop data products for short-term forecasts (wind speed, direction)

• Characterize atmospheric conditions for ramp events and observation error

• Evaluate optimal data assimilation

• Develop a dedicated lidar processing module for short-term forecasting

• More data near wind farms
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• NREL, Neil Kelley
Coherent Doppler Lidar Properties

• Direct measurement of Doppler shift from aerosol particles
• Accurate radial velocity estimates with little bias
• Eye safe operation
• Errors are dominated by atmospheric variability
Doppler LIDAR Range Weighting
Frehlich 1997; Banakh and Smalikho 1997

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

- Global Forecast System (GFS) average velocity structure function (40-50 N)
- ACARS aircraft data (40-50 N)
- Theory for a square model filter with size L=150 km
Definition of Atmospheric Ensembles

- Statistical similar realizations for each time
- For NWP error, each realization has the same "truth" and same local turbulence statistics (e.g., $\varepsilon$ or $C_T^2$)
- Error statistics are the average over the infinite number of realizations
LIDAR Tower Comparison at Riso

“Lidar profilers for wind energy – The state of the art”, Mike Courtney, Petter Lindelöw, and Rozenn Wagner, AWEA WindPower, Chicago, 2009

- Leosphere WindCube located 11 m from tower
- 10 minute average data at 116 m altitude
- Contributions from instrument error and atmospheric turbulence