Wind Resource Assessment Using Long Range Pulsed Doppler Lidar

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Exciting Operational Progress

- Wind shear alerting: Japan, Hong Kong & Las Vegas
- New (2008) capacity-enhancing procedures based on lidar wake vortex observations
  - Improved closely spaced parallel runway operations → FAA National Rule Change
  - Enhanced departure queuing at Paris Charles de Gaulle
- Bankability for mast-replacement ‘vertical’ lidars in wind energy market
Overview

• Wind resource characterization motivations
  – Support to site development
  – Support to operations

• Pulsed Doppler LIDAR background
  – Specifications and capabilities
  – Sample results and validation measurements
    • Siting strategies and comparison results
    • Terrain-following wind speed views

• Summary
Wind Farm Site Development

Prospecting
- Review wind & transmission maps
- Factor topography
- Examine reference site wind data
- Develop preliminary layout
- Select mast anemometer locations

Preliminary Site Design
- Quickly mine available data/information

Wind Measurement
- Install masts & instruments
- Filter data to improve quality
- Correlate to long term wind
- Run wind flow models
- Establish site’s wind statistics and climatology

Long-Term Wind Prediction
- Gather Site-Specific Data Over 1-2 years
- Adjust preliminary layout
- Micro-site turbines
- Calculate energy
- Complete permitting and financial approvals

Site Layout & Energy Predict.
- Optimize Predicted Energy Output
Measure Correlate Predict (MCP)

• Challenge: available reference data is rarely on the site being developed
• Solution: combine short-duration site data with reference site data to yield site-specific long-term wind climatology
  – determine correlation over 1-2 year period
  – apply this relationship to determine an historic estimate at the site
  – apply weighting to finalize the long-term estimate at the site

• Estimate what would have happened over the past several decades
• Climatology and statistics improve accuracy of P90 and rare events (e.g., 50 yr gust)
Wind Characterization Key to Wind Farm Development

Current State

Point Data Collection
- Mast anemometer(s)
- Sodar(s)
- Emerging short-range lidars

Engr/CFD Modeling to Extend to Area Coverage
- Complex terrain, obstacles and/or environments difficult to model accurately

Model-Driven Predictions Anchored at One or a Few Points

Long Data Collection Periods Required to Resolve Uncertainties and Spot Check Problem Areas

Site Layout Often Sub-Optimal

• Current approaches see large (>10-20+% at times) errors in predicted versus observed energy production levels
  – Wind resource characterization is a major factor
Wind Farm Operations

- **Goal**: reduce wind energy integration costs
- Wind integration costs are a strong function of wind variability and uncertainty
- Better monitoring/knowledge of the wind over large areas can result in:
  - Ramp event prediction
  - Improved commitment and dispatch decisions
  - Improved (re)synchronization across multiple farms
  - Reduced fatigue loads and associated O&M costs
Long Range 3D scanning pulsed Doppler LIDAR

- Commonly referred to as a ‘horizontal’ LIDAR
  - Contrasts with short range, ‘vertical’ LIDARs
  - Fundamental principles are the same
- Measures wind at high spatial resolution in large volumes
- ‘High resolution’ means ~100m (x,y), ~5 m (z)
- ‘Large’ means 10-20km horizontal, 200+ m vertical
- Primarily deployed at airports for wind shear alerting to ATC/pilots
- How would this technology benefit the Wind Energy industry?
2 μm wavelength system:
60 m (400 nsec) Pulse
transmitted @ 500Hz

1.6 μm wavelength system
~40 m (270 nsec) Pulse
transmitted @ 750Hz

Beam Is Scanned to Provide
2-3D Spatial Coverage

Portion of Scattered Light Collected
By Telescope

‘Pencil’ Beam Width 10-30 cm

Return Light is Doppler Shifted by Moving Aerosols

Relative Wind Induces a Doppler Frequency Shift in the Backscattered Light; This Frequency Shift Is Detected by the Sensor

Eye Safe!

• Doppler Lidar = Infrared Doppler Radar
• Infrared: Instead of Raindrops, Lidar Uses Natural Particulates
• Doppler: Velocity/Wind Sensing (Strength)
• Radar: Accurate Position Information
Demonstrated ~15 km performance coverage (250+km²) in Colorado

Simple config changes allow trade of update rate and spatial resolution for greater range

Better performance will be achieved for lower altitude, higher aerosol loading environments
Demonstrated >20 km Performance
1 Hz Update Rate, Colorado USA
Demonstrated 25 km Performance
1 Hz Update Rate, Colorado USA

Doppler Spectrum versus Range

Radial Velocity versus Range

SNR versus Range
LIDARs measure relative wind vector along each line of sight or look direction:

\[ V_{LOS}(R) = \mathbf{L} \cdot \mathbf{W}(h, R) \]

\[ \Delta f_{LOS}(R) = -\frac{2}{\lambda} V_{LOS}(R) \]

Harmonic analysis applied

- Amplitude relates to wind speed
- Phase related to wind direction
- DC offset relates to vertical motion (3D)

All of these averaged over the conic cross section at that particular altitude
VAD Technique Applied to Volumetric Long Range Data

- Collect radial velocity data over a large spatial region
- Scan in azimuth at a constant elevation angle --- a tilt
- Apply VAD algorithm to the annular sector and derive vector velocity estimate for center of sector
- Repeat for next overlapping sector
- Derive vertical profile from multiple tilts & ranges
Disparate Requirements for LIDAR

- **Site Development**
  - Mast anemometer augmentation or replacement as virtual tower
    - “Point” measurement: cover swept area of turbine at a single position
    - Short range (<200 m) adequate
  - Large-area mapping to simultaneously sample multiple locations at a site
    - Mid range (3-5 km) may be adequate for small sites
    - Long range (8+ km) needed for larger sites
    - Very long range (20+ km) beneficial for offshore
Disparate Requirements for LIDAR (cont.)

• **Wind Farm Operations**
  – Feed forward control applications?
    • Install short-range LIDAR on each turbine
    • Utilize longer-range LIDAR to provide direct observation for multiple turbines
  – Wind integration applications?
    • LIDAR as part of sensor suite for large-area ‘live’ wind resource mapping
      – Approaching wind shifts, ramp events
      – Drives sensor to very long-range performance (20+ km)
Gust Front Event at LAS
Measurements at RES Site

- Large mesa-like site
- WindTracer® and 50 m fixed mast
- One month of data collection (June 2007)

Scan Strategy

- Volumetric 360 deg scan with 10 minute revisit time
- 16 Tilts utilized to ensure measurements between 70 and 90m AGL available at all viewable points within 6 km of lidar
- Resolution of 100 m radially, 2° in azimuth, <1° elevation
- Indicatively 100m resolution (x,y,z)

GOAL:
‘Terrain-following’ gridded output of wind vectors at 10 minute intervals
Sample Cross-Comparison Data

Sample data from June 7

Lidar provides spatial distribution of velocities, but at a slower update rate at each point in space

Solid agreement for wind speed and direction

Azimuth to Tower: 326.1 degrees (True)
Dist Lidar to Tower: 3442 meters
Correlation Analyses

- Entire month’s data is utilized (June 2007)
- Smoothed anemometer data with a 10 minute wide sliding window average
- Selected best time match condition for lidar scan over the tower
- Lidar data provides ‘instantaneous’ vector wind estimates separated in time by 10 minutes
Wind Speed Comparisons

• Mean wind speeds agree to roughly 0.02 m/sec!

• Correlation is 96%

• RMS difference is 1.1 m/sec
Wind Direction Comparisons

- **Mean/median wind direction agrees to ~2 deg**
- **Correlation** is 96%
- **RMS** difference is 15 deg

*Conditioned on 60-360 deg wind direction and >3 m/sec wind speed*
Terrain-Following Wind Speed Map

Month-Long Average Wind Speed at Nominal Hub Height (80 m)
Terrain-Following Wind Map Showing Onset of Nocturnal Jet

Four Sample Points Showing Distinct Height-Time Speed Development

20 June 2007
Wind Characterization in Support of Wind Farm Development

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Future State
Simultaneous Large Area Data Collection
- 3D Doppler lidar w/ 200 km² coverage
- Potentially augmented w/ precision point sensor
- (Terrain-following) gridded vector maps
- Turbulence mapping also possible

Engr/CFD Modeling Requirements Greatly Relaxed, Accuracy Improved

Data-Driven Prediction and Real Wind Maps

Data Collection Periods Reduced and Rapidly Adapted to Meet Needs

Site Layout Optimized!
Summary

• An exciting time for terrestrial Doppler wind lidar
  – Multiple commercial systems being developed and sold
  – Short range to long range versions

• Credibility growing in multiple markets
  – Operational airport wind hazard measurements
  – Mast anemometer replacement or augmentation

• Wind Energy industry of special focus recently
  – Pulsed Doppler LIDAR demonstrations show promise with excellent early validation results
  – Disparate requirements challenge system design
    • Site selection and wind farm development
    • Wind farm operations: 15+ km performance attractive