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 → Preliminary Site Design → Wind Measurement → Long-Term Wind Prediction → Site Layout & Energy Predict.

Quickly mine available data/information

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

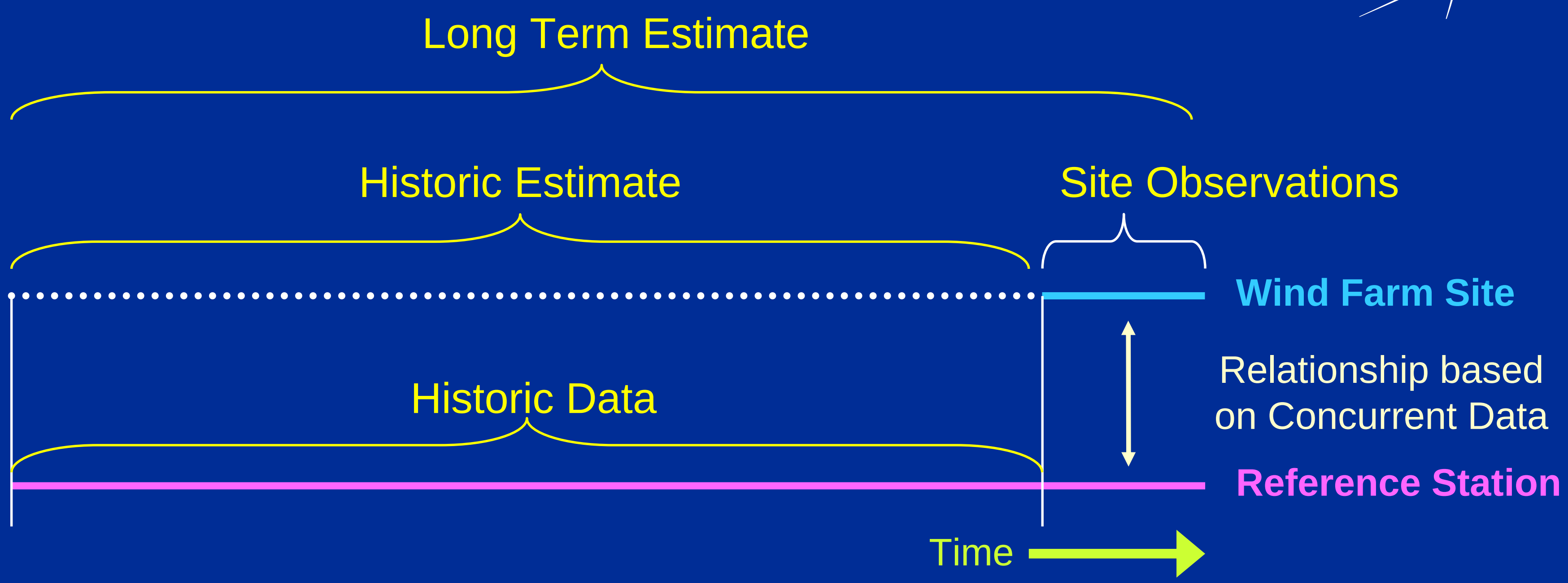
Gather Site-Specific Data Over 1-2 years

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

Optimize Predicted Energy Output

- Adjust preliminary layout
- Micro-site turbines
- Calculate energy
- Complete permitting and financial approvals

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

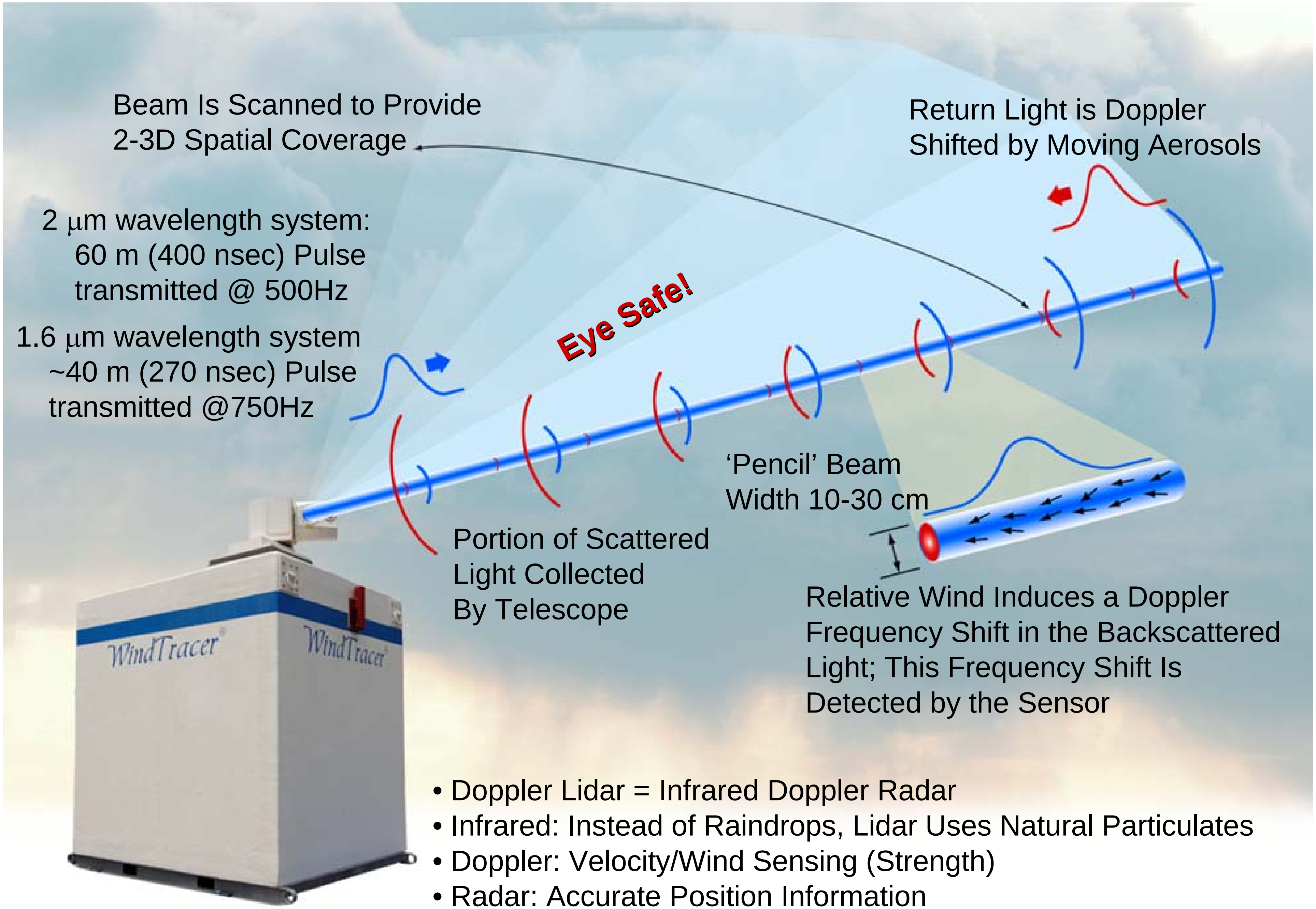
- **Current approaches see large (>10-20+% at times) errors in predicted versus observed energy production levels**
  - **Wind resource characterization is a major factor**

Wind Farm Operations

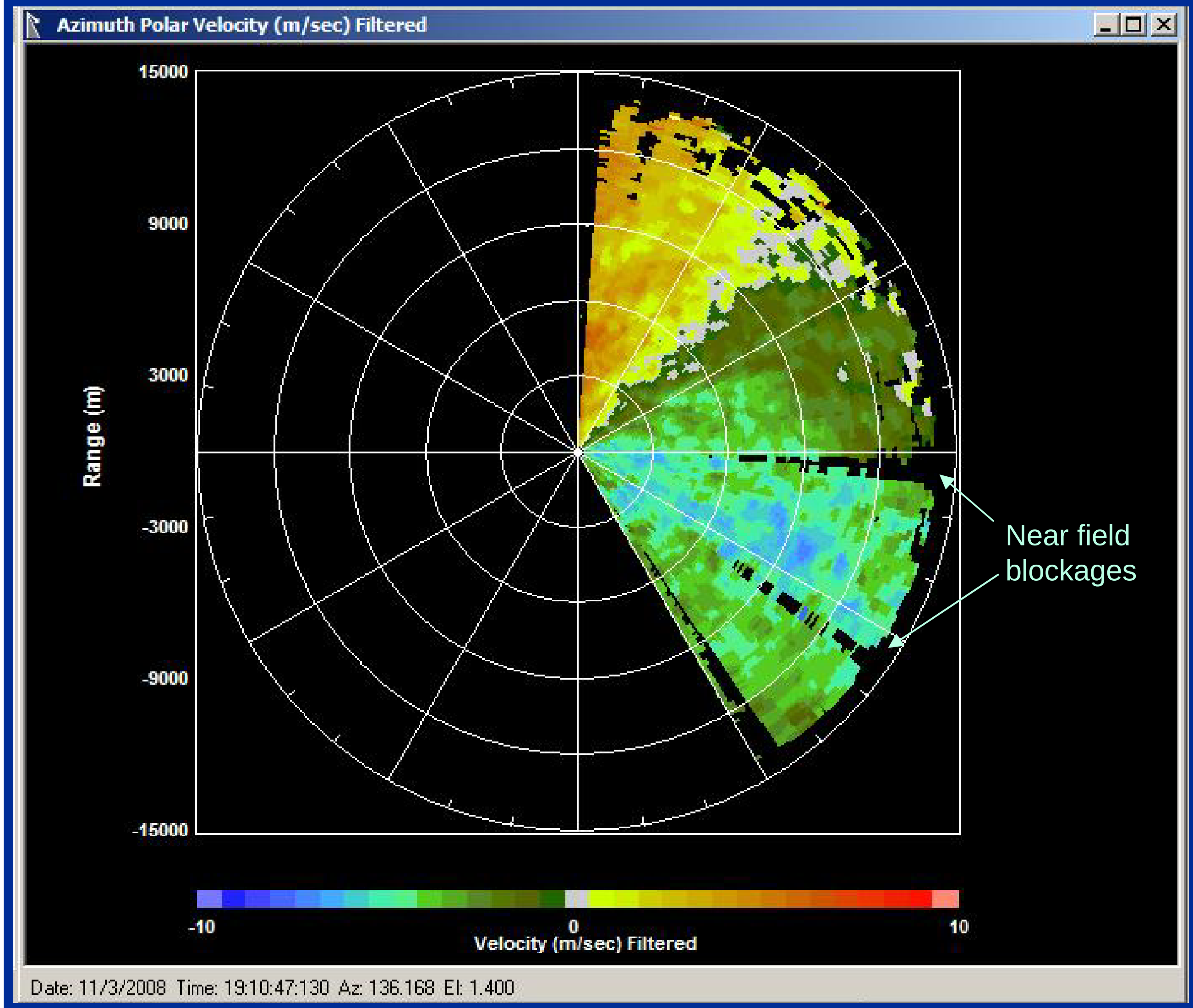
- <u>Goal</u>: reduce wind energy integration costs
- Wind integration costs are a strong function of wind variability and uncertainty
- Better monitoring/knowledge of the wind over large areas can result in:
  - Ramp event prediction
  - Improved commitment and dispatch decisions
  - Improved (re)synchronization 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?


Beam Is Scanned to Provide
2-3D Spatial Coverage
Return Light is Doppler
Shifted by Moving Aerosols
2 µm wavelength system:
60 m (400 nsec) Pulse
transmitted @ 500Hz
1.6 µm wavelength system
~40 m (270 nsec) Pulse
transmitted @750Hz
Eye Safe!
'Pencil' Beam
Width 10-30 cm
Portion of Scattered
Light Collected
By Telescope
Relative Wind Induces a Doppler
Frequency Shift in the Backscattered
Light; This Frequency Shift Is
Detected by the Sensor
WindTracer
WindTracer
• 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+km^2) in Colorado

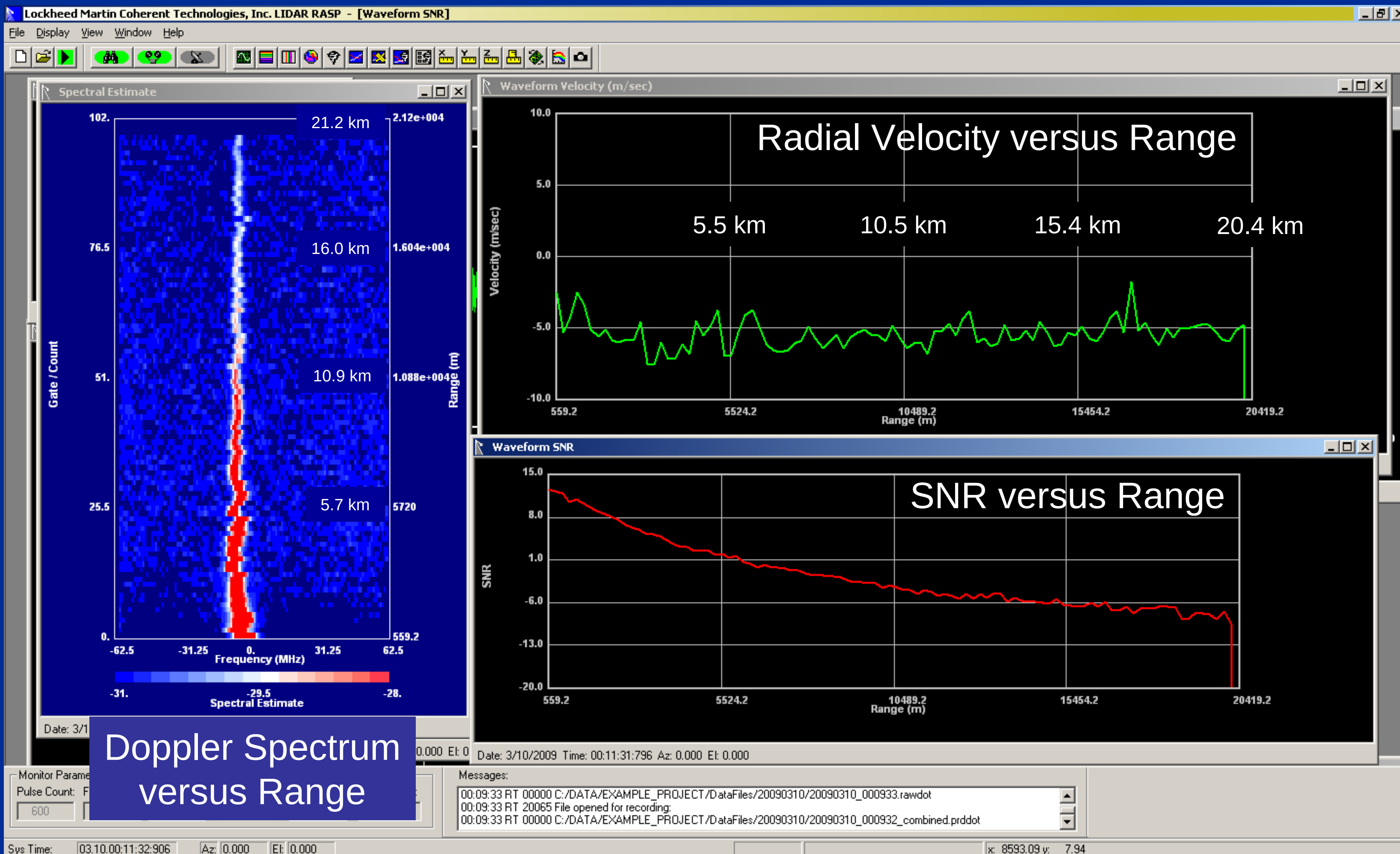


Simple config changes allow trade of update rate and spatial resolution for greater range

Better performance will be achieved for lower altitude, higher aerosol loading environments

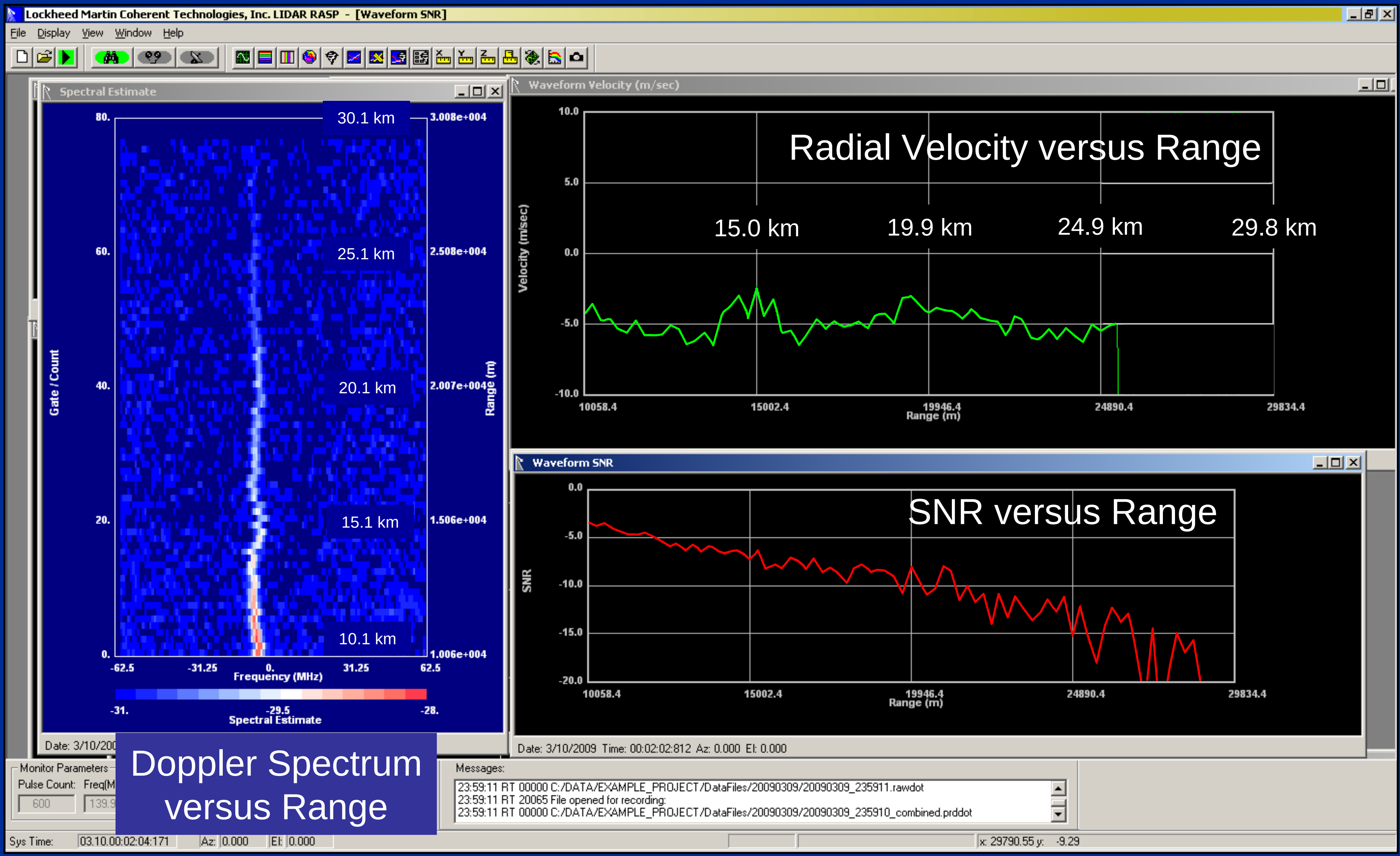
Demonstrated >20 km Performance

1 Hz Update Rate, Colorado USA



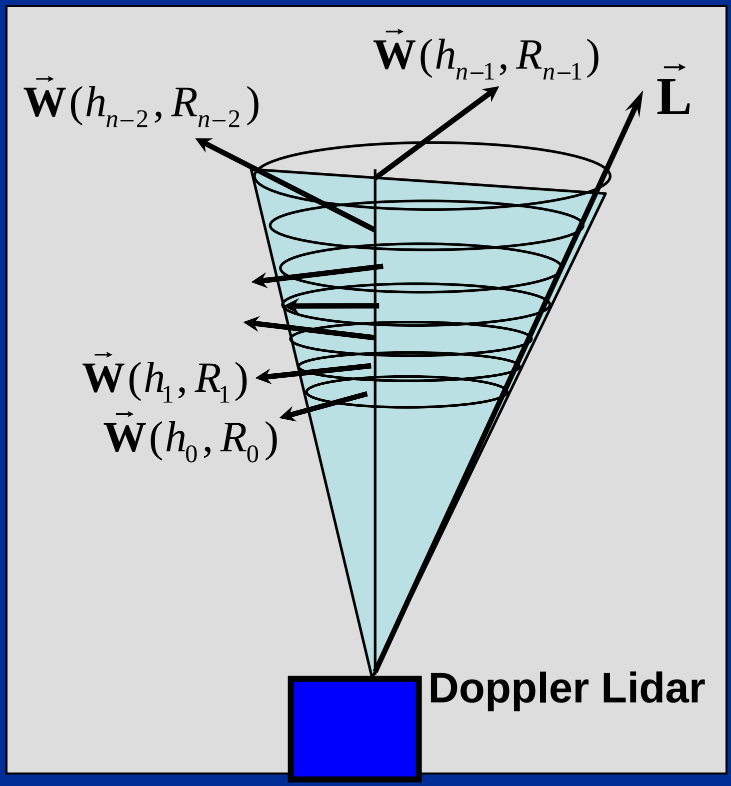
Demonstrated 25 km Performance

1 Hz Update Rate, Colorado USA



Velocity Azimuth Display Vector Wind Technique

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



$$V_{LOS}(R) = \vec{\mathbf{L}} \bullet \vec{\mathbf{W}}(h, R)$$

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

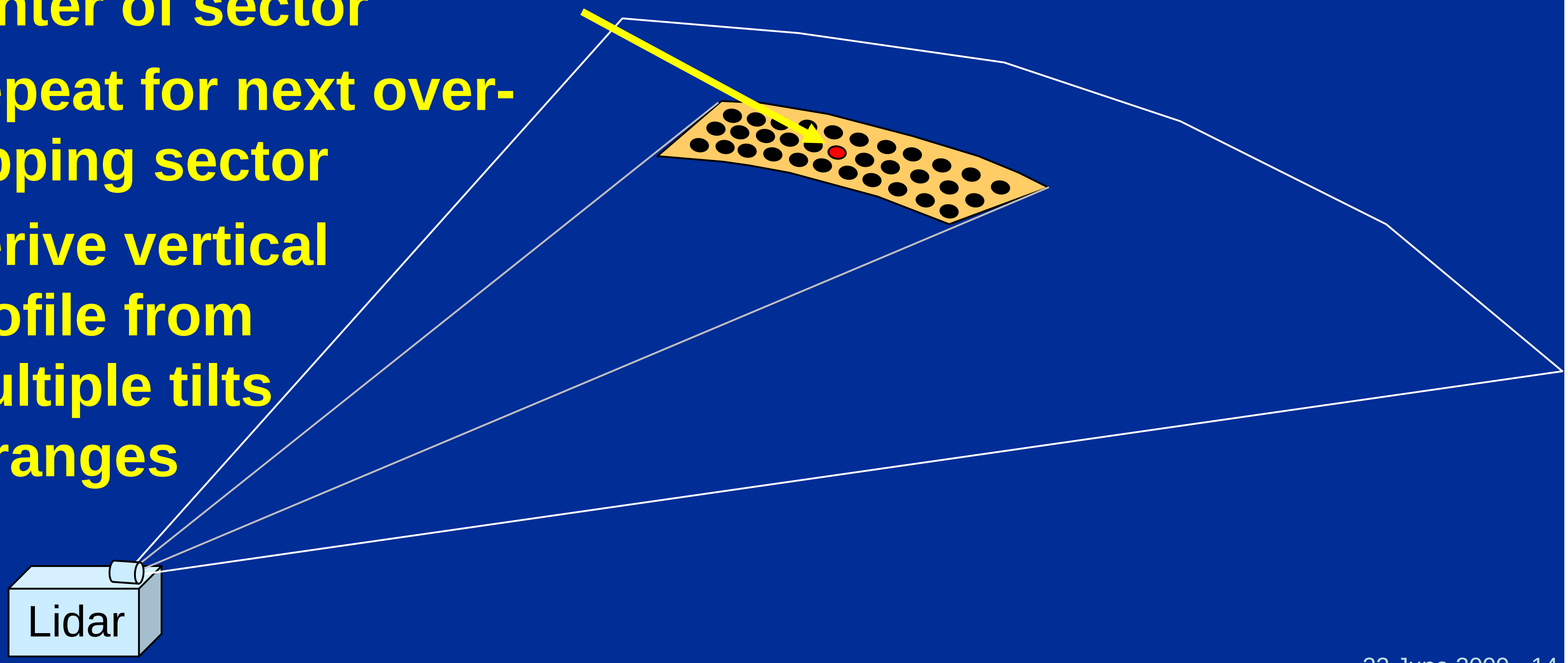
Harmonic analysis applied

- **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 over-lapping sector
- Derive vertical profile from multiple tilts & ranges



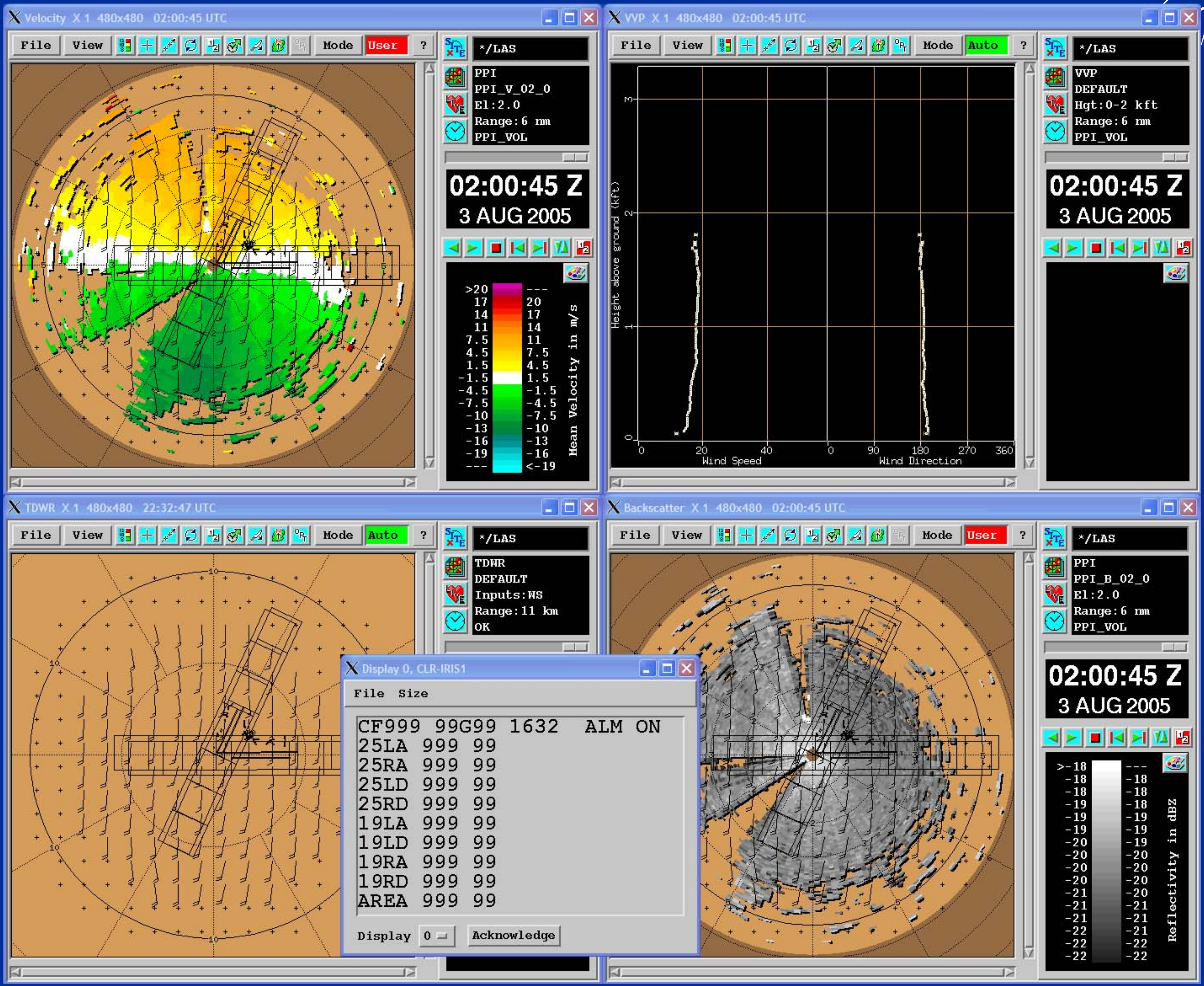
Disparate Requirements for LIDAR

- **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.)

- <u>Wind Farm Operations</u>
  - 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

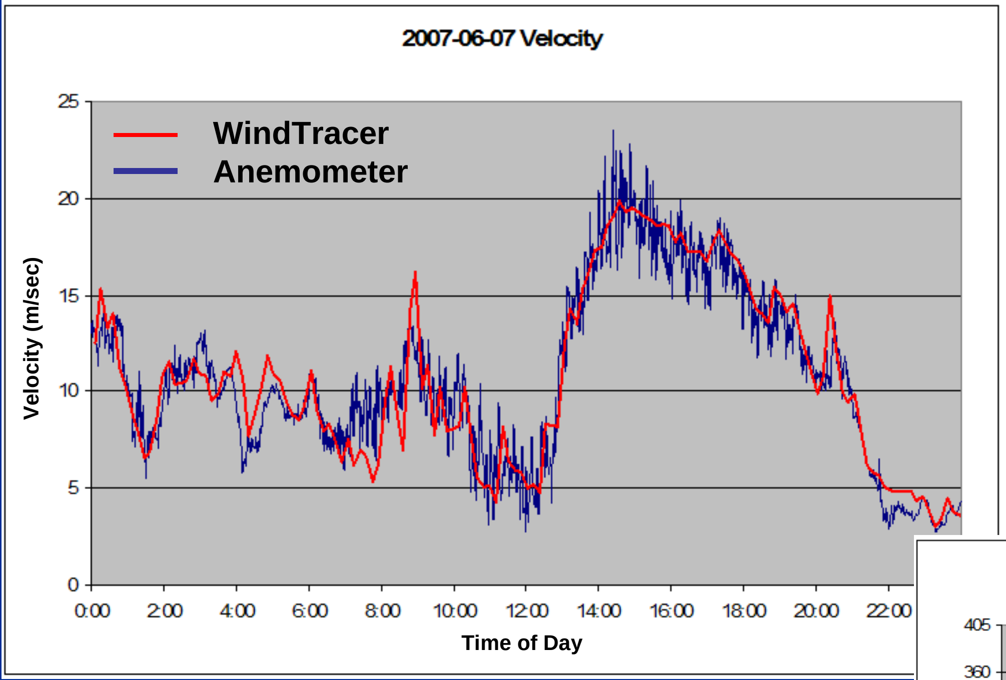
- **Large mesa-like site**
- **WindTracer® and 50 m fixed mast**
- **One month of data collection (June 2007)**

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

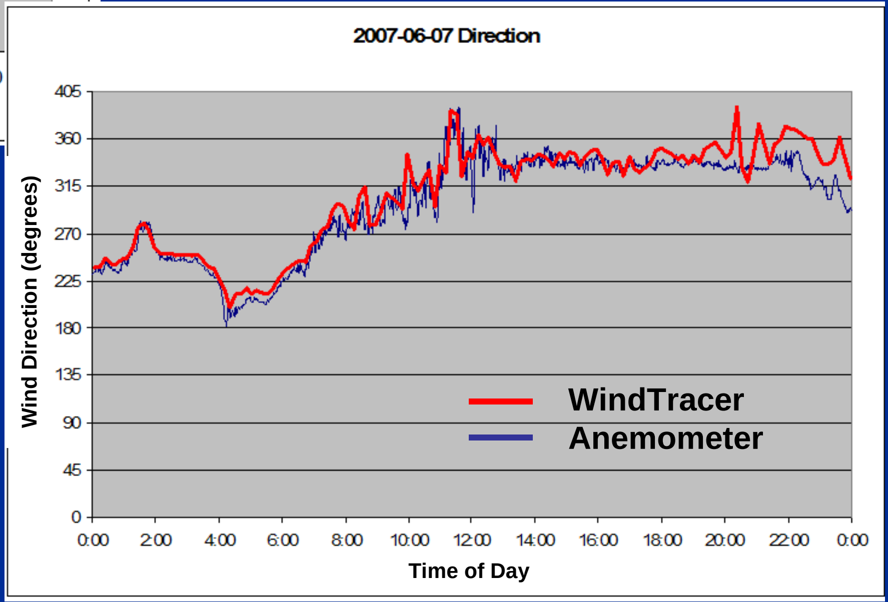
Sample Cross-Comparison Data



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

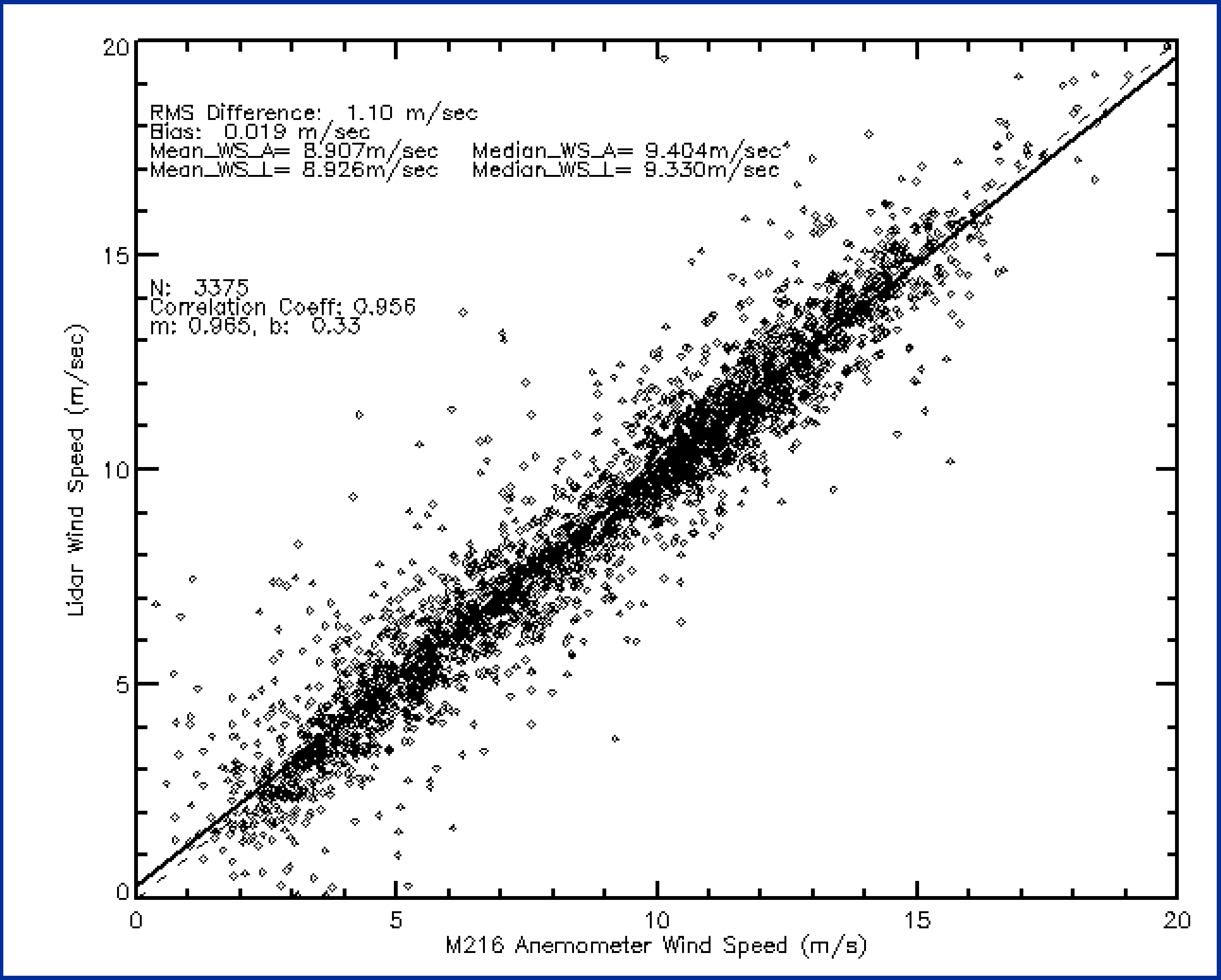
Correlation Analyses

- 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

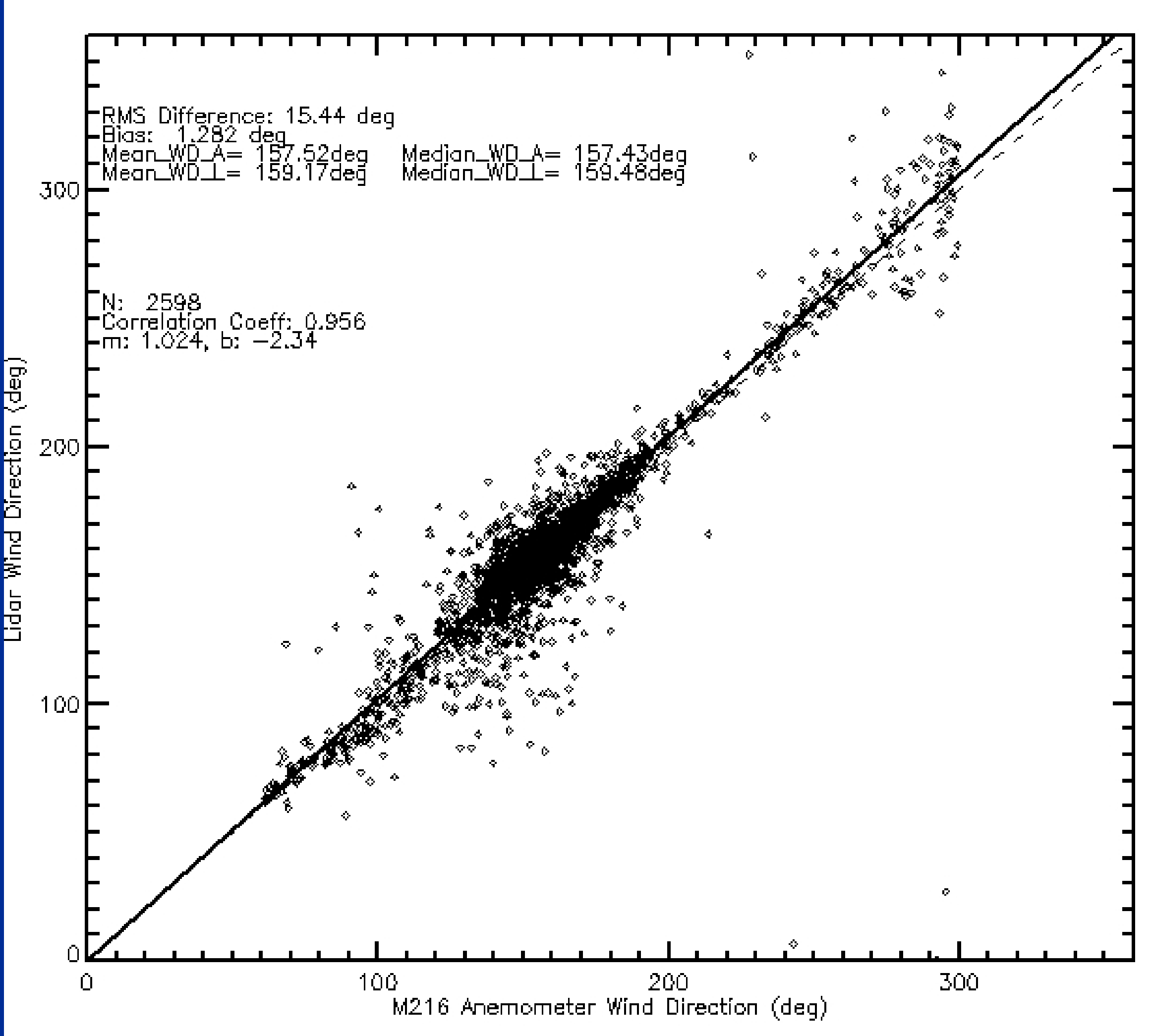
Wind Speed Comparisons

- **Mean wind speeds agree to roughly 0.02 m/sec!**
- **Correlation is 96%**
- **RMS difference is 1.1 m/sec**



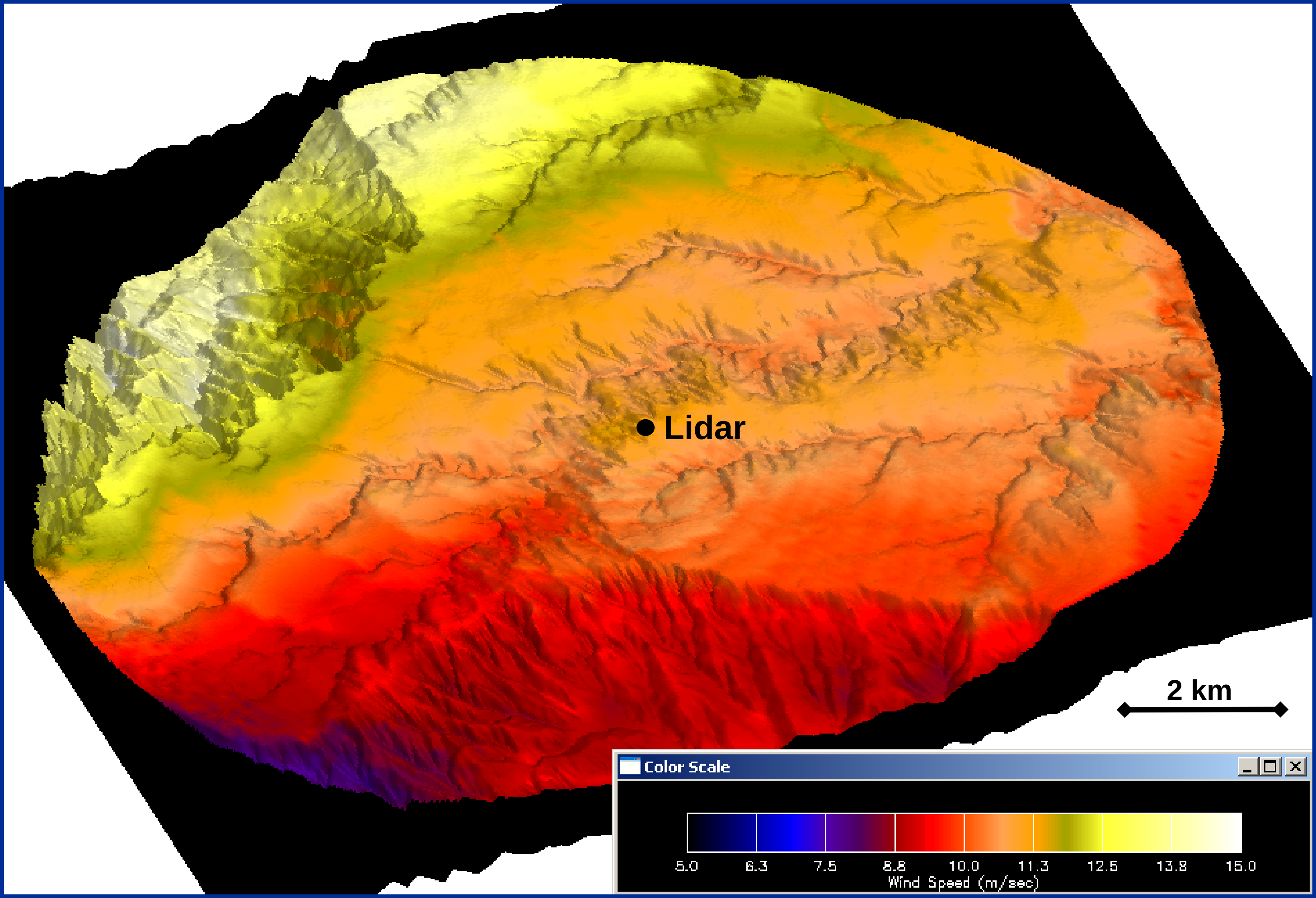
Wind Direction Comparisons

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



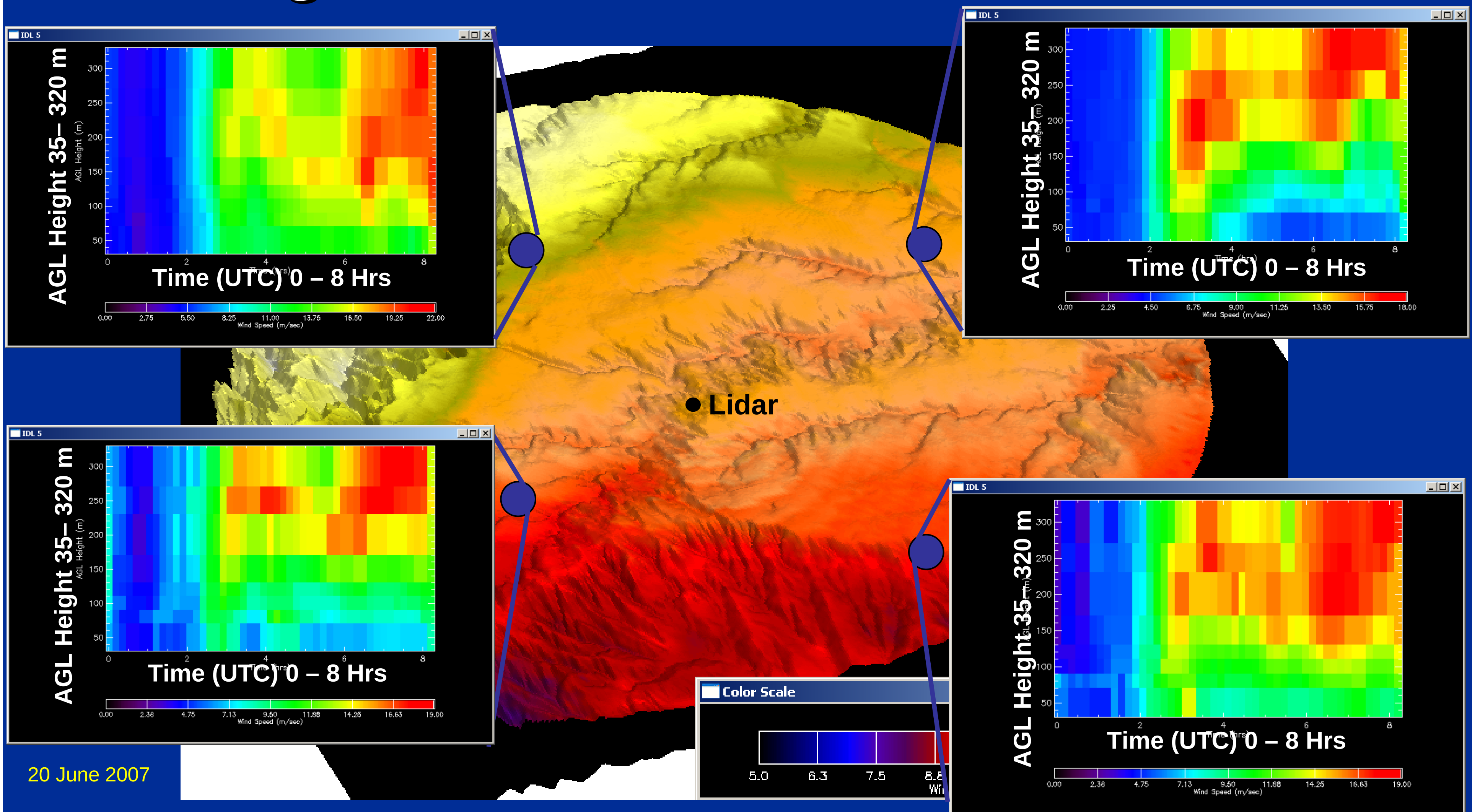
*Conditioned on 60-360 deg wind direction and >3 m/sec wind speed

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

Wind Characterization in Support of Wind Farm Development

Current State

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Future State

Simultaneous Large Area Data Collection
- 3D Doppler lidar w/ 200 km^2 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