Parameter Trade Study of Space-Based Coherent Doppler Lidar Wind Measurement Using NASA’s 2006 Wind Mission Study Parameters

Michael J. Kavaya
NASA Langley Research Center
michael.j.kavaya@nasa.gov

Working Group on Space-Based Lidar Winds
Miami, FL

Feb. 6-9, 2007
Nominal Mission Parameters

- Demo wind measurement requirements: 2 lines of horizontal wind profiles
- 2006 Wind Mission Study vertical resolution: 500/2000/3000
- 400 km, 45 deg nadir, 4 azimuth angles
- 0.25 J, 5 Hz, 0.5 m, no nadir angle collection loss, 2.053 microns, 180 ns
- 3 dB misalignment loss, no SNR reserve, no unexplained loss
- 20 m/s full LOS processing search bandwidth, last pass through data
- LSE = 11.5% not including misalignment loss; 5.8% with misalignment loss
- 60 shot accumulation attempted; 12 s; 85.2 km
- Assume 1.5 s to change azimuth angle
- Pattern repeat = 4 x (12 + 1.5) = 54 s = 390 km
- 0.14 km⁻¹ cloud layer at 9-10 km (GTWS requirement)
- 2-3 km cloud layer blocks half of lidar shots (GTWS requirement)
- Aerosol backscatter profiles: background and enhanced; 50th percentile (GTWS requirement)
- No vertical shear of horizontal wind velocity; always aligned with beam (broadens signal spectrum)
- 1 m/s design 1-σ wind turbulence (broadens signal spectrum)
- 0.5 m/s 1-σ laser difference frequency knowledge error
- Sampling/representativeness error = 0.67 m/s (85 km line in 100 km box)
• Requirements call for >50% success rate after cloud blockage effects (gray area above)

• Error (RMSE) is LOS projected to horizontal direction incl. atmosphere, then incl. horizontal sampling error

 Courtesy Dr. G. David Emmitt
Vertical Resolution Requirement

![Graph showing the relationship between altitude and vertical resolution requirement.](image)
Shot Accumulation

12 s to accumulate, 1.5 s to move
Scan Pattern
400 km orbit, 45° nadir angle, 0° latitude
311, 41, 222, 132°
12 s to accumulate, 1.5 s to move
Two Parameters Required to Describe Wind Measurement Performance of Coherent Doppler Lidar

1. Pr\{good\}, the “probability of a good wind estimate”. Since coherent Doppler lidar is similar to tone detection in noise, when the signal is found above the noise, the frequency/velocity estimate is very accurate. When a noise peak is mistakenly chosen as the signal, the velocity estimate is random over the search space. For fixed conditions, repeated attempts to measure the wind at a particular range gate will produce a group of good wind estimates, and a group of random numbers.

2. The velocity accuracy (error) of the “good” wind estimates
Performance Theory

• Rod G. Frehlich, “Velocity Error for Coherent Doppler Lidar with Pulse Accumulation,” J. Atmos. & Oceanic Tech. 21, 905-920 (June 2004), Section 8 = User Manual
• Valid range of $\Omega$ = # independent samples per range gate = 0.25 – 32
• Valid range of $\Omega/M$: < 0.2 (M = # complex lidar data points/range gate)
• Valid range of $b$ = probability a velocity estimate is bad, Pr{bad}: $0.00001 – 0.7$ (Valid range of Pr{good} = $0.99999 – 0.3$)
• Note: velocity error is underestimated when $b < 0.01$ (per Frehlich)
Two Ways to Show Performance

1. Use the GTWS requirement “probability of a good wind estimate,” \( \Pr\{\text{good} \} \), at all altitudes and compare the simulated aerosol backscatter coefficient (\( \beta \)) profile to the GTWS requirement profile. Simulated \( \beta \) lower than required \( \beta \) is a backscatter margin.

\[
\Pr\{\text{good}\}_{\text{simulated}} = \Pr\{\text{good}\}_{\text{requirement}} \\
\beta_{\text{simulated}} \neq \beta_{\text{requirement}}
\]

2. For altitudes where the simulated \( \beta \) is lower than the requirement \( \beta \), reduce \( \Pr\{\text{good} \} \) until the simulated \( \beta \) rises to equal the requirement \( \beta \). Those altitudes then have a \( \Pr\{\text{good} \} \) margin.

\[
\beta_{\text{simulated}} = \beta_{\text{requirement}} \\
\Pr\{\text{good}\}_{\text{simulated}} > \Pr\{\text{good}\}_{\text{requirement}}
\]

[Simulation limited to: 0.3 < \( \Pr\{\text{good} \} \) < 1]
Aerosol backscatter adequate to 11 km, with margin

Excellent velocity accuracy meets requirement
Performance Approach 1

\( \text{Pr}_{\text{good}}^\text{simulated} = \text{Pr}_{\text{good}}^\text{requirement} \)

- Aerosol backscatter inadequate above 1 km
- Adequate velocity accuracy for "good" measurements
Performance Approach 2

Pr{good}_simulated > Pr{good}_requirement

- Pr{good} > 0.8 to 8 km
- Excellent velocity accuracy meets requirement
Performance Approach 2

\[ \text{Pr}_{\text{good}}^{\text{simulated}} > \text{Pr}_{\text{good}}^{\text{requirement}} \]

- Inadequate performance above 1 km
- Adequate velocity accuracy for “good” measurements
Performance Approach 2

\[ \Pr{\text{good}}_{\text{simulated}} > \Pr{\text{good}}_{\text{requirement}} \]

Combined Background/Enhanced

- Assume 25% of earth is enhanced aerosols
- Meets requirements up to 8 km
Lidar Parameter Trade Study: Conditions of Low But Adequate SNR

- 3 dB $1-\sigma$ transmit/receive misalignment loss ($1-\sigma$ angle = 3.082 $\mu$rad)
- 180 ns pulse duration FWHM
- 11 km altitude
- Enhanced aerosol levels; $\beta = 4.8 \times 10^{-9}$ m$^{-1}$sr$^{-1}$
- Vertical resolution = 2000 m
- $M = 393.1$ (# complex lidar data points/range gate)
- $\Omega = 30.4$ (# independent samples per range gate)
- $\varphi = 1.725$ (# coherent photoelectrons per range gate per shot)
- 60 shots accumulated
- $Pr\{\text{good}\} = 0.5$
- $g/w_{\text{eff}} = 0.80$
- Lidar LOS velocity error = 1.23 m/s
- Total velocity error projected to horizontal w/sampling error = 1.77 m/s
Pulse Duration vs. Pulse Energy

- Assume no vertical wind shear; Assume no wind turbulence
- Assume no laser frequency difference error; Neglect effect on range resolution
- Hold Pr{good} constant

What is happening to the velocity accuracy?
Pulse Duration vs. Velocity Accuracy

- Assume no vertical wind shear; Assume no wind turbulence
- Assume no laser frequency difference error; Neglect effect on range resolution
- Hold Pr{good} constant

![Graph showing the relationship between pulse duration and velocity accuracy.](image)
Spectrum Excess Width vs. Pulse Energy

- Hold Pr{good} constant

Above 1.05 is out of valid simulation range

What is happening to the velocity accuracy?
Spectrum Excess Width vs. Velocity Accuracy

- Hold Pr_{good} constant

Above 1.05 is out of valid simulation range
Velocity Search Bandwidth vs. Pulse Energy

- Full search bandwidth in horizontal direction for last pass through the data
- Hold Pr\{good\} constant

What is happening to the velocity accuracy? ⇒

? = Outside the parameter limits of the simulation
Velocity Search Bandwidth vs. Velocity Accuracy

- Full search bandwidth in horizontal direction for last pass through the data
- Hold Pr{good} constant

? = Outside the parameter limits of the simulation
Telescope Diameter vs. Pulse Energy

- Assume scanner does not reduce collection area
- Assume $1-\sigma$ transmit/receive misalignment angle fixed at 3.082 $\mu$rad
- Hold $Pr\{\text{good}\}$ and velocity accuracy constant

- Larger diameters have more SNR loss for fixed misalignment angle

(nominal operating point)
Wind Shear vs. Pulse Energy

- Vertical shear of horizontal velocity (always aligned with beam)
- Horizontal velocity always aligned with laser beam
- Hold Pr{good} constant
- Plot depends strongly on vertical resolution!

? = Outside the parameter limits of the underlying theory

What is happening to the velocity accuracy? ⇒
Wind Shear vs. Velocity Accuracy

? = Outside the parameter limits of the underlying theory

(nominal operating point)
Vertical Resolution vs. Pulse Energy

• Hold Pr{good} constant

? = Outside the parameter limits of the underlying theory

⇒ Is pulse energy \( \propto \frac{1}{\sqrt{\text{vertical resolution}}} \)?
Vertical Resolution vs. Pulse Energy

Yes

? = Outside the parameter limits of the underlying theory

What is happening to the velocity accuracy? ⇒
Vertical Resolution vs. Velocity Accuracy

? = Outside the parameter limits of the underlying theory
Effect of Two GTWS Cloud Layers

- Cloud layer at 9-10 km = 0.14 km\(^{-1}\)
- Cloud layer at 2-3 km completely blocks 50% of the lidar shots
- Consider wind measurement at 1 km altitude
- Enhanced aerosol levels, \(\beta = 2.5 \times 10^{-7}\) m\(^{-1}\)sr\(^{-1}\)

With clouds included:
- \(E = 30\) mJ, \(Pr\{\text{good}\} = 0.33\), Total wind accuracy = 1.84 m/s

Without clouds included:
- Either \(E = 30\) mJ, \(Pr\{\text{good}\} = 0.8\), Total wind accuracy = 1.83 m/s
- Or \(E = 15\) mJ, \(Pr\{\text{good}\} = 0.33\), Total wind accuracy = 1.83 m/s
Azimuth Change Time vs. Pulse Energy

- Hold shot accumulation time + azimuth change time = 13.5 s
- Hold $\text{Pr}\{\text{good} \}$ and velocity accuracy constant
Biperspective Angle Separation Affects Fore/Aft Overlay Time Delay and therefore Shot Accumulation Time

5° & 175° \(\Rightarrow\) (170°, 824 km, 114 s)

45° & 135° \(\Rightarrow\) (90°, 585 km, 81 s)

85° & 95° \(\Rightarrow\) (10°, 72 km, 10 s)

Ground Track

414 km

V
Biperspective Angle Separation vs. Pulse Energy & Repeat Distance

- Hold Pr\{good\} and velocity accuracy constant
- Hold PRF = 5 Hz
- Hold azimuth change time = 1.5 s
- Sampling error changes not included
Horizontal Repeat Distance vs. Pulse Energy

- Combine two plots on previous slide
- Sampling error changes not included

⇒ Is pulse energy ∝ 1/√horizontal repeat distance?
Horizontal Repeat Distance vs. Pulse Energy

Fit fails as HR distance gets small due to azimuth change time effect
Shot Accumulation vs. Pulse Energy

- Hold $Pr\{\text{good}\} = 0.5$
- Sampling error changes only included if PRF is varied, not if accumulation time is varied

$⇒ Is \text{ pulse energy } \propto 1/\sqrt{\text{shot accumulation}}$?
Shot Accumulation vs. Pulse Energy
PRF vs. Pulse Energy

- Hold $\text{Pr\{good\}} = 0.5$

Since lower energy lasers are easier, go to higher PRF? Not so fast …
PRF vs. Laser Power

- Hold \( \text{Pr\{good\}} = 0.5 \)
- Laser Power = Energy \( \times \) PRF

Since lower average power lasers are easier, go to lower PRF? Not so fast …
LDA Lifetime Theory

\[ \text{Lifetime} \propto (T_U - T_L)^{-N} e^{\frac{E_a}{k_B T_U}} \]

- \( T_U \) = LDA temperature cycle upper limit
- \( T_L \) = LDA temperature cycle lower limit
- \( N \sim 4 \)
- \( E_a \sim 0.9 \text{ eV} \)
- \( T_U(P) \sim 0.27P + 26.3 ^\circ \text{C} \)
- \( T_U - T_L \sim 0.21P + 1.14 ^\circ \text{C} \)
- \( P \) = LDA power
- \( P = (E + 3/7) \times 70 \)
- \( T_U \) and \( T_L \) independent of PRF for \( 3 < \text{PRF} < 20 \)
- Equations good up to about 20 Hz PRF

\( k_B = 1.3806503 \times 10^{-23} \text{ m}^2\text{kg/(s}^2\text{ }^\circ\text{K}) \)

\( ^\circ\text{K} = ^\circ\text{C} + 273.15 \)

1 J = \( 6.24150974 \times 10^{18} \text{ eV} \)
PRF vs. LDA Lifetime

- Hold Pr\{good\} = 0.5
- Assume LDA lifetime reflects laser lifetime

Since higher lifetime is desired, go to higher PRF? Not so fast, …
• Hold Pr\{good\} = 0.5
• Lifetime in seconds more important than lifetime in shots
  (seconds = shots/PRF)

Since higher lifetime is desired, go to lower PRF? _________
Summary and Conclusions

• LaRC computer simulation of global wind profiling coherent-detection Doppler lidar uses latest published theory
• Also includes detailed, bottoms-up section to calculate Lidar System Efficiency (LSE)
• SWA simulation much more sophisticated in modeling atmosphere and its variability
• LaRC simulation permits parametric trade studies with choice of parameters held constant
• If simulation trade results could be verified by experiment, space mission design parameters could be further optimized, yielding more science product and/or less cost
Back Up Slides
DFT

Time Domain Samples

0

\( T_S \)

M Samples

M-1

Frequency Domain Samples

0

\[ 1/T = 1/(MT_S) \]

M/2 + 1 Samples

M/2
Use of Frehlich’s Theory

\[ \lambda, V_{\text{SEARCH}} \Rightarrow T_S \quad T_S, \Delta p \Rightarrow M \]

Pulse duration \( \tau \), XMTR - LO \( \Delta f \) K.E, wind turb., vert. wind shear \( \Rightarrow w_{\text{EFF}} \)

\[ T_S, M, w_{\text{EFF}} \Rightarrow \Omega \]

Select \( b_{\text{THR}} = \) Maximum permitted value

\[ b_{\text{THR}}, M, \Omega, N \Rightarrow \Phi_{\text{THR,1}} \] (Minimum permitted for 1 shot)

\[ b_{\text{THR}}, M, \Omega, N, w_{\text{EFF}} \Rightarrow g \] (RMS error of good wind estimates)

\[ \varphi_{\text{THR,1}}, M, T_S, \text{Lidar Equation} \Rightarrow \beta_{\text{THR}} \]

\( V_{\text{SEARCH}} = \) Full LOS velocity search bandwidth on last pass through data

\( \Delta p = \) range-gate length
\( \tau = \) pulse duration
\( N = \) accumulated shots per wind estimate
\( b = \) probability of a bad wind estimate
\( \Omega = \) independent samples per range gate

T – range-gate time (signal collection time)
\( w = \) signal spectrum width
\( M = \) complex samples per range gate
\( T_S = \) complex data sampling interval
\( \Phi = \) coherent photoelectrons per range gate
Use of Frehlich’s Theory

\[ T_S = \frac{\lambda}{2V_{\text{SEARCH}}} \quad T = \frac{2\Delta p}{c} \]

\[ M = \frac{T}{T_S} = \frac{2\Delta p}{cT_S} = \frac{4\Delta p V_{\text{SEARCH}}}{c\lambda} \]

\[ \Omega = \frac{2w_{\text{VEFF}}MT_S}{\dot{\lambda}} = \frac{4w_{\text{VEFF}}\Delta p}{c\lambda} \quad \frac{\Omega}{M} = \frac{w_{\text{VEFF}}}{V_{\text{SEARCH}}} < 0.2 \]

\( V_{\text{SEARCH}} = \) Full LOS velocity search bandwidth on last pass through data
\( \Delta p = \) range-gate length
\( \tau = \) pulse duration
\( N = \) accumulated shots per wind estimate
\( b = \) probability of a bad wind estimate
\( \Omega = \) independent samples per range gate
# Frehlich’s Theory Dependencies

<table>
<thead>
<tr>
<th></th>
<th>$\Phi_{1,\text{THR}}$ (coh e'/range-gate)</th>
<th>g (m/s)</th>
<th>$\beta_{\text{THR}}$ (m$^{-1}$ sr$^{-1}$)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ (m)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$V_{\text{SEARCH}}$ (m/s)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Search Bandwidth</td>
</tr>
<tr>
<td>$\Delta p$ (m)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Range Gate Length</td>
</tr>
<tr>
<td>$\tau_p$ (s)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Pulse Duration</td>
</tr>
<tr>
<td>$\Delta f$ K.E. (Hz)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>XMTR-LO freq. diff.</td>
</tr>
<tr>
<td>Wind Turb. (m/s)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Wind Shear (m/s/km)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$b_{\text{THR}}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Prob{bad wind estimate}</td>
</tr>
<tr>
<td>$N_{\text{ACCUM}}$ (-)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Shot Accumulation per wind estimate</td>
</tr>
<tr>
<td>Lidar Equation</td>
<td></td>
<td></td>
<td>X</td>
<td>Pulse Energy, Range, Rec'r Area, Extinction, Efficiency, $\lambda$, $V_{\text{SEARCH}}$, $\Delta p$</td>
</tr>
</tbody>
</table>