Expected Characteristics of Global Wind Profile Measurements with a Scanning, Hybrid, Doppler Lidar System

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

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Outline

• Geometry
• Sensor
• Measurement Requirements
• Comparison to Rawinsonde Network
• Tradeoffs

Much help acknowledged:
Wayman E. Baker
G. David Emmitt
Rod G. Frehlich
Bruce M. Gentry
many others
Outline

- Geometry
  - Sensor
  - Measurement Requirements
  - Comparison to Rawinsonde Network
  - Tradeoffs
Two “Horizontal” Wind Profile “Tracks”
Hybrid Doppler Wind Lidar – Two Successive Orbits

Equator:
2570 km/23 deg.

400 km
Sun Synchronous
Hybrid Doppler Wind Lidar – Two Successive Orbits

- 2050 km
- 1470 km
- 290 km
- 37 deg latitude
Hybrid Doppler Wind Lidar – One Measurement Pattern

290 km = 180 st. mi.

Along-Track Repeat Distance
390 km/54 sec.
Hybrid Doppler Wind Lidar
Lidar Shot Accumulation for LOS Wind Profile

Return light: t+3.9 ms, 30 m, 4.4 μrad
Second shot: t+200 ms, 1535 m, 227 μrad
First Aft Shot t + 81 s

Nadir tilt rate ~ 1.1 μrad/ms

Los profile:
Measurement time = 24 s
Elapsed time = 93 s

Line LOS wind profiles
1 line "horiz" wind profiles

First Fore Shot t = 0

Los direction:
Nadir tilt rate ~ 1.1 μrad/ms

Fore
Aft

Ground Track
7.2 km/s
390 km in 54 s

292 km
585 km
400 km

2 lines LOS wind profiles
1 line "horiz" wind profiles

0.2/0.01 s = 1444/72 m
60/1800 shots = 12 s = 85 km
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Hybrid Pulsed Doppler Wind Lidar System

- **Direct Detection Pulsed Doppler Lidar** – 355 nm
- **Coherent Detection Pulsed Doppler Lidar** – 2053 nm

**Wind Sensor**

- 400 km, sun-synch.
- 4 fixed 50 cm telescopes
- 45 deg. nadir angle

**Direct Detection**
- 800 mJ x 100 Hz = 80 W
- WPE ~ 10%

**Coherent Detection**
- 250 mJ x 5 Hz = 1.25 W
- WPE ~ 2%

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Courtesy: G. David Emmitt
Wind Sensor

Hybrid Doppler Lidar Synergisms

• Coherent works better as altitude goes down
• Direct works better as altitude goes up
• Overlapping altitudes provide intercomparison checks
• Coverage of coherent will be improved if direct measurement is used
  as guide for velocity search
• Coherent surface returns can be used to calibrate spacecraft attitude
  for both lidars
• Coherent can measure below a cloud deck by poking through holes
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Wind Measurement Requirements

- Societal Benefit Requirements
  - Science Requirements
    - Wind Measurement Requirements
      - Assumed Atmospheric Parameters
        - Assumed Orbit Parameters
        - Assumed Earth Surface Parameters
          - Assumed Lidar Efficiencies
            - Coherent Doppler Lidar Parameters
              - Direct Doppler Lidar Parameters
                - Spacecraft Requirements
                  - Mission Design & Cost
Wind Measurement Requirements
NASA/NOAA

• Large effort to formulate wind measurement requirements occurred in 2001 by NASA, NOAA, university, and private industry scientists under purview of NASA’s Global Tropospheric Wind Sounder program
• Complete requirements including definitions, comments, and design atmospheres fill 24 pages in:
• Published requirements are “almost” current. Some tweaking has occurred since.
**Wind Measurement Requirements**

**NASA/NOAA (Partial List)**

<table>
<thead>
<tr>
<th></th>
<th>Science Demonstration</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Vertical Depth of Regard (DOR)</td>
<td>0-20</td>
<td>0-20</td>
</tr>
<tr>
<td>Maximum Vertical Resolution:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropopause to Top of DOR</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Top of BL to Tropopause (~12 km)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Surface to Top of BL (~2 km)</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum Horizontal Resolution(^A)</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Minimum Number of Horizontal(^A) Wind Tracks(^B)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Minimum Number of Collocated LOS Wind Measurements for Horizontal(^A) Wind Calculation</td>
<td>2 = pair</td>
<td>2 = pair</td>
</tr>
<tr>
<td>Maximum Velocity Error(^C) Above BL</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>In BL</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Minimum Wind Measurement Coverage(^D)</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

\(^A\) Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an “effective” horizontal wind measurement. The two LOS winds are reported to the user.  
\(^B\) The 4 cross-track measurements do not have to occur at the same along-track coordinate; staggering is OK.  
\(^C\) Error = 1σ LOS wind random error, projected to a horizontal plane; from all lidar, geometry, pointing, atmosphere, signal processing, and sampling effects. The true wind is defined as the linear average, over a 100 x 100 km box centered on the LOS wind location, of the true 3-D wind projected onto the lidar beam direction provided with the data.  
\(^D\) Scored per vertical layer per LOS measurement not counting thick clouds
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Doppler Lidar Mission Compared to Rawinsonde Network

World rawinsonde network
- 850 worldwide locations (81 in USA)
  - average earth spacing = 775 km
  - average land spacing = 425 km
  - average coterminous USA spacing = 310 km
- 2/day launches
- 1700 rawinsonde launches/day
- 1700 vector wind profiles/day

Orbiting Hybrid Doppler Lidar System
- 2 vector wind profiles/350 km
- 2 vector wind profiles/48.5 s
- 3566 vector wind profiles/day

Factor of 2.1 more vector wind profiles
- More evenly distributed including oceans and lakes
- Quality and calibration knowledge
- Consistent delivery and latency
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Tradeoffs

Coherent Detection Doppler Wind Lidar

Velocity measurement performance is a function of

\[ \frac{E \times \sqrt{\text{PRF} \times \sqrt{\text{Vert Res}}} \times D^2 \times e^{-\frac{1,1 D \theta_{\text{MISAL}}}{\lambda}}}{R^2} \]

Direct Detection Doppler Wind Lidar

Velocity Error \( \propto \frac{R}{D \sqrt{E \times \text{PRF} \times \text{Vert Res}}} \)

<table>
<thead>
<tr>
<th>Tradeoffs</th>
<th>Coherent</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Resolution, VR</td>
<td>VR \times HR / WT = constant</td>
<td></td>
</tr>
<tr>
<td>Horizontal Resolution, HR</td>
<td>VR \times VP^2 = constant</td>
<td>HR \times VP^2 = constant</td>
</tr>
<tr>
<td>Number Wind Tracks, WT</td>
<td>WT / VP^2 = constant</td>
<td></td>
</tr>
<tr>
<td>Velocity Performance, VP (Direct VP = velocity error)</td>
<td>PRF \times VR \times HR \times VP^2 / WT = constant</td>
<td>E \times VR \times HR \times VP^2 / WT = constant</td>
</tr>
<tr>
<td>(Coherent VP = minimum backscatter requirement)</td>
<td>E^2 \times VR \times HR \times VP^2 / WT = constant</td>
<td>D^4 \times VR \times HR \times VP^2 / WT = constant \text{ if } \theta_{\text{MISAL}} \times D = constant</td>
</tr>
<tr>
<td></td>
<td>D^2 \times VR \times HR \times VP^2 / WT = constant</td>
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</table>
Questions
Backup Slides
LOS Velocity Error Budget

Level 1 Velocity Error (1 Shot, LOS)

Level 2 Velocity Error (1 Shot, LOS)

Level 3 Velocity Error (1 Shot, Horiz)

Level 4 Velocity Error (1 Shot, Horiz)

Level 5 Velocity Error (N Shots, Horiz)

Atmospheric Wind Variability 1

Atmospheric Wind Variability 2

Atmospheric Wind Variability 3

Pointing Stability, 12 s

Boresight Stability, ~10 ms

Nadir Angle

Atmospheric Backscatter

Atmospheric Extinction

Each Shot Pointing Knowledge

Measurement Altitude Knowledge

Local Horizontal Knowledge

Relativity

Doppler Lidar System

Velocity Estimation Algorithms

Shot Accumulation Pattern & Measurement Cell Size (Representativeness Error)
LOS Velocity Error Budget

• Level 1 – Basic Doppler lidar system with processing algorithms
• Level 2 – Add atmospheric effects and relativity for single shot
• Level 3 – Add conversion to horizontal and correct tagging of measurement for user
• Level 4 – Add accumulation of N shots for one LOS profile
• Level 5 – Add sampling or representativeness error
Wind Sensor

Coherent Detection
250 mJ x 5 Hz = 1.25 W
WPE ~ 2%

Direct Detection
800 mJ x 100 Hz = 80 W
WPE ~ 10%

Courtesy: G. David Emmitt
\[ \phi_N = \arcsin \left( \frac{\cos \phi_{\text{INC}}}{\cos \psi_{\text{LAT}}} \right) \]
Orbiting Doppler Wind Lidar at 400 km

Pointing Geometry - Side View

\[ \theta_T = \arcsin \left( \frac{(R_E + Z_L) \sin \theta_L}{R_E + Z_T} \right) \]

\( Z_L = 400 \text{ km} \)
\( \theta_L = 45 \text{ deg.} \)
\( Z_T = 0 \text{ km (example)} \)
\( \theta_T = 48.7 \text{ deg.} \)
\( V_L = 7676 \text{ m/s} \)
\( R_T = 585 \text{ km} \)
\( R_R = 414 \text{ km} \)
\( R_E = 6371 \pm 10.7 \text{ km} \)