DAWN
Doppler Aerosol WiNd lidar

(hurricane)
Genesis and Rapid Intensification Processes (GRIP)
Science Team Meeting
El Segundo, CA

Michael J. Kavaya
NASA Langley Research Center

June 6, 2011
Acknowledgements

NASA SMD
Ramesh Kakar
AITT-07 “DAWN-AIR1”
GRIP
Jack Kaye $ Augmentation

NASA SMD ESTO
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LRRP, IIP-04 “DAWN”
IIP-07 “DAWN-AIR2”
Airplane Change & Rephasing

NASA LaRC Director Office, Steve Jurczyk, $ Augmentation
NASA LaRC Engineering Directorate, Jill Marlowe, John Costulis, $Augmentation
NASA LaRC Chief Engineer, Clayton Turner, 1 FTE

NASA LaRC Science Directorate
Garnett Hutchinson, Stacey Lee, and Keith Murray
## Project Personnel (DAWN-AIR1, DAWN-AIR2, & GRIP)

*also were DAWN operators on GRIP flights*

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Location</th>
<th>Responsibilities</th>
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</thead>
<tbody>
<tr>
<td>Dr. Michael J. Kavaya*</td>
<td>PI, LaRC</td>
<td></td>
<td>Overall project coordination including cost and schedule control and reporting. Lead, coherent lidar &amp; data processing</td>
</tr>
<tr>
<td>Dr. Robert A. Atlas</td>
<td>Co-I, NOAA AOML Dir.</td>
<td></td>
<td>Science planning and data analysis</td>
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<tr>
<td>Dr. Jeffrey Y. Beyon*</td>
<td>Co-I, LaRC</td>
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<td>Lead, data acquisition hardware and software</td>
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<tr>
<td>Garfield A. Creary*</td>
<td>LaRC</td>
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<td>Project Manager</td>
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<tr>
<td>Dr. G. David Emmitt</td>
<td>Co-I, SWA Pres.</td>
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<td>Science planning, data analysis, lidar attitude knowledge</td>
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<tr>
<td>Dr. Grady J. Koch*</td>
<td>Co-I, LaRC</td>
<td></td>
<td>Lead, lidar system overview, lidar receiver design, lidar remote sensing</td>
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<tr>
<td>Paul J. Petzar*</td>
<td>LaRC</td>
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<td>Lead, electronics</td>
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<tr>
<td>Dr. Upendra N. Singh</td>
<td>Co-I, LaRC</td>
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<td>Pulsed laser design, lidar remote sensing</td>
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<tr>
<td>Bo C. Trieu*</td>
<td>Co-I, LaRC</td>
<td></td>
<td>Lead, mechanical and thermal lidar subsystems</td>
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<tr>
<td>Dr. Jirong Yu*</td>
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<td>Lead, pulsed laser design, lidar remote sensing</td>
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<tr>
<td>Dr. Yingxin Bai</td>
<td>SSAI</td>
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<td>Laser alignment</td>
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<tr>
<td>Bruce W. Barnes</td>
<td>LaRC</td>
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<td>Software</td>
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<tr>
<td>Frank L. Boyer</td>
<td>LaRC</td>
<td></td>
<td>Mechanical engineering</td>
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<tr>
<td>Dr. Joel F. Campbell</td>
<td>LaRC</td>
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<td>Data processing</td>
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<td>Dr. Songsheng Chen</td>
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<td>Laser alignment</td>
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<tr>
<td>Michael E. Coleman</td>
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<td>Larry J. Cowen</td>
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<td>Joseph F. Cronauer</td>
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<td>Scheduling</td>
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<td>Fred D. Fitzpatrick</td>
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<td>Electronics technician</td>
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<td>Mark L. Jones</td>
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<td>INS/GPS software</td>
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<td>Nathan Massick</td>
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<td>Ed A. Modlin</td>
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<td>Mechanical technician</td>
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<td>Anna M. Noe</td>
<td>LaRC</td>
<td></td>
<td>Aircraft accommodation</td>
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<tr>
<td>Don P. Oliver</td>
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<td></td>
<td>Aircraft accommodation</td>
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<tr>
<td>Karl D. Reithmaier</td>
<td>SSAI</td>
<td></td>
<td>Mechanical design</td>
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<tr>
<td>Geoffrey K. Rose</td>
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<td>Mechanical engineering</td>
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<tr>
<td>Teh-Hwa Wong</td>
<td>SSAI</td>
<td></td>
<td>Mechanical engineering</td>
</tr>
<tr>
<td>William A. Wood</td>
<td>LaRC</td>
<td></td>
<td>Software</td>
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</tbody>
</table>
Pulsed Coherent Lidar Wind Measurement - 7

Frequency Estimation Error

- Abscissa is 7 orders of magnitude of SNR
- Upper ordinate is g/w [-]
- g – velocity error of “good” wind estimates [m/s]
- w is return signal spectral width [m/s]
- Wind turbulence $\sigma_v$ [m/s] usually dominates value of w
- $g/w$ is constrained between 0.1 and 1.1, only 1 order of magnitude!
- b – fraction of wind estimates that are bad
- b is the deciding parameter!
- $\Omega$ – 0.19 range gate length / pulse length
- M – number of data samples

Fig. 8. The standard deviation $g$ of the “good” ML estimates for mean frequency and the fraction $b$ of “bad” estimates as a function of $\Phi$ for $\Omega = 0.5$. The results of the simulation are given by the best-fit empirical models [Eqs. (39) and (40)] for $M = 32$ (solid), 64 (dotted), and 128 (dashed).
DAWN Ground-Based Wind Performance
at Howard University, Beltsville, MD

sonde on February 24, 2009 at 17:59 local

Wind Speed
• root-mean-square of difference between two sensors for all points shown = 1.06 m/s

Wind Direction
• root-mean-square of difference between two sensors for all points shown = 5.78 deg
Nominal Scan Pattern: DAWN During GRIP Campaign

5 different azimuth angles from -45° to +45°
2 sec shot integration; 2 sec scanner turn time

2 s, 288 m

144 m/s ground speed

0°
-22.5°
+22.5°
-45°
+45°

Example:
1 pattern = 22 s = 3,168 m

Along-Track & Temporal Resolution
Swath Width Depends on Flight And Measurement Altitudes

e.g., Flight Altitude = 10,586.4 m
Measurement Altitude = 0 m
Swath Width = 8,688 m

Trade Off
Fast revisit time to less azimuth angles vs.
Slower revisit time to more azimuth angles (less cloud blockage?, wind variability studies, measure w)

Note: weather models assimilate LOS winds
Nominal Scan Pattern: DAWN During GRIP Campaign

Actual DC-8 and dropsonde trajectories for 9-1-2010
Dropsonde launched at 17:20:15.49 Zulu
Dropsonde hit water 17:33:36.5 Zulu. Fall time = 201 sec

196 seconds = 3 min, 16 sec = 28,224 m

Same dropsonde shown for two arbitrary launches relative to lidar scan pattern

- DC-8 forward motion = 29 km
- 1 scan pattern = 22 sec
- Several different lidar scan patterns may collocate with the dropsonde at different altitudes
DAWN Data Products
All vs. Along-Track Dimension

**Near Term**
1. 5 LOS wind profiles vs. altitude
2. 5 LOS relative aerosol backscatter profiles vs. altitude
3. Profile of u, v, and w vs. altitude (MAIN PRODUCT)

**Farther Term**
4. Wind turbulence profiles vs. altitude
5. Correlations of wind, wind turbulence, and aerosol backscatter
6. Assimilation of wind data into NWP models (NOAA)
7. Study of near ocean surface velocities (wind, spray, wave, current)
8. Multiple profiles of u, v, and w vs. altitude for investigating wind spatial variability (3 out of 5)

**GRIP Science Team**
9. Fusion of wind data with other GRIP or non-GRIP data for hurricane research (GRIP science team)
DAWN Vertical Coverage During GRIP
Strong Function of Cloudiness

- DC-8 taking off from Fort Lauderdale to fly into Earl
- Signal return affected by aerosol backscatter, atmospheric extinction, and $1/R^2$ (DC-8 altitude)
- Solid gray not measured
- Note almost complete profiles from 5:00 – 5:13 pm Zulu!
- Integration is 20 shots or 2 sec. (showing azimuth 0 deg only of 5 azimuths)
- Will measure entire profile next time …
Why Entire Profiles Next Time

• Post-GRIP: Discovered burn on telescope secondary mirror likely entire GRIP ~ 10 dB loss. Already fixed 4/28/11.
• Post-GRIP: Discovered slight lidar misalignment, at altitude had to cool laser to keep it working. This cooling misaligned the receiver ~ 3 dB loss for most of GRIP. Already fixed.
• Planned 250 mJ, 10 Hz laser but actually 200 mJ, 10 Hz. Already fixed.
• So we effectively flew a 200/10/2 = 10 mJ, 10 Hz laser
• Next time will be 250 mJ, 10 Hz

For GRIP data, we still need to:
• Implement best noise whitening
• Implement zero padding for multiple shot frequency registration
• Get 5-axis processing working
• Combine several scan patterns by altitude bins for handoff to science team
## DAWN Horizontal Coverage During GRIP

<table>
<thead>
<tr>
<th>Science Flight</th>
<th>DC-8 Flight Minutes</th>
<th>DAWN Data Minutes</th>
<th>DAWN to DC-8 Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/17 Zulu</td>
<td>281.2</td>
<td>176.0</td>
<td>0.63</td>
</tr>
<tr>
<td>8/24</td>
<td>437.4</td>
<td>368.9</td>
<td>0.84</td>
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<tr>
<td>8/29-30</td>
<td>502.8</td>
<td>427.4</td>
<td>0.85</td>
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<tr>
<td>8/30</td>
<td>399.9</td>
<td>380.6</td>
<td>0.95</td>
</tr>
<tr>
<td>9/1-2</td>
<td>478.1</td>
<td>469.15</td>
<td>0.98</td>
</tr>
<tr>
<td>9/2</td>
<td>466.5</td>
<td>444.3</td>
<td>0.95</td>
</tr>
<tr>
<td>9/6-7</td>
<td>441.2</td>
<td>407.6</td>
<td>0.92</td>
</tr>
<tr>
<td>9/7-8</td>
<td>420.8</td>
<td>395.5</td>
<td>0.94</td>
</tr>
<tr>
<td>9/12-13</td>
<td>500.4</td>
<td>463.6</td>
<td>0.93</td>
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<tr>
<td>9/13-14</td>
<td>500.6</td>
<td>421.8</td>
<td>0.84</td>
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<tr>
<td>9/14-15</td>
<td>410.8</td>
<td>334.8</td>
<td>0.82</td>
</tr>
<tr>
<td>9/16-17</td>
<td>486.4</td>
<td>475.5</td>
<td>0.98</td>
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<tr>
<td>9/17</td>
<td>485.8</td>
<td>422.3</td>
<td>0.87</td>
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<tr>
<td>9/21</td>
<td>443.9</td>
<td>399.6</td>
<td>0.90</td>
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<tr>
<td>9/22</td>
<td>456.2</td>
<td>400.1</td>
<td>0.88</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>6711.9</strong></td>
<td><strong>5987.1</strong></td>
<td><strong>0.89</strong></td>
</tr>
</tbody>
</table>

Note: Shutter 7 open minutes < flight minutes, DAWN fractions a little higher

Very roughly 0.367 min/DAWN scan … total 16,000 scans … 328 dropsondes
Latitude = 29.95 N
Longitude = 75.75 W
GPS Altitude = 10,611 m
Over Atlantic Ocean
Ground Speed = 224.6 m/s
True Heading = 146 degrees
September 7, 2010
Lidar scan number 74 of data folder 18:30:23
19:24:14 – 19:24:34; 2-axis

Latitude = 20.418 N
Longitude = 65.7 W
GPS Altitude = 9,673 m
Over Atlantic Ocean
Ground Speed = 218 m/s
True Heading = 88.7 degrees
September 2, 2010
Lidar scan number 99 of data folder 16:11:47

Latitude = 31.34 N
Longitude = 77.74 W
GPS Altitude = 10,650 m
Over Atlantic Ocean
Ground Speed = 240.5 m/s
True Heading = 76.5 degrees

T and RH, Not quality controlled
Didn’t Know Flight Campaigns Were So Fun
Back Up Slides
DAWN
Doppler Aerosol WiNd lidar

Fiscal years 2008 – 2010

Compactly and robustly package the 2-micron, Ho:Tm:LuLiF, pulsed laser technology developed at Langley for eventual global wind measurements from earth orbit (Jay’s section)

Langley has previously demonstrated a world record 1200 mJ of pulse energy with this technology

Simulations of the winds space mission indicate a requirement of 250 mJ pulse energy at 5 Hz

Laser derating of technology is wise for space missions

DAWN Transceiver (Transmitter + Receiver)
250 mJ/pulse, 10 pulses/sec.
5.9” x 11.6” x 26.5”, 75 lbs.; 15 x 29 x 67 cm, 34 kg
DAWN System Integration

- DAWN TXCVR
- Telescope
- Newport Scanner (RV240CC-F)
- DC8 Port/Window/Shutter
- 29” x 36” x <37” Tall
- Sealed Enclosure & Integrated Lidar Structure
- 3/8” Cooling Tube
Pulsed Coherent-Detection 2-Micron Doppler Wind Lidar System

Lidar System

Laser & Optics

Scanner

Telescope

Pulsed Transmitter Laser
(includes CW injection laser)

Detector/Receiver

Polarizing Beam Splitter

λ/4 Plate

Transceiver

Laser Chillers

Electronics
(Power Supplies, Controllers)

Computer, Data Acquisition, and Signal Processing
(including software)

Propagation Path (Atmosphere)

Target (Atmospheric Aerosols)
DAWN Arriving Palmdale
In VALIDAR Trailer
DAWN Optics Mounted in DC-8 Cargo Level
Three Cabin Stations with 2 or 3 Operators

1. Laser Control (L)  2. Data Processing (R)

3. 3 Laser Chillers
Frequencies, Angles, and Velocities

\[ f_0 = f_{AOM} - f_{JITTER} \quad \left[ f_{AOM} > 0; \text{assume } f_{AOM} > |f_{JITTER}| \right] \]

\[ f_k = f_{JITTER} + f_{AC} + f_W \quad \left[ \text{assume } |f_{AC}| > |f_{JITTER} + f_W| \right] \]

\[ f_R - f_T = \frac{2}{\lambda_T} \left[ |\vec{V}_A| \cos \Omega_{A-L} - |\vec{V}_W| \cos \Omega_{W-L} \right] \]

\[
\cos \Omega_{A-L} = \sin \theta_A \sin \theta_L \cos (\phi_A - \phi_L) + \cos \theta_A \cos \theta_L \\
\cos \Omega_{W-L} = \sin \theta_W \sin \theta_L \cos (\phi_W - \phi_L) + \cos \theta_W \cos \theta_L
\]
# Juggling 4 Coordinate Systems

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
<td>Coordinate System</td>
<td>Aircraft Body Coordinates Forward-Right-Down FRD</td>
<td>North-East-Down Coordinates NED</td>
<td>East-North-Up Coordinates ENU</td>
<td>NED Except “Air Coming From”* “SWD”</td>
</tr>
<tr>
<td>Right-Hand, Perpendicular Axes</td>
<td>Axes glued to aircraft body</td>
<td>Axes fixed in air wherever you are</td>
<td>Axes fixed in air wherever you are</td>
<td>No such axes</td>
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<tr>
<td>2 Laser Beam Direction Angles</td>
<td>$\theta_L$, $\phi_L$ from optics offsets and lidar scanner</td>
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<tr>
<td>3 Aircraft Rotations</td>
<td>Yaw = Heading, Pitch, Roll from INS/GPS</td>
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<tr>
<td>3 Aircraft Velocity Components</td>
<td></td>
<td>$V_{AE}$, $V_{AN}$, $V_{AU}$ from INS/GPS</td>
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<tr>
<td>3 Desired Wind Components</td>
<td></td>
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<td>$V_{WN}$, $V_{WE}$</td>
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<tr>
<td>Equations</td>
<td>Down = Belly Direction</td>
<td>$V_{AN} = V_{AE}$</td>
<td>$V_{AU}$</td>
<td>$V_{AN}^{*} = -V_{AN}$</td>
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<td></td>
<td>$V_{AE} = V_{AN}$</td>
<td></td>
<td>$V_{AE}^{*} = -V_{AE}$</td>
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<tr>
<td></td>
<td></td>
<td>$V_{AD} = -V_{AU}$</td>
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<td>$V_{AD}^{*} = V_{AD}$</td>
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</tbody>
</table>

Use INS/GPS yaw, pitch, roll to go between these two coordinate systems. Simple equations go between these pairs of coordinate systems.
Each pair of lines drawn represents shot accumulation consisting of 2 sec and 20 laser shots.

Each scan pattern has 5 of these “20 string harps” tilted rectangles. Each “harp string” is approximately a cylinder of 20 cm diameter.

Example of range gate length, 153.5 m in range, 133 m in height.
Wind Measurement Volume and Time
Assume DC-8 at 10.6 km or 34.7 Kft; going 144 m/s or 280 knots

Single Laser Pulse
• Light travels 12.242 km slant range to surface in 40.8 microsec (light in atmosphere)
• Beam diameter grows from 15 cm at DC-8 to 30 cm at surface
• Illuminated measurement volume $\sim \pi \times (0.1 \text{ m})^2 \times$ range gate length $\sim 5 \text{ m}^3$
• DC-8 flies forward 6 mm
• Repeats every 100 ms or 14.4 m; along-track duty cycle = 0.04%

LOS Wind Profile
• Consists of 20 laser shots evenly spaced over 2 s and 288 m
• Light in atmosphere time = $20 \times 40.8 \text{ microsec} = 817 \text{ microsec}$
• Illuminated measurement volume = $20 \times 5 \text{ m}^3 \sim 100 \text{ m}^3$
• Repeats every 4 s and 576 m along track distance; along-track duty cycle = 0.02% or 50%

u,v,w Wind Profile
• Consists of 5 LOS wind profiles at different azimuth angles
• Light in atmosphere time = $5 \times 817 \text{ microsec} = 4.1 \text{ ms}$
• Illuminated measurement volume = $5 \times 100 \text{ m}^3 \sim 500 \text{ m}^3$
• Repeats every 22 s and 3168 m along track distance
• Along-track duty cycle = 0.02% or 50% or 100%
DAWN Compared to Commercial Doppler Lidar Systems

Coherent detection wind lidar figure of merit*

\[
\text{(Minimum Required Aerosol Backscatter)}^{-1} \propto E \sqrt{PRF} D^2
\]

<table>
<thead>
<tr>
<th>Lidar System</th>
<th>Energy</th>
<th>PRF</th>
<th>D</th>
<th>FOM</th>
<th>FOM Ratio</th>
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<tbody>
<tr>
<td>Lockheed Martin CT WindTracer</td>
<td>2 mJ</td>
<td>500 Hz</td>
<td>10 cm</td>
<td>4,472</td>
<td>40</td>
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<tr>
<td>Leosphere Windcube</td>
<td>0.01</td>
<td>20,000</td>
<td>2.2</td>
<td>7</td>
<td>25,400</td>
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<tr>
<td>LaRC DAWN</td>
<td>250</td>
<td>10</td>
<td>15</td>
<td>177,878</td>
<td>1</td>
</tr>
</tbody>
</table>

The LaRC DAWN advantage in FOM may be used to simultaneously improve aerosol sensitivity, maximum range, range resolution, and measurement time (horizontal resolution).

*SNR is not a good FOM for coherent detection wind
DAWN Lidar Specifications

Mobile and Airborne
NASA DC-8
LaRC VALIDAR Trailer

Lidar System
15-cm diameter off-axis telescope
Dual balanced heterodyne detection
InGaAs optical detectors
Integrated INS/GPS

Pulsed Laser
Ho:Tm:LuLF, 2.05 microns
2.8 m folded resonator
~250 mJ pulse energy
10 Hz pulse rate
180 ns pulse duration
Master Oscillator Power Amplifier
Laser Diode Array side pumped, 792 nm
~Transform limited pulse spectrum
~Diffraction limited pulse spatial quality
Designed and built at LaRC

Lidar System in DC-8
Optics can in cargo level
Centered nadir port 7
One electronics rack in cargo level
Two electronics racks in passenger level
Refractive optical wedge scanner, beam deflection 30.12 deg
Conical field of regard centered on nadir
All azimuth angles programmable
DAWN Operation in GRIP

• DAWN was completed and shipped to Palmdale on 7/15/10 as required, much earlier than the AITT and IIP completion dates of 3/31/11 and 11/30/11

• DAWN operated and collected data for a large fraction of the 25 DC-8 flights (3 shakedown, 1 checkout, 6 ferry, and 15 science flights), and of the 139 total flight hours (113 science hours)

• Many of the flight hours were over or in thick clouds, which blocked the laser beam

• The laser pulse energy decrease from unplanned cooling at altitude was quickly mitigated, and workarounds implemented by the science flights

• Cloud layers revealed in the laser signal were frequently corroborated with the LASE display

• Post GRIP examination revealed a burned telescope secondary mirror which may have cost 10 dB or more in SNR

• Coverage of the atmosphere vertically was probably reduced due to the SNR loss

• Data analysis is proceeding and has already revealed lidar agreement with dropsonde when SNR is high
Telescope & Scanner

coherent lidar uses the same path for transmit and receive—transmitted path is shown here.
DAWN Assembly for Optical Alignment, and Pointing Control & Knowledge

Scan Pattern During GRIP

Example:
1 pattern = 22 s = 5.1 km
Along-Track & Temporal Resolution
Swath Width Depends on Flight Level
e.g., 6.5 km for 8 km FL

0 deg Azimuth at Surface is 4.6 km fore of DC-8
Not in the INS/GPS Manual

- Assumes sequence of rotation is yaw, then pitch, then roll
- Assumes sense of rotation is rotating axes rather than rotating vector
- Assumes true north, not magnetic north
1 Direction, 1 Laser Shot
Nominal Data Capture Parameters

ADC = 500 Msamples/sec, $\lambda = 2.0535$ microns, zenith angle = 30 deg., round-trip range to time conversion = $c/2 = 149.896$ m/microsec
Periodogram: Estimating Signal Frequency
After $N_p$ Shot Accumulation
One Range Gate, One Realization

Mean Data Level $= L_D$
Data Fluctuations $= \sigma_D = L_D / \sqrt{N_p}$

Mean Signal Power = area under mean signal bump but above mean noise level. $P_S = A_S = [(L_D - L_N) \cdot \Delta f \cdot 1]$ (if signal in one bin)

Mean Noise Level $= L_N$
Noise Fluctuations $= \sigma_N = L_N / \sqrt{N_p}$

Mean Noise Power = area under mean noise level $= P_N = A_N = L_N \cdot \Delta f \cdot (#$ Noise Bins)

$\Phi = (L_D - L_N)/L_N$

Data $= Signal + Noise$, $D = S + N$

$\int_{0}^{\infty} (Mean \ Periodogram) \ df = Ave. \ (Signal + Noise) \ Power$
Coherent or Heterodyne Lidar

Fractional wavelength or frequency change $\sim 7 \times 10^{-7} \sim 0.7$ ppm

1.4599306 $10^{14}$ Hz or 1.4599286 $10^{14}$ Hz

CW LO Laser

Pulsed Laser

Telescope

Detector

ADC

Computer

1.4599296 $10^{14}$ Hz

100 $10^6$ Hz
DAWN Pulsed Coherent Doppler Wind Lidar
Engineering/Science Parameter Tradeoffs

(Hold each expression constant for parameter trades)

1. Before Lidar Design and Fabrication

\[
z_{\text{AIRCRAFT}}^2 \Phi_{\text{MIN}}^{1,1,1} \left[ C_1 \ln \left( V_{\text{SEARCH}} \Delta z / (c \lambda \cos(\theta)) \right) + C_2 \right] \frac{N_{\text{AZIMUTHS}} V_{\text{H,AIRCRAFT}}}{ED^2 T^2 [\cos(\theta)]^5 \beta_{\text{MIN}}} \sqrt{\frac{(PRF) \Delta x \Delta z}{}}
\]

(1)

2. After Fabrication, Before Data Collection

\[
z_{\text{AIRCRAFT}}^2 \left[ C_1 \ln \left( V_{\text{SEARCH}} \Delta z \right) + C_3 \right] \frac{N_{\text{AZIMUTHS}} V_{\text{H,AIRCRAFT}}}{T^2 \beta_{\text{MIN}}} \sqrt{\Delta x \Delta z}
\]

(2)

Trade: aircraft height and velocity, vertical and horizontal resolution, minimum detectible aerosol level, atmospheric transmission, number of measured azimuth directions, and velocity search space

3. After Data Collection, Before Dissemination

\[
\left[ C_1 \ln \left( V_{\text{SEARCH}} \Delta z \right) + C_3 \right] \frac{1}{\beta_{\text{MIN}} \sqrt{\Delta x \Delta z}}
\]

(3)

Trade: vertical and horizontal resolution, minimum detectible aerosol level, and velocity search space

---

\[z = \text{altitude [m]}\]
\[z_{\text{AIRCRAFT}} = \text{aircraft altitude}\]
\[R = \text{range of lidar to target [m]}\]
\[R_{\text{MAX}} = z_{\text{AIRCRAFT}} / \cos(\theta)\]
\[\theta = \text{laser beam nadir angle [radians]} \quad [30^\circ]\]
\[\Phi = \text{detected coherent photoelectrons per shot per range gate [-]}\]
\[C_2 \Phi_{\text{MIN}}^{1,1,1} = \text{minimum usable } \Phi \text{ for 1 shot & 1 m range gate}\]
\[& \text{1 frequency bin search BW (} N_{\text{SEARCH}} = 1 \text{) } \sqrt{m}\]

\[N_{\text{SEARCH}} = 4 \Delta RV_{\text{SEARCH}} / (c \lambda) \quad [-]\]
\[\Delta R = \text{Data processing range gate length [m]}\]
\[V_{\text{SEARCH}} = \text{search band for wind velocity [m/s]}\]
\[\Delta z = \text{height resolution = } \Delta R \cos(\theta) \quad [m]\]
\[c = \text{speed of light [m/s]} \quad \lambda = \text{laser wavelength [m]} \quad [2.05 \times 10^{-6}m]\]
\[c\lambda / 4 \approx 150; \quad c\lambda / (4\Delta R) \approx 150 / \Delta R\]
\[E = \text{lidar laser pulse energy [J]} \quad [250 \text{ mJ}]\]
\[D = \text{circular receiver collection diamet [m]} \quad [0.15 \text{ m}]\]
\[T = \text{1-way atmospheric intensity transmission [-]}\]
\[\beta = \text{aerosol backscatter coefficient [m}^{-1} \text{sr}^{-1}]\]
\[N_{\text{AZIMUTHS}} = \text{number lidars scanner azimuths per repeated pattern [-]}\]
\[V_{\text{H,AIRCRAFT}} = \text{Aircraft horizontal velocity [m/s]}\]
\[\Delta x = \text{along-track horizontal resolution (pattern repeat) [m]}\]
## Wind Measurement Performance

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity accuracy (m/s)</td>
<td>1-2</td>
</tr>
<tr>
<td>Vertical resolution (km)</td>
<td>Selectable, typically 133 m</td>
</tr>
<tr>
<td>Horizontal integration per LOS (s)</td>
<td>Selectable, typically 2 s (~460 m)</td>
</tr>
<tr>
<td>Nadir Angle (deg)</td>
<td>30</td>
</tr>
<tr>
<td>Scan Pattern</td>
<td>5 azimuth angles/pattern (selectable) 1 pattern/22 s (~5000 m) (processing speed limited)</td>
</tr>
<tr>
<td>Range of regard (km)</td>
<td>0 – 12 (DC-8 to surface)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DAWN on DC-8</th>
<th>3-D Winds Decadal Survey Space Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Energy</td>
<td>0.25 J</td>
<td>0.25 J</td>
</tr>
<tr>
<td>Pulse Rate</td>
<td>10 Hz</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Receiver Optical Diameter</td>
<td>0.15 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td># Telescopes</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Scanner</td>
<td>Wedge</td>
<td>N/A</td>
</tr>
<tr>
<td>Nadir Angle</td>
<td>30 deg</td>
<td>45 deg</td>
</tr>
</tbody>
</table>
Pulsed Coherent Lidar Wind Measurement - 1

• 2-micron Tm:Ho:LuLF laser pulse $\tau = 180$ ns duration $\sim 54$ m long in atmosphere

• Rotating optical wedge scanner provides possible laser directions on surface of a cone with 30-degree half angle

• Axis of cone is nominally nadir, but changes with aircraft attitude (roll, pitch), and exact mounting

• Location of wind measurement determined by 1) aircraft position, 2) direction of laser, and 3) distance away along laser beam

• If $t = 0$ is firing of pulse, then return signal at $t$ is from ranges $c(t/2 - \tau/2)$ to $ct/2$. For example, $\tau = 180$ ns, $t = 10$ microseconds, signal is from 1471.98 to 1498.96 m (27 m). The entire 54 m laser pulse contributes to this signal

• Time from firing pulse gives distance away, leading to measurement position
Pulsed Coherent Lidar Wind Measurement - 2

- Laser pulse optical frequency = 1.4599296 $10^{14}$ Hz (Tm,Ho:LuLiF at 2.053472 microns)
- Return signal Doppler shifted by line-of-sight (LOS) lidar platform and wind velocities
  (+973,960 Hz per m/s of closing velocity, neglecting relativity)
- Optical detector surface mixes return signal with local oscillator (LO) beam to lower
  signal frequency by 8-14 orders of magnitude
- Maximum design horizontal wind (e.g., 100 m/s): horizontal wind bandwidth = 200 m/s
  or 194.792 MHz; LOS wind bandwidth = 97.396 MHz (at 30 deg. nadir)
- Pulsed laser to LO frequency offset and/or platform velocity designed to position 0 m/s
  wind signal at freq. $f_0$; possible signal freq. go from $f_0 - 48.7$ to $f_0 + 48.7$ MHz
- Return signal digitized at rate high enough to capture highest frequency, $f_0 + 48.7$ MHz,
  for example $f_S = 500$ Msample/second. Sample spacing = 2 ns
- Also mix LO with outgoing laser pulse, digitize, determine pulse-LO frequency
  difference, determine $t = 0$, and store these numbers for each pulse
• Now the data are in a computer 😊
• Locate correct \( t = 0 \) position in data
• Return signal divided into end-to-end time chunks of duration \( \Delta t \) for processing
• Range gate length is \( \Delta R = (c\Delta t)/2 \). For example, \( \Delta t = 1.024 \) microseconds, \( \Delta R = 153.5 \) m  
  [Height resolution is \( \Delta R \times \cos(\text{beam nadir angle}) \sim \Delta R \times 0.866 \) at 30 deg.]
• On each range gate, perform a 1024 ns/2 ns = 512 point FFT and calculate periodogram  
  (periodogram is energy content vs. frequency)
• Periodogram output frequency spacing = \( 1/\Delta T = 0.976562 \) MHz (1.003 m/s); highest frequency = \( f_S/2 = 250 \) MHz (256.7 m/s); number of output complex numbers = \( 250/0.976562 = 256 \); number of real output numbers = \( 2 \times 256 = 512 \)
• Repeat for multiple laser pulses and build up an average periodogram for each range gate
• Perform frequency estimation routine on accumulated periodogram for each range gate
  (e.g., determine frequency of highest peak in periodogram = “peak finding”)

• Correct frequency estimate by pulse-LO frequency difference

• Correct frequency estimate by platform (DC-8) velocity projected to LOS direction

• You now have a range (or height) profile of the wind velocity projected to the LOS direction

• Later probe the same air mass from a different azimuth direction and repeat all of the
  above for second, different perspective profile of the LOS wind (e.g., first
  azimuth = 45 deg. and second azimuth = 135 deg.; equal cross-track distances)

• Choice A: assume zero vertical wind and combine the two LOS profiles into a horizontal
  vector wind profile (magnitude and direction vs. altitude) or

• Choice B: Use a third azimuth direction; assume the wind at the new cross-track distance is
  the same; calculate the horizontal vector and vertical wind profiles

• You now have a horizontal wind profile 😊
“heterodyne detection can allow measurement of the phase of a single-frequency wave to a precision limited only by the uncertainty principle”

Michael A. Johnson and Charles H. Townes
Optics Communications 179, 183 (2000)
Dropsondes

- Airborne Vertical Atmospheric Profiling System (AVAPS)
- Vaisala
- Wind data every 0.5 sec
- < 400 g
- 7-cm diameter x 41-cm long
- Square-cone parachute
- Fall velocity = 12 m/s at sea level
September 1, 2010
Lidar scan number 118 of data folder 16:17:36
17:19:27 – 17:19:47; 5-axis

Latitude = 29.95 N
Longitude = 75.75 W
GPS Altitude = 10,611 m
Over Atlantic Ocean
Ground Speed = 224.6 m/s
True Heading = 146 degrees