Advancing Coherent-Detection 2-Micron Doppler Wind Lidar Technology towards Space Qualification

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<th>NASA Langley</th>
<th>Beyond Photonics</th>
<th>Simpson Weather Assoc.</th>
<th>Fibertek</th>
<th>NASA/ESTO</th>
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Multi-Decade Desire for Global Wind Measurements
A Very Strong Science Pull

- 2018 – National Research Council Earth Science Decadal Survey
  - 3-D Winds in 14 Priority Targeted Observables
  - 3-D Winds in 7 recommended Explorer missions
  - 3-D Winds in 3 recommended Incubation missions (NASA removed)
- 2018 – NOAA, NOAA Satellite Observing System Architecture (NSOSA) Study
  - 3-D Winds in 14 “Earth Weather” observations “High Leverage/Impact Category”
- 2018 – WMO, Observing Systems Capability Analysis and Review (OSCAR) Tool Data Base
  - 24 entries for “Wind, Horizontal”
  - Global measurements of ... horizontal wind vectors are urgently needed”
- 2007 – National Research Council Earth Science Decadal Survey
  - 3-D Winds in 15 missions recommended to NASA
  - “There is a clear requirement for a high-resolution observing system for atmospheric winds with full global coverage”
  - AEOLUS launch scheduled for August 2018!
Space Mission Concept: Vertical Profiles of Horizontal Winds
Pulsed Wind Lidar Optical Detection and Backscatter
Target Candidates for Space

<table>
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<tr>
<th>Atmospheric Target</th>
<th>Optical Detection</th>
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<tbody>
<tr>
<td>Molecules</td>
<td>Coherent (Heterodyne)</td>
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<tr>
<td>Aerosols, Clouds</td>
<td>2-Micron</td>
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- NASA Langley Coherent Wind Lidar
- NASA-NOAA “Hybrid” Wind Lidar Concept
- ESA AEOLUS, launch planned Aug. 2018 (1 LOS)
- Ball Aerospace OAWL
Depiction of Complementarity of a Space-Based Hybrid Wind Lidar

Altitude

Direct Doppler Lidar
“+ vertical coverage”

- Increasing Extinction

Coherent Doppler Lidar
“+ accuracy, resolution, provides wind turbulence”

- Decreasing Aerosols

Wind Comparison Opportunities

Velocity Error
Coherent-Detection Doppler Wind Lidar Technology Advancement

1972
Airborne Coherent Wind Lidar with CO₂ Laser

1990
Coherent Wind Lidar with 20-mJ 2-Micron Laser

1993
Airborne Coherent Wind Lidar with 2-Micron Laser (NASA Langley)

1993
Airborne Coherent Wind Lidar with CO₂ Laser

2003
1000-mJ 2-Micron Laser (NASA Langley)

2010
DAWN Airborne Coherent Wind Lidar, 250-mJ, 10 Hz 2-Micron Laser (NASA Langley)

2010
DAWN Airborne Coherent Wind Lidar, 250-mJ, 10 Hz 2-Micron Laser (NASA Langley)

1980
Coherent Detection Doppler Wind Lidar Technology Advancement

Doppler Aerosol WiNd (DAWN) Airborne Science Campaigns

<table>
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<tr>
<th>Year</th>
<th>Campaign Details</th>
<th>Location</th>
<th>Description</th>
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<tr>
<td>2010</td>
<td>Genesis and Rapid Intensification Processes (GRIP)</td>
<td>Fort Lauderdale, FL</td>
<td>Hurricane Research</td>
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<td>2014</td>
<td>Polar Winds – Greenland</td>
<td>Kangerlussuaq, Greenland</td>
<td>Polar Warming Research &amp; ADM Cal/Val Practice</td>
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<td>2015</td>
<td>Polar Winds - Iceland</td>
<td>Keflavik, Iceland</td>
<td>Polar Warming Research &amp; ADM Cal/Val Practice</td>
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<td>2017</td>
<td>CPEX</td>
<td>Fort Lauderdale, FL</td>
<td>Convection Research</td>
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<tr>
<td>2018</td>
<td>3 NASA Earth Venture Suborbital Proposals</td>
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Example of DAWN DC-8 to Surface Horizontal Wind Profile During CPEX

DAWN Typical Operation

6 June 2017
20:56:12 Zulu
15 cm receiver
100 mJ/pulse
10 Hz
1 W laser average power

20 shots/LWP
= 2 s/LWP
= 2 J optical energy emitted/LWP

5 LOS angles/HWP
= 100 laser pulses/HWP
= 10 s measurement time/HWP
= 10 J optical energy emitted/HWP

(~42 s elapsed time/HWP due to slow scanner turn speed and computer processing speed)

Courtesy Dr. David Emmitt, SWA
Example of Advanced Processing Algorithms Retrieving Additional Winds

Quicklook (V1)  
Processed Profile (V3)

Weak signal

Information retrieved with Adaptive Integration Algorithm

Courtesy Dr. David Emmitt, SWA
Coherent 2-Micron Wind Lidar Technology Advancement for Space “WIND-SP” Project

• NASA ESTO

• 3-year effort, 2017 – 2020

• Deliverables
  1. Conceptual design of a global wind space mission and instrument that proves the feasibility of returning valuable science
  2. Operational ground-based coherent detection lidar demonstrator instrument focusing on space advancement including coherent-detection Doppler wind lidar components & functions required for space
  3. Roadmap going forward that shows an understanding of the current design gaps and a logical progression towards a space mission

• Project Team
  • NASA Langley Research Center, Lead – 2053-nm pulsed transmitter laser, heterodyne detection, electronics, structure, computer control, software, data processing
  • Beyond Photonics – 2053-nm CW lasers, optical bench, transceiver enclosure, electronics, thermal
  • Simpson Weather Associates, Science Lead – mission concept, lidar parameter trades, advanced processing algorithms
  • Fibertek – 1940-nm Tm fiber pump laser
Optical Block Diagram Highlighting Lidar Technologies to be Advanced

- **CW Seed Laser - Fore**
- **CW Seed Laser - Aft**
- **Fiber CW Pump Laser**
- **Pulsed XMTR Laser**
- **Seed Switch**
- **Fore/Aft Switch**
- **“Transceiver”**

**Diagram Details:**
- CW Seed Laser - Fore
  - Δf
  - HET DET
  - HET DET
  - Δf
- CW Seed Laser - Aft
  - Δf
  - HET DET
  - HET DET
  - Δf
- CW LO Laser
- Fiber CW Pump Laser
- Pulsed XMTR Laser
  - Δf_{TX}
  - MON
  - EN DET
  - RES DET
- Fore/Aft Switch
  - T/R
  - T/R
  - HET DET
- “Transceiver”
Lidar Technologies to be Advanced & Their Space Function

- **Tm Fiber Pump Laser**
  - Develop space qualifiable laser

- **2-Micron Pulsed Transmit Laser**
  - Ho:LuLF, 56 mJ, 200 Hz, end-pumped
  - More wind measurements below, inside, and at tops of clouds [~70% cloudy; ~90% over oceans]
  - Lower pulse energy - less chance of optical damage
  - Easier heat removal from laser crystal – less chance of fracturing

- **Dual 5 GHz Tunable 2-Micron CW Seed Lasers**
  - Smaller, higher efficiency, fiber coupled
  - Remove orbit velocity & earth rotation Doppler shifts for much narrower receiver BW & ADC freq.
  - Dual GHz frequency offset circuits to tune the seed lasers
  - 5 GHz room temperature optical detectors for feedback loops, high QE not required
  - Single job, fore or aft – no large frequency jumps

- **2-Micron CW Local Oscillator Laser**
  - Smaller, higher efficiency, fiber coupled
  - Used for frequency offset circuits, outgoing pulse frequency difference optical detector, dual-balanced heterodyne optical detectors

- **EO Seed Laser Optical Switch**
  - Enables dual seed lasers instead of one laser with large frequency jumps

- **EO Fore/Aft Direction Optical Switch**
  - Enables two nonmoving telescopes
  - Enables fore/aft measurements with option for only a single lidar system operating

- **Dual-Balanced Heterodyne Optical Detectors for Atmospheric Signal**
  - High quantum efficiency, up to 90%
  - Room temperature
  - Integrated with custom optimized bias & preamplifier circuits
  - Fiber coupled; optimally located

- **Transceiver/Optical Bench**
  - Compact, rugged, rigid, thermal control
  - Auto-aligning
  - Low risk & cost
  - Space qualifiable components
  - Designs can be converted to graphite and heat pipe cooling
Advanced Coherent Wind Lidar Transceiver

Preliminary Concept

Transceiver Pressurized Enclosure
23” dia x 10.5” high

Courtesy: Dr. Sammy Henderson, Beyond Photonics
Designing a Pathfinder Wind Lidar Space Mission

Boundary Layer Mission Concept & Simulations

DAWN Airborne Validation

Pathfinder Space Wind Lidar Mission

New Higher Laser $f_L$ with Same Laser FOM; Lidar System

Past Space Simulations Using DAWN Laser FOM

Cloud Study with CALIPSO Data

\[
\text{Science} \propto \frac{1}{\beta_{MIN}} \propto FOM_{\text{LASER}} = \frac{E_{\text{LASER}} \gamma_{\text{LASER}}^{0.285}}{1 + (M_{\text{LASER}}^2)^2}
\]

Boundary Layer Science Advocacy:
- 2017 NRC Earth Science Decadal Survey (1/18)
- NAS Boundary Layer Workshop (10/17)
Example of Pathfinder Mission Concept Wind Products & Coverage

(420 km, 30 deg nadir, 60 cm, 56 mJ, 200 Hz, 1 km vertical resolution)

1.4 sec
10 km Cloud Gap Resolution

12 sec
80 km Resolution

HLOS wind error < 2 m/s

25 km altitude

% Successful Measurements
- Aerosol Backscatter
- Clouds

Courtesy Dr. David Emmitt, SWA
Future Tasks

• Validate advanced transceiver in flights including cloudy regions
• Space qualification tests
• Laser lifetime demonstration
• Fabricate 60-cm telescope prototype
• Fabricate engineering model
• Demonstrate pre-launch alignment validation GSE
Concluding Remarks

• Global horizontal winds are a critical science need
• The DAWN airborne lidar demonstrated the laser parameters required for space
• Currently developing required 2-micron coherent Doppler wind lidar components/functions for space
• Developing a higher pulse rate 2-micron laser matching DAWN FOM for greater science product in earth’s cloudy skies and for lower laser/optics risk
• Computer simulations of performance show highly desired boundary layer and other science products from a pathfinder mission
• The pathfinder mission will also refine/correct models of the atmosphere, clouds, surface reflectance, lidar technology, and wind velocity estimation algorithms for optimization of future wind missions
• Interest has been expressed in international collaboration with NASA, for example, Japan, France, and India. ESA is about to demonstrate a direct wind lidar in space.
Extra Slides
Why Coherent Wind Lidar is a Good Wind Sensor

• **Very Accurate Velocity Measurement**
  • Aerosols much heavier than molecules; less Brownian motion
  • Long laser pulse for narrow spectral width
    • Atmosphere dominated signal spectral width
  • Full signal spectrum captured
  • Processing in software more flexible than using optical elements
  • Frequency estimation; not intensity estimation
  • Result:
    • LOS velocity error ~ 20 – 110% of signal spectral width
    • Shot averaging, surface return, contextual information, etc. further reduces LOS error

• **High Photon Efficiency**
  • Heterodyne detection with LO provides immunity to background light
  • Sufficient LO power on detector effectively eliminates all noise except LO shot (quantum) noise
  • Receiver bandwidth from IF electronics, not an optical element, much narrower
  • Frequency estimation more photon efficient than intensity estimation
  • Result:
    • Excellent horizontal & vertical resolution
    • Equal day/night operation

• **Multiple Data Processing Options & Additional Data Products**
  • Full signal spectrum captured
  • Processing in software more flexible than using optical elements; optimize for conditions
  • Result:
    • Multiple trades of resolution, aerosol sensitivity, probability of outliers, velocity search space, etc.
    • Wind turbulence (second moment)

➢ Coherent lidar well suited to space wind measurement
Coherent Wind Lidar has Two Wind Measurement Figures of Merit
Not Just Velocity Accuracy

gΦ which is $\propto CNR_w$, is a better parameter than SNR for coherent lidar wind estimation

Over seven (7) orders of magnitude of Φ (e.g., aerosol backscatter):

Velocity error $\sigma_E$ stays between 20% and 110% of the signal spectrum width $\sigma_S$, which is an accurate wind estimate

More important than velocity error, the fraction of wind estimates $P_G$ that are "good", i.e., grouped near the true wind value steeply falls from 1 to 0 within two orders of magnitude (typical $P_G$ requirement is 50% - 90%)

In the case shown $P_G = 0.5$ corresponds to $\Phi \approx 50$ and $\sigma_E/\sigma_S \sim 80\%$. Or $P_G = 0.9$ corresponds to $\Phi \approx 107$ (approx. doubled) and normalized error $\sigma_E/\sigma_S \sim 50\%$. 

Fig. 8. The standard deviation $g$ of the "good" ML estimates for mean frequency and the fraction $h$ 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).
Coherent-Detection Wind Measurement
Visualizing the Probability of a “Good” Estimate $P_G$

Actual lidar data (not DAWN) – velocity estimate vs. pulse; 6000 shots at 4.9 Hz

- 6,000 wind estimates over 1,200 seconds reveal how increasing $\Phi$ increases probability of a good estimate, and reduces wind estimate error

- The “bad” wind estimates are uniformly distributed over the processing algorithm’s allowed velocities

![Graph showing wind estimates vs. time]

Higher $\Phi$ at $R = 1$ km

Lower $\Phi$ at $R = 5$ km
Coherent-Detection Wind Measurement
Improvement From Shot Averaging

- Actual lidar data (not DAWN) – velocity estimate vs. pulse; 6000 shots at 4.9 Hz; R = 5 km “lower F”
- Shot accumulation improves both “good” probability and velocity accuracy

1 laser pulse

10 laser pulses averaged
Doppler Aerosol WiNd (DAWN) Profiling Lidar System

Ho:Tm:LuLF laser, 2.053 microns
250 mJ, 10 Hz, 200 ns
15-cm telescope, off-axis, afocal
Step-stare rotating wedge scanner
30° nadir angle
Up to 12 azimuth (LOS) angles/horizontal wind profile
(example 5 angles in figure below)
Dual-balanced heterodyne detection
500 MHz ADC signal sampling
Computer software shot averaging, range gate segmentation for vertical resolution, frequency estimation

~2.5 km (depends on shot averaging, A/C speed)
• The following represent an initial set of science experiments/objectives
  • Investigate inter-hemispherical transports via LLJs and within tropical convergence zones (ITCZ); How prevalent and energetic are LLJs over the oceans?
  • Develop improved parameterization schemes for PBL depths and growth rates for use in global weather and climate models...especially marine BLs.
  • Investigate the role of vertical shear of the horizontal wind in regions of deep convection and in tropical cyclone maintenance and suppression.
  • Investigate dynamic impacts such as speed and directional shear on the global trans-oceanic transport of pollution.

Courtesy Dr. David Emmitt, SWA
Space Mission Concept: Measure Air Mass from Two Perspectives

ESTO WIND-SP

Shot N Return, 3.1 ms, 24 m forward, 3.5 μrad nadir tilt

Laser Shot N + 1: 5 ms, 38.4 m, 5.7 μrad

Aft Laser Shot N 46 s

Shot N 2400 shots, 12 s, 86.7 km

TX1 RX1 TX2

200 Hz, 36.1 m
Example of Pathfinder Mission Concept Wind Products & Coverage

1.4 sec
10 km Cloud Gap Resolution

12 sec
80 km Resolution

25 km altitude
Baseline Laser

Threshold Laser

ESTO WIND-SP
HLOS wind error < 2 m/s

Courtesy: David Emmitt
End-to-End Mission Concept Design

- Several NASA space instrument & mission design studies performed in the past
- Studies baselined coherent lidar laser parameters of DAWN at 250 mJ, 5 or 10 Hz
- Simpson Weather Associates sophisticated space wind lidar performance simulation utilized DAWN laser parameters for mission design & science products
- Coherent wind lidar laser figure of merit (FOM) is linked to aerosol backscatter sensitivity

\[
\frac{1}{\beta_{MINIMUM}} \propto FOM_{LASER} \approx \frac{E_{LASER} \sqrt{PRF_{LASER}} \tau_{"0.285"}^{0.285}}{1 + (M_{LASER}^2)^2}
\]

- Backscatter $\beta$, $E$ – energy, pulse repetition frequency (PRF), duration $\tau$, beam quality $M^2$
- New Langley laser baseline and threshold requirements duplicate aerosol backscatter sensitivity of 250 mJ, 10 and 5 Hz, respectively
- Baseline 56 mJ, 200 Hz, 200 ns, 1.1; threshold 42 mJ, 200 Hz, 150 ns, 1.1
- Computer simulation new & previous results predict science products of new laser
Wind Lidar Space Mission Velocities

- Speed of Light: 3.0E+08 m/s
- S/C Motion (proj.): 2884.2 m/s
- Earth Motion (proj.): 174.1 m/s
- Design Maximum Horizontal Wind (proj.): 53.1 m/s
- Design full horizontal search BW: 37.6 m/s
- Desired Wind Precision: 1.0 m/s
1 km horizontal path, 1 atm, 296K, US Standard Atmosphere, H₂O, CO₂