Atmospheric Boundary Layer Lidar PathfindEr (ABLE): Crosscutting DIAL for Humidity Profiling

Amin R. Nehrir

amin.r.nehrir@nasa.gov

Rory Barton-Grimley\textsuperscript{1}, Anthony Notari\textsuperscript{1}, David Harper\textsuperscript{1}, Trevor Jackson\textsuperscript{1}, Charles Antill\textsuperscript{1}, Tory Scola\textsuperscript{1}, Alex Zahn\textsuperscript{1}, Brian Carroll\textsuperscript{1}, Patrick Burns\textsuperscript{2}, Manoj Kanskar\textsuperscript{3}, Jes Sherman\textsuperscript{4}, Leif Johansson\textsuperscript{4}, Wayne Welch\textsuperscript{5}

\textsuperscript{1}NASA Langley Research Center, Hampton, VA
\textsuperscript{2}Fibertek Inc., Herndon, VA
\textsuperscript{3}nLIGHT, Vancouver, WA
\textsuperscript{4}Freedom Photronics, Santa Barbara, CA
\textsuperscript{5}Welch Mechanical Designs, Aberdeen, MD
The 2017 Decadal Survey and the World Climate Research Program Grand Challenges highlight the need for:

- accurate, high vertical resolution water vapor measurements in the PBL and aloft
- a deeper understanding of the role of clouds in weather and climate systems which requires accurate and high vertical resolution humidity observations around clouds
Observational Needs from Grand Challenges to the Decadal Survey

The 2017 Decadal Survey and the World Climate Research Program Grand Challenges highlight the need for:

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How Do we Currently Observe Atmospheric Water Vapor?

- Passive infrared (IR) and microwave (MW) observations form the backbone of NWP and climate science communities.
- IR and MW sounders provide global coverage, but have limited sensitivity to the lower troposphere and have coarse vertical resolution.
- GNSS-RO provides extremely high vertical resolution, however, unraveling temperature from humidity signal poses a challenge.
Differential Absorption Lidar (DIAL) – Principles and Characteristics

- DIAL measures the differential attenuation of lidar signals between on and off transmitted wavelengths
- Multiple wavelengths can extend dynamic range from UT/LS down to PBL
- Accuracy in the PBL is independent of humidity and aerosol signals aloft
- DIAL directly measures water vapor without need for calibration or a priori information on atm. state

Retrieved Number Density Profile

\[ n(r) = \frac{1}{2\Delta r \Delta \sigma(r)} \ln \left( \frac{P_{off}(r_2)}{P_{on}(r_2)} \cdot \frac{P_{on}(r_1)}{P_{off}(r_1)} \right) \]

Random Error

\[ \frac{\Delta n}{n} \propto (\Delta x)^{-0.5} (\Delta R)^{-1.5} \]

- trade precision for resolution
- along track averaging
- vertical averaging
Airborne DIAL Heritage – High Altitude Lidar Observatory (HALO)
DIAL Pathfinder – Atmospheric Boundary Layer Lidar PathfindEr

- Develop a pathfinder mission concept and advance associated technologies to enable the first demonstration of DIAL in space
  - Water vapor profiling from mid-troposphere to PBL
  - 200-400 m resolution in the PBL, 1 km in mid-trop
  - 50-75km along track resolution

- Novel laser technologies enable crosscutting science spanning disparate science focus areas
  - Weather and dynamics (including PBL)
  - Atmospheric composition and radiation
  - Carbon Cycle

- Set stage for synergistic observing system with other active and passive sounders

- Balance performance/complexity with affordable and flexible design to fit within future cost capped missions
Development approach

1. Develop space qualifiable Er:YAG laser transmitter
2. Increase efficiency of 1532 nm pump diodes to enable operation on smallsat
3. Develop photonic integrated circuit seed laser as injection seeding source
4. Develop satellite instrument concept capable of rideshare launch on ESPA Grande
Pulsed Laser Advancement – Challenges and Driving Requirements

- 820 nm spectral band is attractive for space-based water vapor DIAL
  - Absorption lines provide sensitivity to the mid-lower troposphere
  - Enhanced Rayleigh scattering compared to SWIR
  - Allows for use of efficient, single photon sensitive Si detectors
  - Spectrum accessed by efficient emerging laser technologies

- Laser transmitter is one of the primary challenges for space-based DIAL
  - High efficiency and low complexity for small SWaP
  - High peak and average power, frequency agile and good beam quality

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### Near Infrared Laser Survey

<table>
<thead>
<tr>
<th>Laser</th>
<th>Efficiency to 820 nm</th>
<th>Power (W)</th>
<th>~Pulse Energy</th>
<th>Complexity</th>
<th>Maturity</th>
<th>Materials/Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti:Sapphire</td>
<td>1-2%</td>
<td>5-10</td>
<td>100 mJ</td>
<td>5 parts</td>
<td>Mature</td>
<td>Diodes Nd 2x Ti:Sapphire</td>
</tr>
<tr>
<td>OPO</td>
<td>1-2%</td>
<td>5-10</td>
<td>50-80 mJ</td>
<td>5 part</td>
<td>Mature</td>
<td>Diodes Nd 2x OPO/OPA</td>
</tr>
<tr>
<td>Tm:LiYF₄ (YLF)</td>
<td>5-8%</td>
<td>20-30</td>
<td>10-15 mJ</td>
<td>2 parts</td>
<td>Emerging</td>
<td>Diodes Tm:YLF</td>
</tr>
<tr>
<td>Er:YAG</td>
<td>2-3%</td>
<td>6-10</td>
<td>3-5 mJ</td>
<td>3 parts</td>
<td>Emerging</td>
<td>Diodes Er:YAG 2x</td>
</tr>
</tbody>
</table>

A transmitter for space-based mission has been a challenge pursued for >3 decades
Pulsed Laser Advancement – Reducing complexity and enabling crosscutting science

- Doubled Er:YAG provides access to appropriate strength water vapor lines in the NIR
- Reduced complexity compared to heritage airborne DIAL transmitters
- Dual wavelength Er:YAG allows for crosscutting science that addresses several 2017 Decadal Survey Target Observables
  - Water vapor profiles and PBL heights – PBL Incubation
  - Methane columns – Earth Explorer
  - Aerosol/cloud distributions – ACCP Continuity

HALO Methane Columns
Pulsed Laser Advancement – Er:YAG Performance

- Er:YAG laser developed for airborne applications meets many of the requisite characteristics for space-based DIAL
- Observed 1645/822 nm pulse energy agrees with laser rate equation models
- Single frequency and high spectral purity operation demonstrated via injection seeding
- Worlds first and only demonstration of all electro-optic cavity stabilization (i.e. no moving parts)

Energy vs PRF

Injection Seeding

High Voltage Driver
Pulsed Laser Advancement – Technology Advances

• Er:YAG technology advances
  - Increase PRF from 1kHz to >2kHz with >6 mJ at 1645 nm
  - Increase optical to optical efficiency from 10% to 20%
  - Replace TEC for Er:YAG gain heads with heat pipes resulting in 25% reduction in power consumption
  - Heat pipe thermal management of optical bench

• Design and build a TRL 5 laser optical module for future qualification

• Er:YAG offers the world’s first direct measure of the critical water vapor cycle plus the highest resolution spatial sampling of methane sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1645/823 nm</td>
<td>1645/823 nm</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>6.5 mJ</td>
<td>6-7 mJ</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>1 kHz</td>
<td>2-3 kHz</td>
</tr>
<tr>
<td>Average Power</td>
<td>6.5 W</td>
<td>13-14 W</td>
</tr>
<tr>
<td>SHG Efficiency</td>
<td>50%</td>
<td>50-60%</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>120 ns</td>
<td>100-120 ns</td>
</tr>
<tr>
<td>Linewidth</td>
<td>19 MHz</td>
<td>&lt;100 MHz</td>
</tr>
<tr>
<td>Spectral Purity</td>
<td>1000:1</td>
<td>≥ 1000:1</td>
</tr>
<tr>
<td>Wavelength Tuning</td>
<td>shot-to-shot</td>
<td>shot-to-shot</td>
</tr>
<tr>
<td>System Efficiency</td>
<td>1.4%</td>
<td>≥ 5%</td>
</tr>
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</table>
Pump Laser—Increase Efficiency and Brightness

- Increase efficiency of commercially available 1532 nm pump diodes from ~20% to >40% with ≥ 35 W output power

- Multi-pronged approach to increasing efficiency
  - Optimize diode epitaxial design
  - Achieve higher brightness through optical mode control
  - Increase optical throughput
  - Increase thermal conductivity

- Preliminary results demonstrate >35% efficiency with 3x brightness

- Improved efficiency and brightness allows for optimization of pulsed laser architecture and power scaling for more capable mission concepts
Seed Laser – Bridging the gap from airborne to flight

- Seed laser is the heart of DIAL systems and can affect the accuracy of the DIAL retrieval.
- Discrete components used in airborne systems not compatible with SWaP constraints on SmallSats.
- Photonic integration employed to significantly reduce SWaP and increase reliability.

**TRL 9 Airborne**

**Photonic Integration**

**TRL 5 Flight**
Seed Laser – Photonic Integrated Circuit

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PIC Seed Laser Source – Architecture

Transmitter Timing Diagram

Seed Laser Lock

Pulsed Laser Lock

InP Platform

InP Platform

B M

Gain Phase

FM

Secondary Laser

SOA

Primary Laser

PLL Electronics

RF Inputs

RF Outputs

FPGA

Drive Electronics

Oscillators

Offset Frequency (GHz)

Time (µs)

Laser Fire

\(\lambda_{\text{mid trop.}}\)

\(\lambda_{\text{PBL}}\)

\(\lambda_{\text{off}}\)
PIC Seed Laser Source – Preliminary Results

• PIC exhibits requisite performance for space-based DIAL
  - Primary seed laser has >5x the required power for line locking allowing for adequate derating
  - >20 mW from secondary seed laser allows efficient seeding of Er:YAG pulsed laser
  - Both primary and secondary lasers have broad continuous tuning range
  - Demonstrated rapid scanning across CH$_4$ lines suitable for step-locked optical phase lock loop

• Current focus is on characterizing bandwidth of balanced detectors and coupling to RF components
Spacecraft Accommodations and Systems Engineering

- Spacecraft accommodation survey identified several ESPA class buses suitable for capable lidars
- Highly evolving industry shows promise for accommodating space-based DIAL SWaP requirements
- Preliminary systems engineering study demonstrates the feasibility of DIAL on SmallSat platforms

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Energy (822/1645 nm)</td>
<td>3.5 mJ/3.5 mJ</td>
</tr>
<tr>
<td>Repetition Frequency</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Telescope Diameter</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Field of View (H₂O/CH₄)</td>
<td>50/200 µrad</td>
</tr>
<tr>
<td>H₂O DIAL Detector</td>
<td>Si Photon Counting</td>
</tr>
<tr>
<td>CH₄ Detector</td>
<td>InGaAs APD</td>
</tr>
<tr>
<td>Payload Power</td>
<td>~400 W</td>
</tr>
<tr>
<td>Orbit</td>
<td>Polar – 500 km</td>
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</table>
Acknowledgments